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(54) **SYNCHRONOUS-RECTIFIED DC TO DC CONVERTER WITH IMPROVED CURRENT SENSING**

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G05F 1/613 (2006.01)

(52) **U.S. Cl.** **323/224; 323/283; 323/288**

(58) **Field of Classification Search** **323/283, 323/282, 288, 224**

See application file for complete search history.

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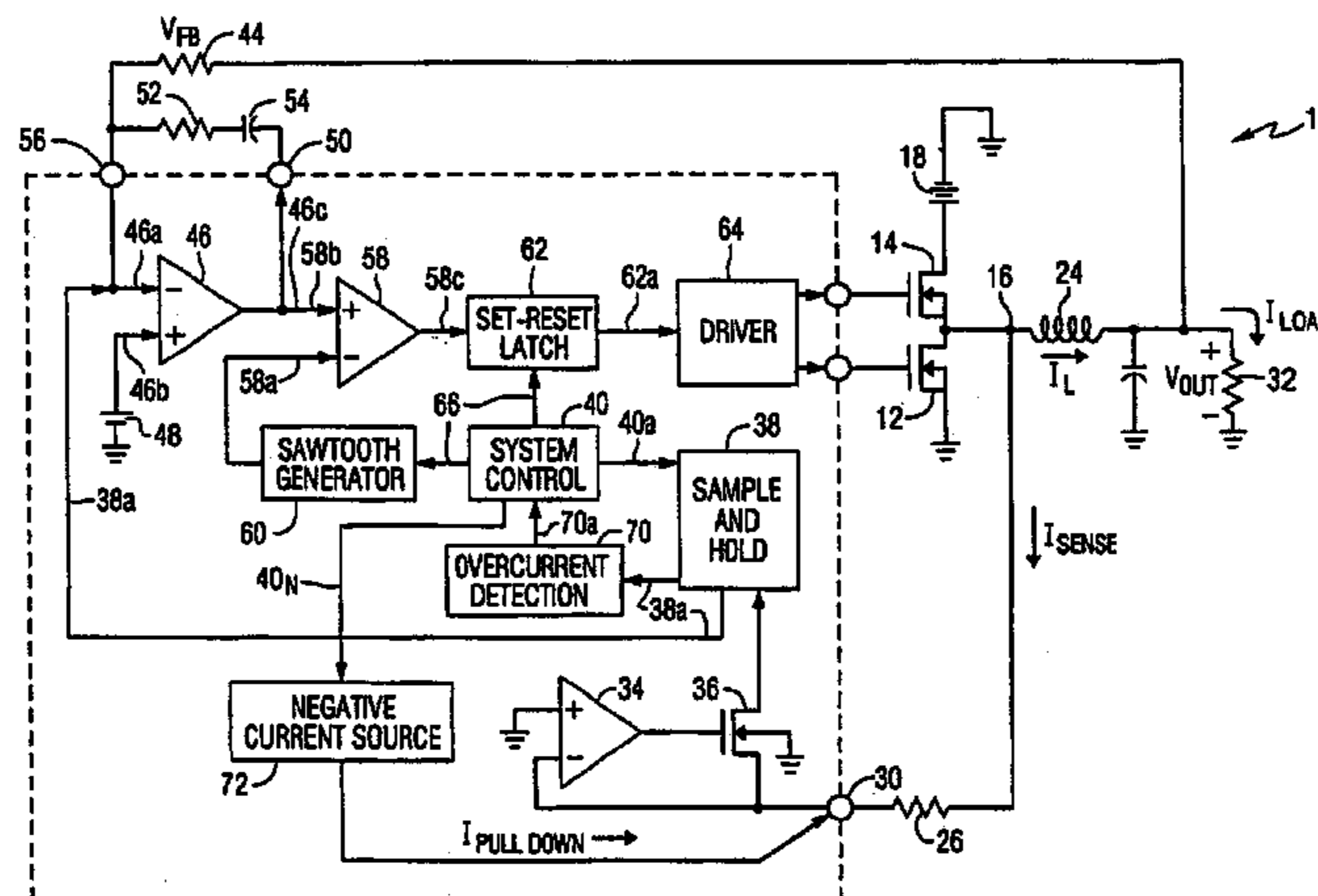
Primary Examiner—Shawn Riley

