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(54) **DUAL-STAGE INDUCTORLESS SWITCHED-CAPACITOR CONVERTER WITHOUT DIVISOR DEPENDENCY**

(71) Applicant: **Silego Technology Inc.**, Wilmington, DE (US)
(72) Inventors: **Kevin Yi Cheng Chang**, Chandler, AZ (US); **Julian Tyrrell**, Swindon (GB)
(73) Assignee: **SILEGO TECHNOLOGY INC.**, Wilmington, DE (US)

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(58) **Field of Classification Search**
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H02M 3/157; H02M 3/158
See application file for complete search history.

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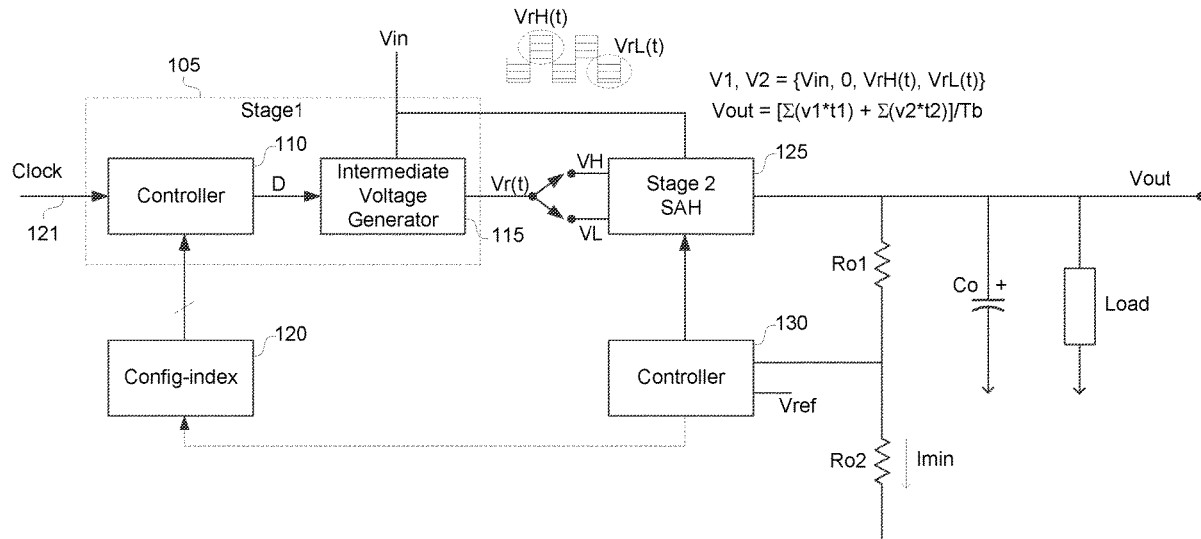
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Primary Examiner — Adolf D Berhane
(74) *Attorney, Agent, or Firm* — Haynes and Boone, LLP

(57) **ABSTRACT**

A switched-capacitor converter is provided that includes an intermediate voltage generator having a flying capacitor. A sampling and hold circuit samples a top plate voltage for the flying capacitor and samples a bottom plate voltage for the flying capacitor to form an output voltage for the switched-capacitor converter.

20 Claims, 5 Drawing Sheets



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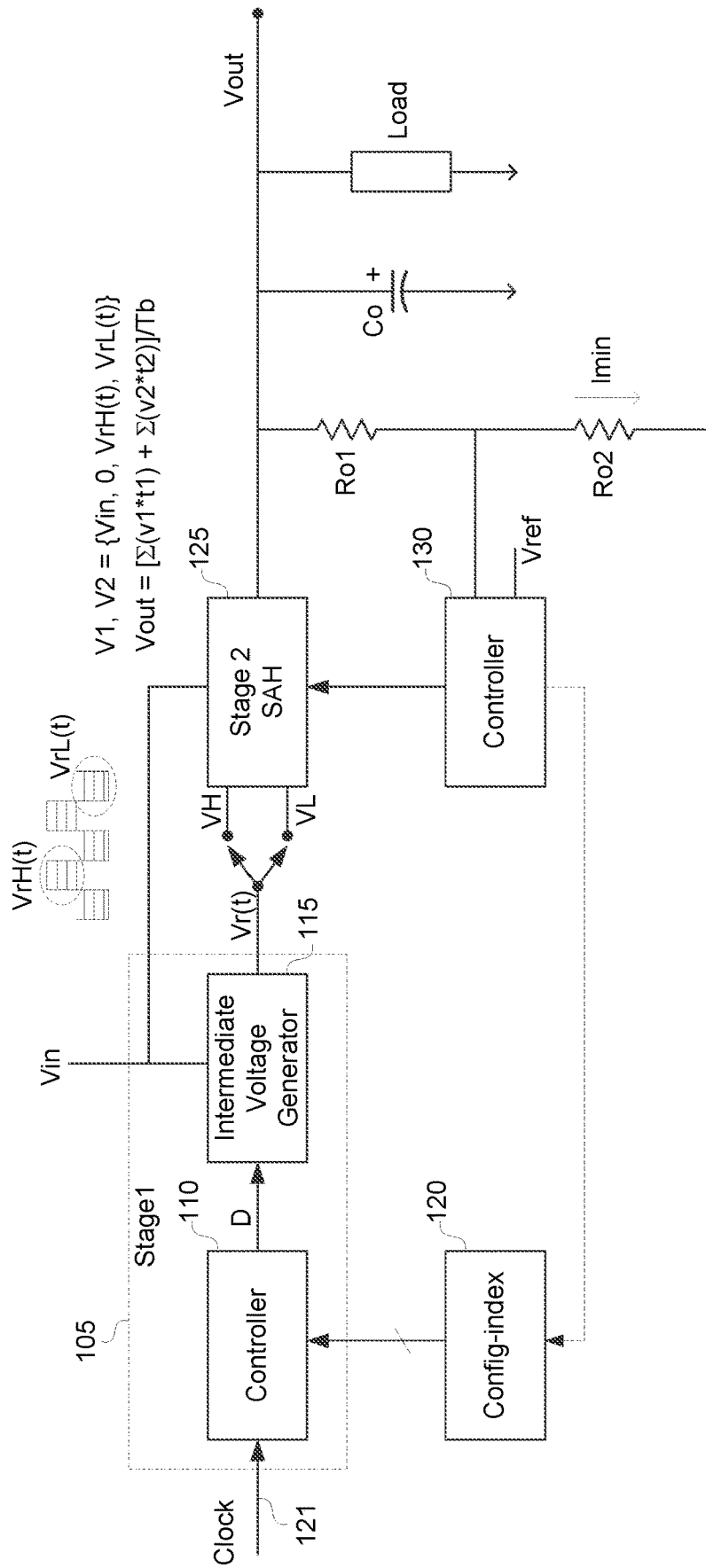


FIG. 1

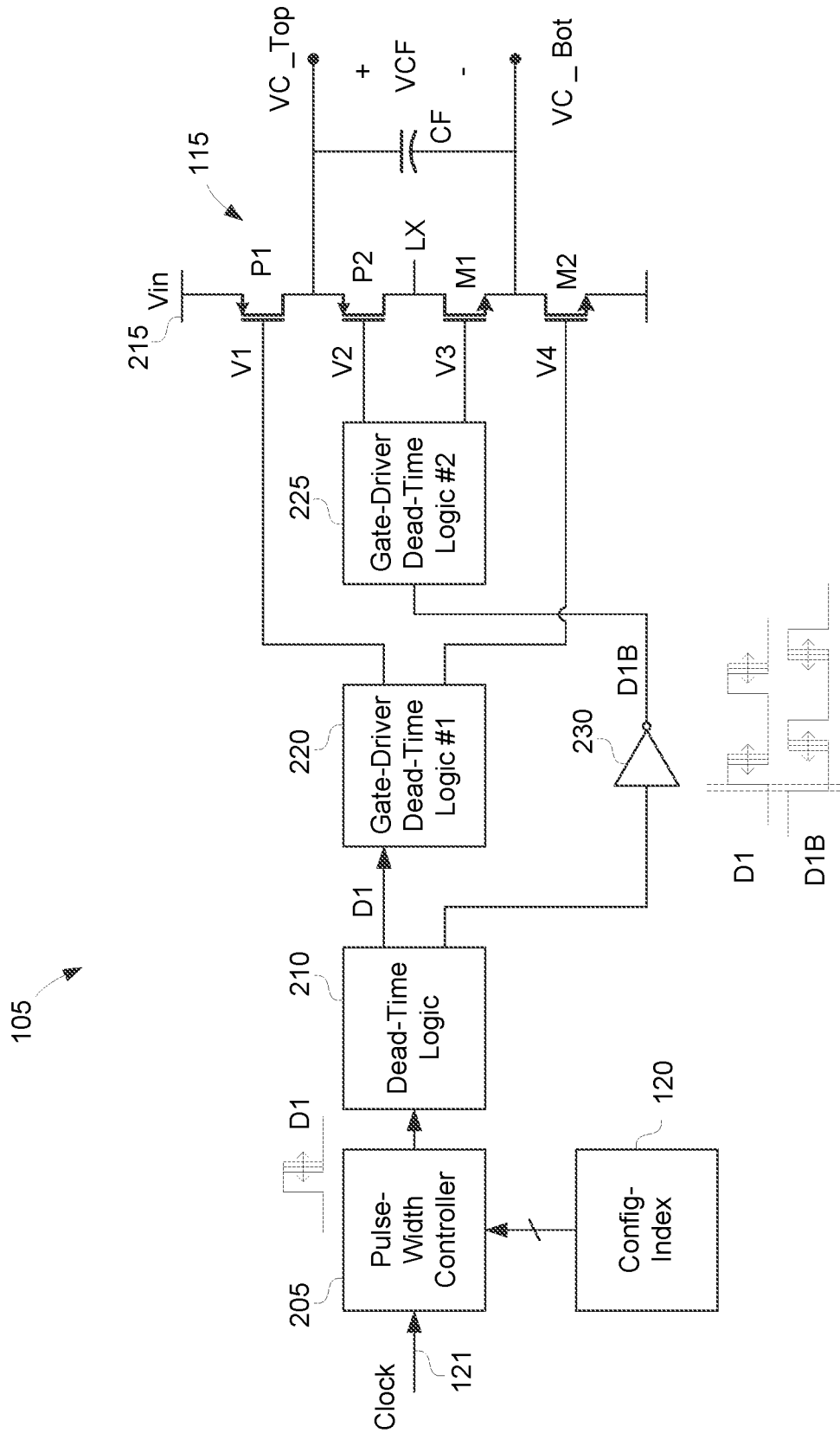


FIG. 2

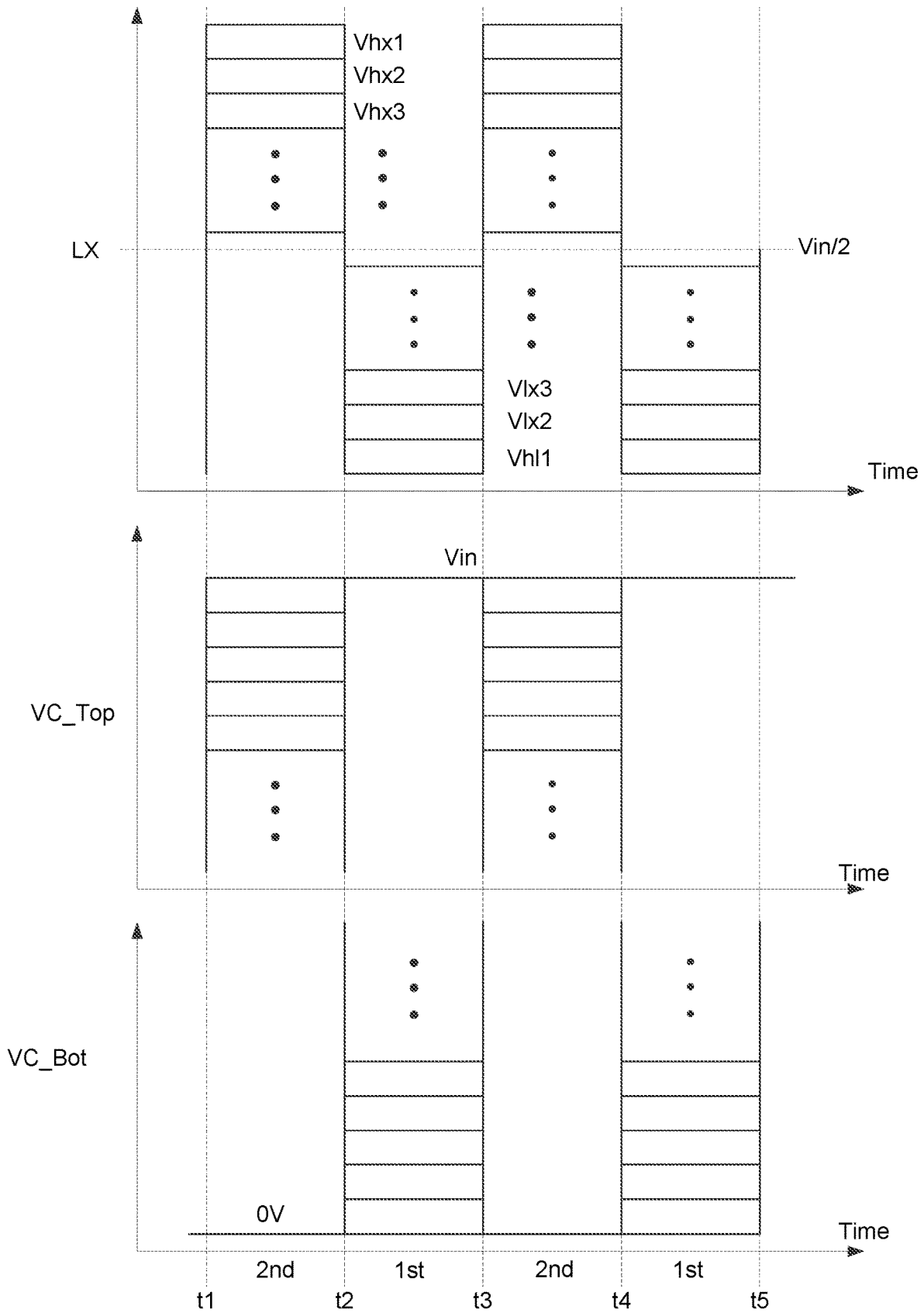


FIG 3

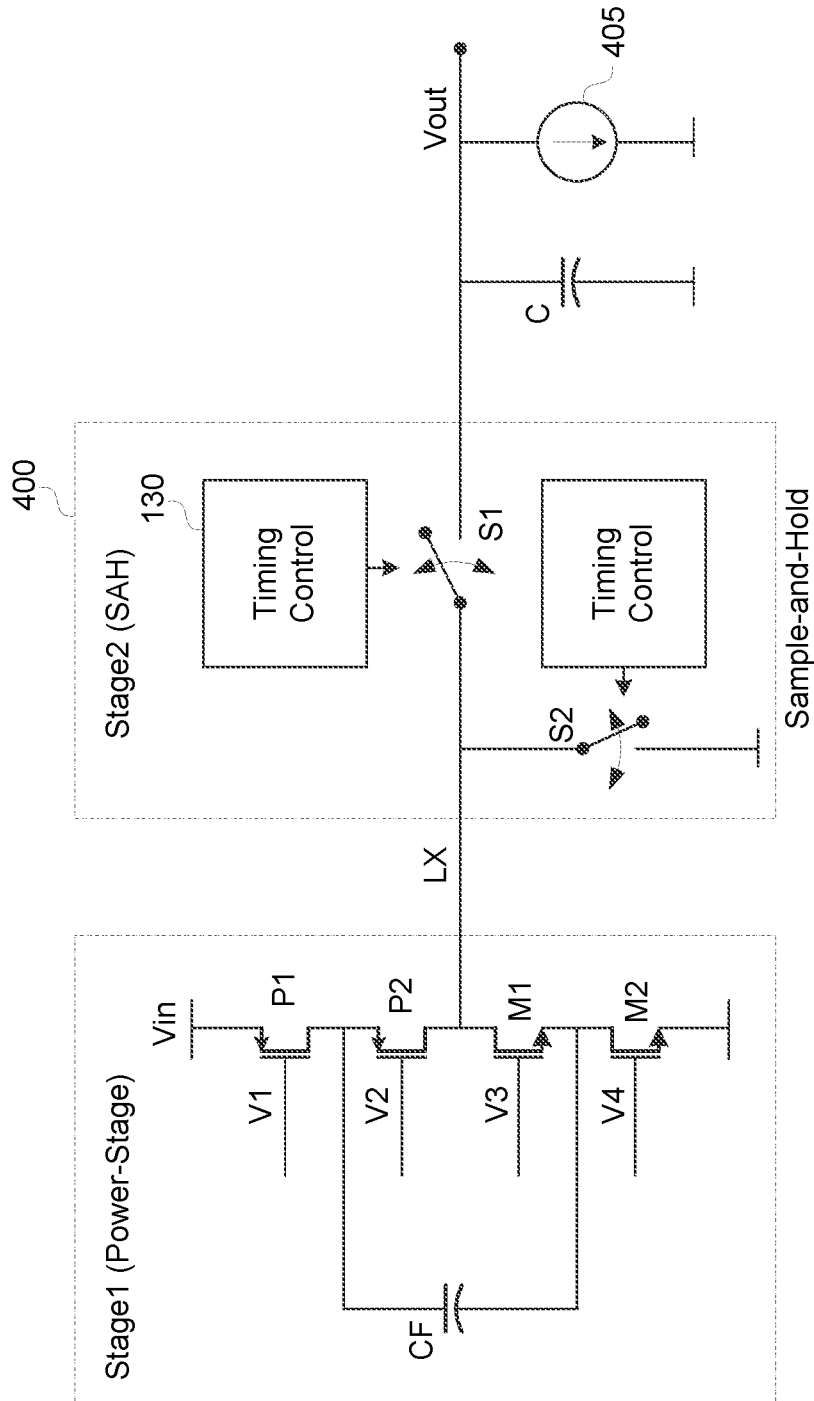


FIG. 4

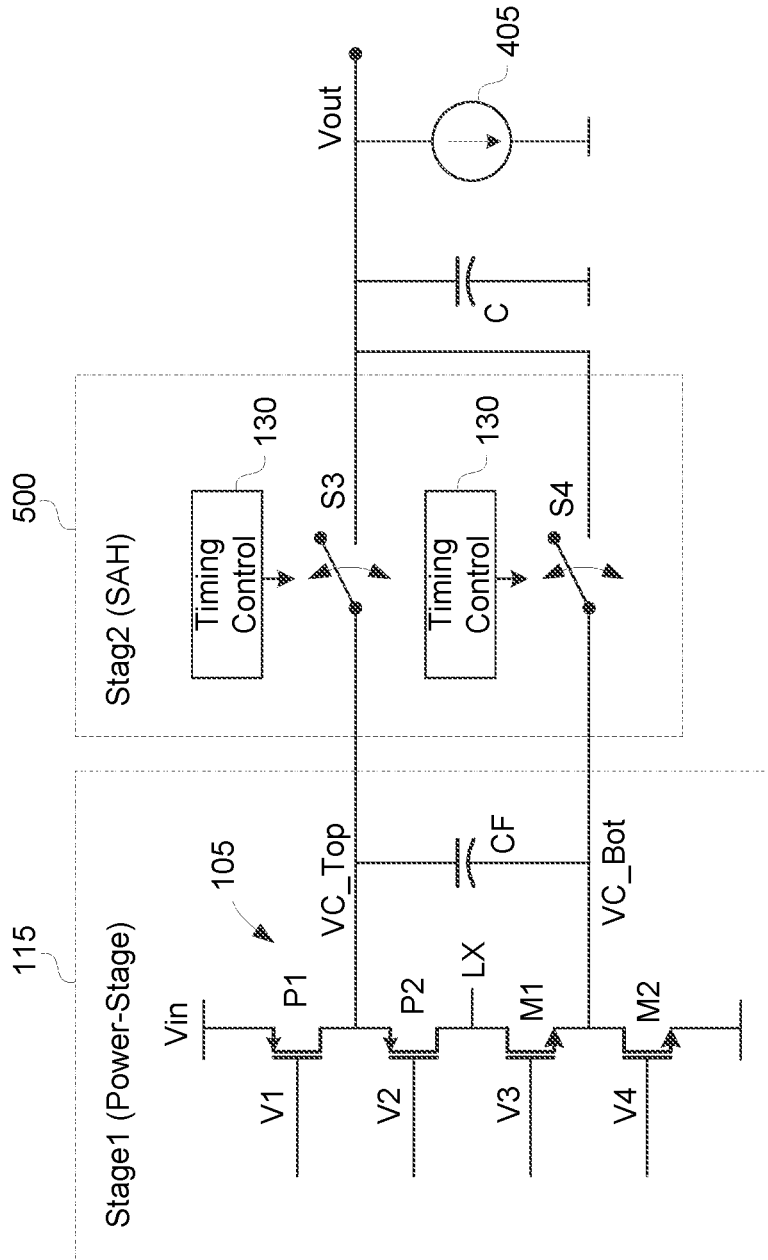


FIG. 5

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DUAL-STAGE INDUCTORLESS SWITCHED-CAPACITOR CONVERTER WITHOUT DIVISOR DEPENDENCY

TECHNICAL FIELD

This application relates to switched-capacitor converters, and more particularly to an inductorless switched-capacitor converter without divisor dependency.

BACKGROUND

A switched-capacitor converter typically generates an output voltage that is inversely proportional to a divisor such as 1.5, 2, or 3. The switched-capacitor converter divides an input voltage by the divisor to form the output voltage. As compared to a buck converter, a switched-capacitor converter offers a number of advantages such as low cost (no inductor), ease of integration, high efficiency, and fast transient responses. But conventional switched-capacitor converters are limited by the fixed divisor relationship between its input and output voltages.

Accordingly, there is a need in the art for switched-capacitor converters without divisor dependencies between their input and output voltages.

SUMMARY

In accordance with a first aspect of the disclosure, a switched-capacitor converter is provided that includes: a first switching stage including a flying capacitor, wherein the first switching stage is configured in a first switching configuration during a first portion of a clock signal period to charge the flying capacitor with an input voltage and is configured in a second switching configuration during a second portion of the clock signal period to charge a switch node with the flying capacitor; and a sampling and hold circuit configured to couple the switch node to a sampling capacitor for a first sampling time during the second switching configuration and further configured to couple the switch node to the sampling capacitor for a second sampling time during the first switching configuration to form an output voltage for the switched-capacitor converter across the sampling capacitor.

In accordance with a second aspect of the disclosure, a switched-capacitor converter is provided that includes: a first switching stage including a flying capacitor, wherein the first switching stage is configured in a first switching configuration during a first portion of a clock signal period to charge the flying capacitor with an input voltage and is configured in a second switching configuration during a second portion of the clock signal period to charge a switch node with the flying capacitor; and a sampling and hold circuit configured to couple a top plate of the flying capacitor to a sampling capacitor for a first sampling time during the second switching configuration and further configured to couple a bottom plate of the flying capacitor to the sampling capacitor for a second sampling time during the first switching configuration to form an output voltage for the switched-capacitor converter across the sampling capacitor.

In accordance with a third aspect of the disclosure, a method for a switched-capacitor converter is provided that includes: charging a flying capacitor during a first switching configuration for an intermediate voltage generator for a first portion of a clock signal period; charging a switch node with the flying capacitor during a second switching configuration for the intermediate voltage generator for a second portion

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of the clock signal period; coupling a top plate for the flying capacitor to a sampling capacitor for a first sampling time during the second switching configuration for the intermediate voltage generator; and coupling a bottom plate of the flying capacitor to the sampling capacitor for a second sampling time during the first switching configuration for the intermediate voltage generator to develop an output voltage for the switched-capacitor converter across the sampling capacitor.

These advantageous features may be better appreciated through a consideration of the detailed description below.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of an example switched-capacitor converter in which the output voltage does not have a divisor dependency in accordance with an aspect of the disclosure.

FIG. 2 is circuit diagram of an example first stage for a switched-capacitor converter in accordance with an aspect of the disclosure.

FIG. 3 illustrates some example top plate, bottom plate, and switching node voltages for the first stage of FIG. 2.

FIG. 4 illustrates a second stage embodiment in which the switching node voltage from the first stage is sampled in accordance with an aspect of the disclosure.

FIG. 5 illustrates a second stage embodiment in which the top and bottom plate voltages from the first stage are sampled in accordance with an aspect of the disclosure.

Embodiments of the present disclosure and their advantages are best understood by referring to the detailed description that follows. It should be appreciated that like reference numerals are used to identify like elements illustrated in one or more of the figures.

DETAILED DESCRIPTION

To eliminate the divisor dependency for its output voltage, a switched-capacitor converter is disclosed that includes a first stage and a second stage. The first stage may also be referred to as a power stage and includes four first switch transistors in series. A first one of the switch transistors connects between an input voltage rail for an input voltage and a second one of the switch transistors. The second switch transistor connects from the first switch transistor through a switching node to a third transistor. The third transistor couples to ground through the fourth transistor. A flying capacitor includes a top plate that connects to a node between the first and second switch transistors. Similarly, the flying capacitor includes a bottom plate that connects to a node between the third and fourth switch transistors. The following discussion will assume that the first and second switch transistors are PMOS switch transistors and that the third and fourth switch transistors are NMOS transistors, but it will be appreciated any suitable type of switch transistors may be used in alternative embodiments.

A power stage controller controls the switch transistors in the power stage to alternate between two configurations. In a first configuration, the first switch transistor and the third switch transistor are both on while the second switch transistor and the fourth switch transistor are both off. In this first configuration, an input voltage rail drives a top plate of the flying capacitor through the switched-on first switch transistor. The bottom plate of the flying capacitor drives the switching node through the switched-on third switch transistor. An output current thus flows from the input voltage rail through the flying capacitor to the switching node to charge the flying capacitor in the first configuration. In the

second configuration, the second switch transistor and the fourth switch transistors are both on while the first switch transistor and the third switch transistor are both off. The flying capacitor thus discharges during the second configuration to charge the switching node.

The power stage controller controls a pulse width modulation of the two switching configurations so that the pulse widths are complementary. For example, if the duty cycle for the first switching configuration is D , the duty cycle for the second switching cycle will be approximately $1-D$. To prevent an overlap between the two switching configurations, there is some dead time such that the two switching configurations are approximately complementary as compared to being exactly complementary. In the second switching configuration, the bottom plate of the flying capacitor is grounded whereas the top plate is being charged. Depending upon the duty cycle D , the top plate voltage will range from a low of $V_{in}/2$ to a high of V_{in} , wherein V_{in} is the input voltage on the input voltage rail. In particular, as D approaches one, the top plate voltage will approach V_{in} during the first switching configuration. In contrast, the top plate voltage will fall towards $V_{in}/2$ as D approaches zero.

Similarly, the bottom plate voltage will range between zero and $V_{in}/2$ during the first switching configuration. The switching node voltage (which is also denoted herein as the LX voltage) has a similar voltage profile to the top plate voltage during the first switching configuration and to the bottom plate voltage during the second switching configuration. By changing the duty cycle D , the power stage controller controls the voltages for the top plate, the bottom plate, and the switching node in the first switching configuration and in the second switching configuration.

The second stage is a sample-and-hold stage that samples and holds selected voltages from three nodes in the first stage: the top plate, the bottom plate, and the switching node. For example, the second stage samples and holds the top plate voltage during the first switching configuration and then samples and holds the bottom plate voltage during the second switching configuration. Alternatively, the second stage samples and holds the switching node voltage during the first switching configuration and then samples and holds the switching node voltage during the second switching configuration. To provide an output voltage that has no divisor dependency, the second stage mixes the resulting sampled voltages from the two switching configurations to produce an output voltage for the switched-capacitor converter. In a switched-node embodiment, only the switched node is selected for by the second stage, which is also denoted herein as a sample-and-hold stage or as a sample-and-hold circuit. In a flying-capacitor embodiment, the sample-and-hold stage samples and holds the top and bottom plate voltages from the flying capacitor. In a more general embodiment, the sample-and-hold stage may select between the flying capacitor plates and the switching node to provide the desired output voltage.

An example inductor-less switched-capacitor converter **100** is shown in FIG. 1. A power stage **105** includes a power stage controller **110** that controls the duty cycle D of the first switching configuration for a switched-capacitor intermediate voltage generator **115** and controls the complementary duty cycle of the second switching configuration for intermediate voltage generator **115**. As will be explained further herein, intermediate voltage generator **115** is formed by the four switching transistors and the flying capacitor. A digital word denoted as the configuration index **120** (Config-index)

sets the duty cycle as controlled by controller **110**. The duty cycle D is defined with regard to a switching period for a clock signal **121**.

A second stage for switched-capacitor converter **100** is formed by a sampling and hold (SAH) circuit **125**. SAH circuit **125** samples and holds an intermediate voltage $V_r(t)$ from intermediate voltage generator **115**. This intermediate voltage can be sampled from the top plate of the flying capacitor, the bottom plate of the flying capacitor, or the switch node. Depending upon the switching configuration for intermediate voltage generator **115**, the intermediate voltage will either be a high voltage V_H that is above $V_{in}/2$ or will be a low voltage V_L that is below $V_{in}/2$, where V_{in} is the input voltage for intermediate voltage generator **115**. In general, SAH circuit **125** may not only sample and hold the V_H and V_L voltages but also can sample and hold the input voltage V_{in} and ground. The voltage sampled for a time t_1 is denoted as V_1 whereas the voltage sampled for a time t_2 is denoted as V_2 . V_1 and V_2 are thus selected from the set consisting of V_{in} , ground, V_H , or V_L . The times t_1 and t_2 cannot be greater than the corresponding switching configuration duration for intermediate voltage generator **115**. SAH circuit **125** samples and holds the voltage V_1 for time t_1 and samples and holds the voltage V_2 for time t_2 . Based upon the sampling times t_1 and t_2 for SAH circuit **125** and the sampled voltages V_1 and V_2 , an output voltage V_{out} as stored across an output capacitor C_o is a function of a ratio of $((V_1*t_1) \text{ and } V_2*t_2)/t_b$, where t_b is the period for clock signal **121**. A controller **130** controls the times t_1 and t_2 based upon a comparison of a reference voltage (V_{ref}) to a feedback voltage such as obtained by dividing the output voltage through a voltage divider formed by a resistor R_{o1} and a resistor R_{o2} . In some embodiments, controller **130** can also control the configuration index **120**. In other embodiments, the configuration index **120** may be a fixed value. For example, D_1 may be fixed to a 50% value in some embodiments.

Power stage **105** is shown in more detail in FIG. 2. Power stage controller **110** includes a pulse-width modulator **205** that responds to the clock signal **121** and the configuration index **120** to generate the pulse width D_1 for the first switching configuration. A dead-time logic circuit **210** ensures that there is a dead time between the first switching configuration and the second switching configuration.

Intermediate voltage generator **115** includes a PMOS first switching transistor **P1** having a source connected to an input voltage rail **215** that carries the input voltage V_{in} . A drain for first switching transistor **P1** connects to a top plate of the flying capacitor **CF**. The top plate voltage for flying capacitor **CF** is denoted as V_{C_Top} . The drain for first switching transistor **P1** also connects to a source for PMOS second switching transistor **P2**. The drain for second switching transistor **P2** connects to the switch node **LX** and also to a drain for an NMOS third switching transistor **M1**. The source for third switching transistor **M1** connects to the bottom plate of the flying capacitor **CF** having a bottom plate voltage denoted as V_{C_Bot} . The source for third switching transistor **M1** also connects to a drain for an NMOS fourth switching transistor **M2** having a source connected to ground.

Intermediate voltage generator **115** also includes a first gate driver **220** that responds to the pulse width signal D_1 to drive the gates of the first switching transistor **P1** and the fourth switching transistor **M2** accordingly. The first switching transistor **P1** will thus be on when the pulse width signal D_1 is asserted whereas the fourth switching transistor **M2** will be off. Intermediate voltage generator **115** also includes

a second gate driver **225** that responds to an inverted version **D1B** of the pulse width signal **D1** as inverted by an inverter **230**. In response to the inverted version **D1B** of the pulse width signal **D1**, second gate driver **225** drives the gates of second switching transistor **P2** and third switching transistor **M1**. The third switching transistor **M1** will thus be on while the pulse width signal **D1** is asserted whereas the second switching transistor **P2** will be off. The first switching configuration is thus selected while the pulse width signal **D1** is asserted. When the pulse width signal **D1** is de-asserted to ground, first switching transistor **P1** and third switching transistor **M1** will both be off while the second switching transistor **P2** and the fourth switching transistor **M2** will both be on. The second switching configuration is thus selected while the pulse width signal **D1** is de-asserted.

Some example waveforms for the switch node voltage **LX**, the top plate voltage **VC_Top**, and the bottom plate voltage **VC_Bot** are shown in FIG. **3**. The second switching configuration is selected for starting from a time **t1** to a time **t2**. Depending upon the pulse width **D1**, the top plate voltage **VC_Top** will range from a high value of **Vin** to a low value of **Vin/2** during the second switching configuration. Since the second switching transistor **P2** is on during the second switching configuration, the **LX** node voltage and the top plate voltage **VC_Top** are equal during the second switching configuration. Some example **LX** node voltages (which also equal the corresponding top plate voltages) during the second switching configuration are designated as **Vhx1**, **Vhx2**, and **Vhx3**. The bottom plate voltage **VC_Bot** is ground during the second switching configuration since the fourth switching transistor **M2** is on. The second switching configuration is again repeated from a time **t3** to a time **t4**.

The first switching configuration is selected for from time **t2** to time **t3**. The top plate voltage **VC_Top** equals the input voltage **Vin** during this time. The bottom plate voltage **VC_Bot** ranges from **Vin/2** to ground depending upon the pulse width **D1**. The switch node **LX** voltage equals the bottom plate voltage **VC_Bot** during the second switching configuration since the third switching transistor **M1** is on. Some example voltages for the switch node **LX** voltage (which is also equal to the bottom plate voltage **VC_Bot**) are designated as **Vlx1**, **Vlx2**, **Vlx3**. The first switching configuration is repeated from time **t4** to a time **t5**.

An example sampling and hold circuit **400** for sampling the **LX** node voltage is shown in FIG. **4**. Intermediate voltage generator **115** is as discussed with regard to FIG. **2**. SAH circuit **400** samples the **LX** node voltage to obtain the high voltage **VH** sample for time **t1** during the second switching configuration for intermediate voltage generator **115**. Similarly, SAH circuit **400** samples the **LX** node voltage to obtain the low voltage **VL** sample for time **t2** during the first switching configuration for intermediate voltage generator **115**. SAH circuit **400** samples the **LX** node voltage through a transistor switch **51** that is closed for the sampling times **t1** and **t2** as controlled through timing controller **130**. The sampled voltage charges a sampling capacitor **C** that is reset through a current source **405**. In some embodiments, SAH circuit **400** includes a second transistor switch **S2** for resetting the **LX** node voltage as also controlled by timing controller **130**.

The sampling of the top and bottom plate voltages by a SAH circuit **500** is shown in FIG. **5**. Intermediate voltage generator **115** is again as discussed with regard to FIG. **2**. During the second switching configuration, timing controller **130** closes a transistor switch **S3** for the sampling time **t1** to couple the top plate of the flying capacitor to the sampling capacitor **C**. The top plate voltage **VC_Top** is thus sampled

by SAH circuit **500** for the sampling time **t1** during the second switching configuration of intermediate voltage generator **115**. During the first switching configuration, timing controller **130** closes a transistor switch **S4** for the sampling time **t2** to couple the bottom plate of the flying capacitor to the sampling capacitor **C**. The bottom plate voltage **VC_Bot** is thus sampled by SAH circuit **500** for the sampling time **t2** during the first switching configuration of intermediate voltage generator **115**.

Note that SAH circuits **400** and **500** are equivalent in that the **LX** node voltage and the top plate voltage **VC_Top** are equal during the second switching configuration for intermediate voltage generator **115**. Similarly, the **LX** node voltage and the bottom plate voltage **VC_Bot** are equal during the first switching configuration for intermediate voltage generator **115**. In both embodiments, the sampling time **t1** is limited by the duration of the second switching configuration in that the sampling time **t1** is not longer than the duration of the second switching configuration but may be shorter. Similarly, the sampling time **t2** is not longer than the duration for the first switching configuration but may be shorter.

Those of some skill in this art will by now appreciate that many modifications, substitutions and variations can be made in and to the materials, apparatus, configurations and methods of use of the devices of the present disclosure without departing from the scope thereof. In light of this, the scope of the present disclosure should not be limited to that of the particular embodiments illustrated and described herein, as they are merely by way of some examples thereof, but rather, should be fully commensurate with that of the claims appended hereafter and their functional equivalents.

We claim:

1. A switched-capacitor converter, comprising:
 - a first switching stage including a flying capacitor, wherein the first switching stage is configured in a first switching configuration during a first portion of a clock signal period to charge the flying capacitor with an input voltage and is configured in a second switching configuration during a second portion of the clock signal period to charge a switch node with the flying capacitor; and
 - a sampling and hold circuit configured to couple the switch node to a sampling capacitor for a first sampling time during the second switching configuration and further configured to couple the switch node to the sampling capacitor for a second sampling time during the first switching configuration to form an output voltage for the switched-capacitor converter across the sampling capacitor.
2. The switched-capacitor converter of claim **1**, further comprising:
 - a controller configured to control a duration of the first sampling time and a duration of the second sampling time responsive to an error between the output voltage and a desired value for the output voltage.
3. The switched-capacitor converter of claim **1**, wherein the first switching stage comprises:
 - an input voltage rail for the input voltage;
 - a first switch transistor having a source connected to the input voltage rail;
 - a second switch transistor having a source connected to a drain of the first switch transistor;
 - a third switch transistor having a drain connected to a drain of the second switch transistor; and
 - a fourth switch transistor having a source connected to ground and having a drain connected to a source of the

third switch transistor, wherein the flying capacitor has a top plate connected to the drain of the first switch transistor and has a bottom plate connected to the drain of the fourth switch transistor, and wherein the switch node is connected to the drain of the second switch transistor and to the drain of the third switch transistor.

4. The switched-capacitor converter of claim 3, wherein in the first switching configuration the first switch transistor and the third switch transistor are both on and the second switch transistor and the fourth switch transistor are both off, and wherein in the second switching configuration the first switch transistor and the third switch transistor are both off and the second switch transistor and the fourth switch transistor are both on.

5. The switched-capacitor converter of claim 4, wherein the sampling capacitor includes a first terminal connected to ground, and wherein the sampling and hold circuit further includes a fifth switch transistor coupled between the switch node and a second terminal of the sampling capacitor.

6. The switched-capacitor converter of claim 5, wherein the first switch transistor and the second switch transistor are both PMOS transistors, and wherein the third switch transistor and the fourth switch transistor are both NMOS transistors.

7. The switched-capacitor converter of claim 5, further comprising a controller configured to control a duration of the first switching configuration and a duration of the second switching configuration responsive to an error between the output voltage and a desired value for the output voltage.

8. A switched-capacitor converter, comprising:

a first switching stage including a flying capacitor, wherein the first switching stage is configured in a first switching configuration during a first portion of a clock signal period to charge the flying capacitor with an input voltage and is configured in a second switching configuration during a second portion of the clock signal period to charge a switch node with the flying capacitor; and

a sampling and hold circuit configured to couple a top plate of the flying capacitor to a sampling capacitor for a first sampling time during the second switching configuration and further configured to couple a bottom plate of the flying capacitor to the sampling capacitor for a second sampling time during the first switching configuration to form an output voltage for the switched-capacitor converter across the sampling capacitor.

9. The switched-capacitor converter of claim 8, further comprising:

a controller configured to control a duration of the first sampling time and a duration of the second sampling time responsive to an error between the output voltage and a desired value for the output voltage.

10. The switched-capacitor converter of claim 8, wherein the first switching stage comprises:

an input voltage rail for the input voltage;
a first switch transistor having a source connected to the input voltage rail;

a second switch transistor having a source connected to a drain of the first switch transistor;

a third switch transistor having a drain connected to a drain of the second switch transistor; and

a fourth switch transistor having a source connected to ground and having a drain connected to a source of the third switch transistor, wherein the top plate of the flying capacitor is connected to the drain of the first switch transistor and the bottom plate of the flying

capacitor is connected to the drain of the fourth switch transistor, and wherein the switch node is connected to the drain of the second switch transistor and to the drain of the third switch transistor.

11. The switched-capacitor converter of claim 10, wherein in the first switching configuration the first switch transistor and the third switch transistor are both on and the second switch transistor and the fourth switch transistor are both off, and wherein in the second switching configuration the first switch transistor and the third switch transistor are both off and the second switch transistor and the fourth switch transistor are both on.

12. The switched-capacitor converter of claim 11, wherein the sampling capacitor includes a first terminal connected to ground, and wherein the sampling and hold circuit further includes:

a fifth switch transistor coupled between the top plate of the flying capacitor and a second terminal of the sampling capacitor; and

a sixth switch transistor coupled between the bottom plate of the flying capacitor and the second terminal of the sampling capacitor.

13. The switched-capacitor converter of claim 11, wherein the first switch transistor and the second switch transistor are both PMOS transistors, and wherein the third switch transistor and the fourth switch transistor are both NMOS transistors.

14. The switched-capacitor converter of claim 13, further comprising a controller configured to control a duration of the first switching configuration and a duration of the second switching configuration responsive to an error between the output voltage and a desired value for the output voltage.

15. A method for a switched-capacitor converter, comprising:

charging a flying capacitor during a first switching configuration for an intermediate voltage generator for a first portion of a clock signal period;

charging a switch node with the flying capacitor during a second switching configuration for the intermediate voltage generator for a second portion of the clock signal period;

coupling a top plate for the flying capacitor to a sampling capacitor for a first sampling time during the second switching configuration for the intermediate voltage generator; and

coupling a bottom plate of the flying capacitor to the sampling capacitor for a second sampling time during the first switching configuration for the intermediate voltage generator to develop an output voltage for the switched-capacitor converter across the sampling capacitor.

16. The method of claim 15, wherein charging the flying capacitor during the first switching configuration for the intermediate voltage generator for the first portion of the clock signal period comprises coupling the top plate of the flying capacitor to an input voltage rail and coupling the bottom plate of the flying capacitor to the switch node.

17. The method of claim 16, wherein charging the switch node comprises coupling the bottom plate of the flying capacitor to ground and coupling the top plate of the flying capacitor to the switch node.

18. The method of claim 15, further comprising:

adjusting a duration of the first sampling time and a duration of the second sampling time responsive to an error between the output voltage and a desired value for the output voltage.

19. The method of claim 15, wherein a duty cycle of the first switching configuration is 50%.

20. The method of claim 15, further comprising adjusting a duty cycle of the first switching configuration responsive to an error between the output voltage and a desired value 5 for the output voltage.

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