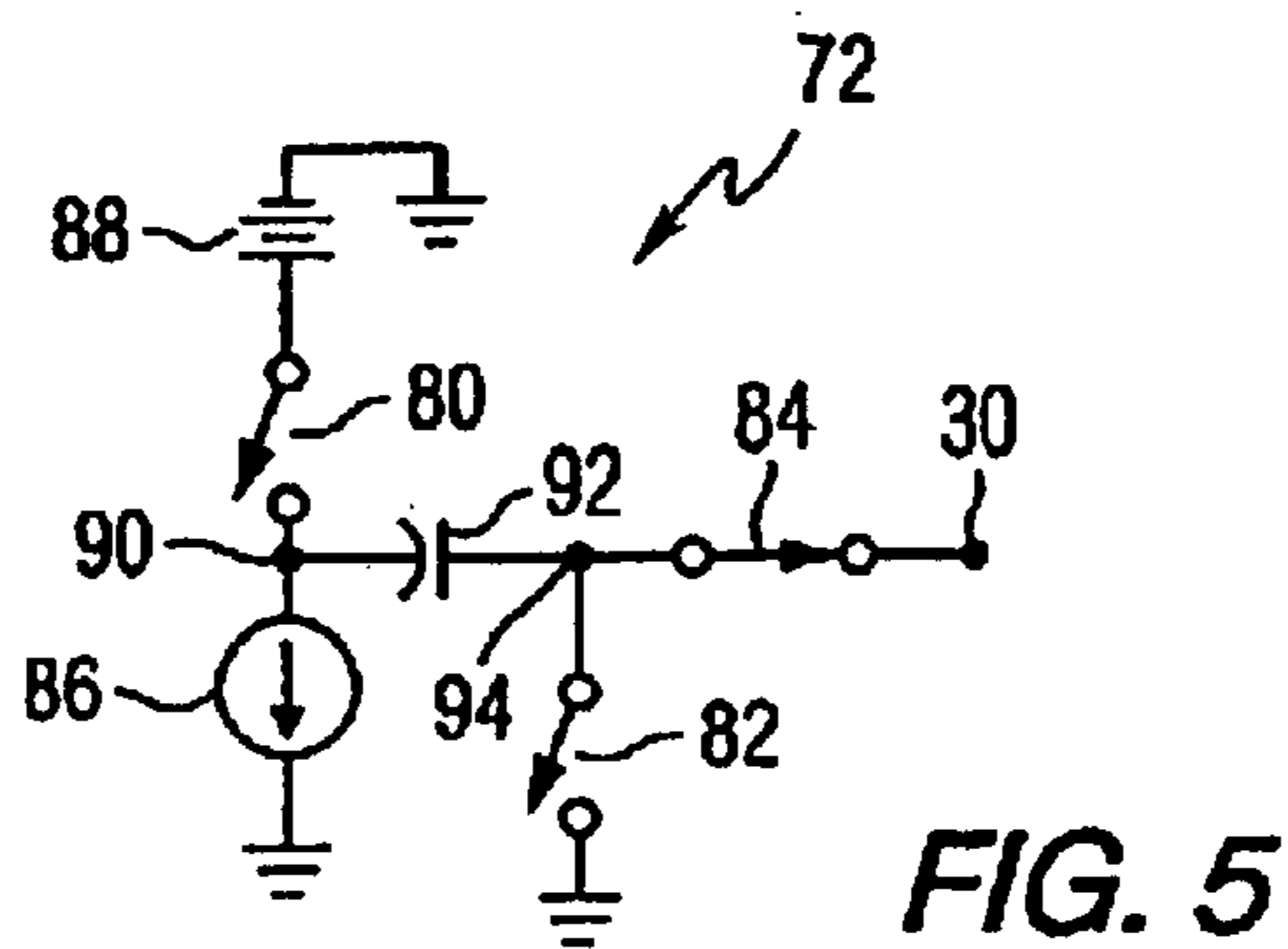
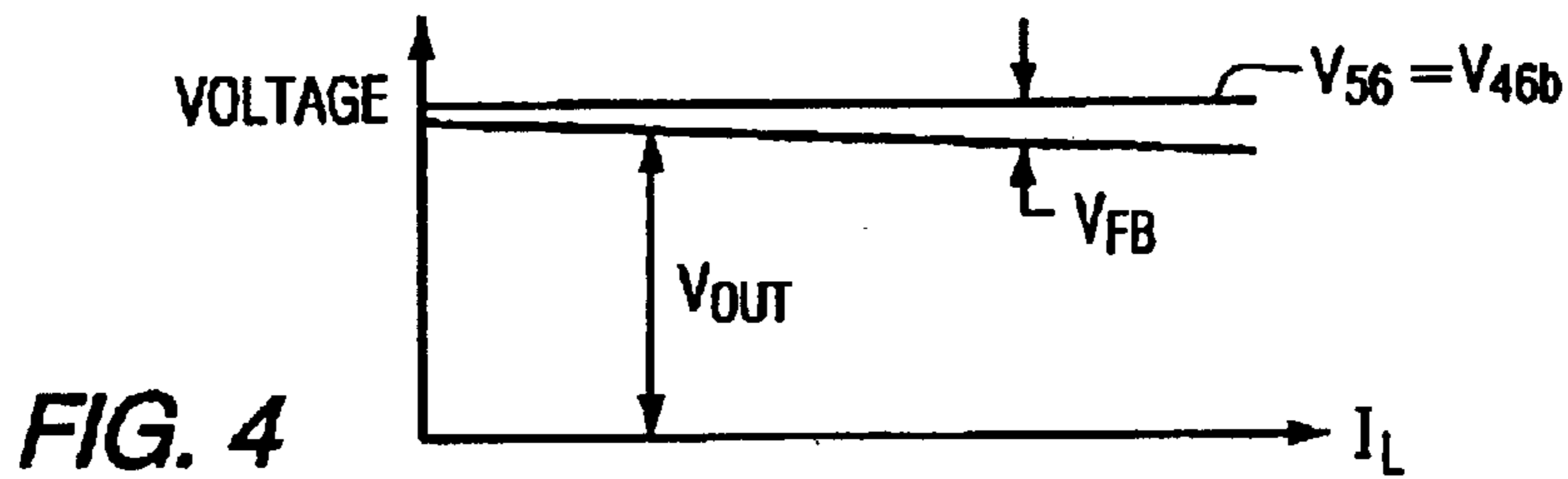
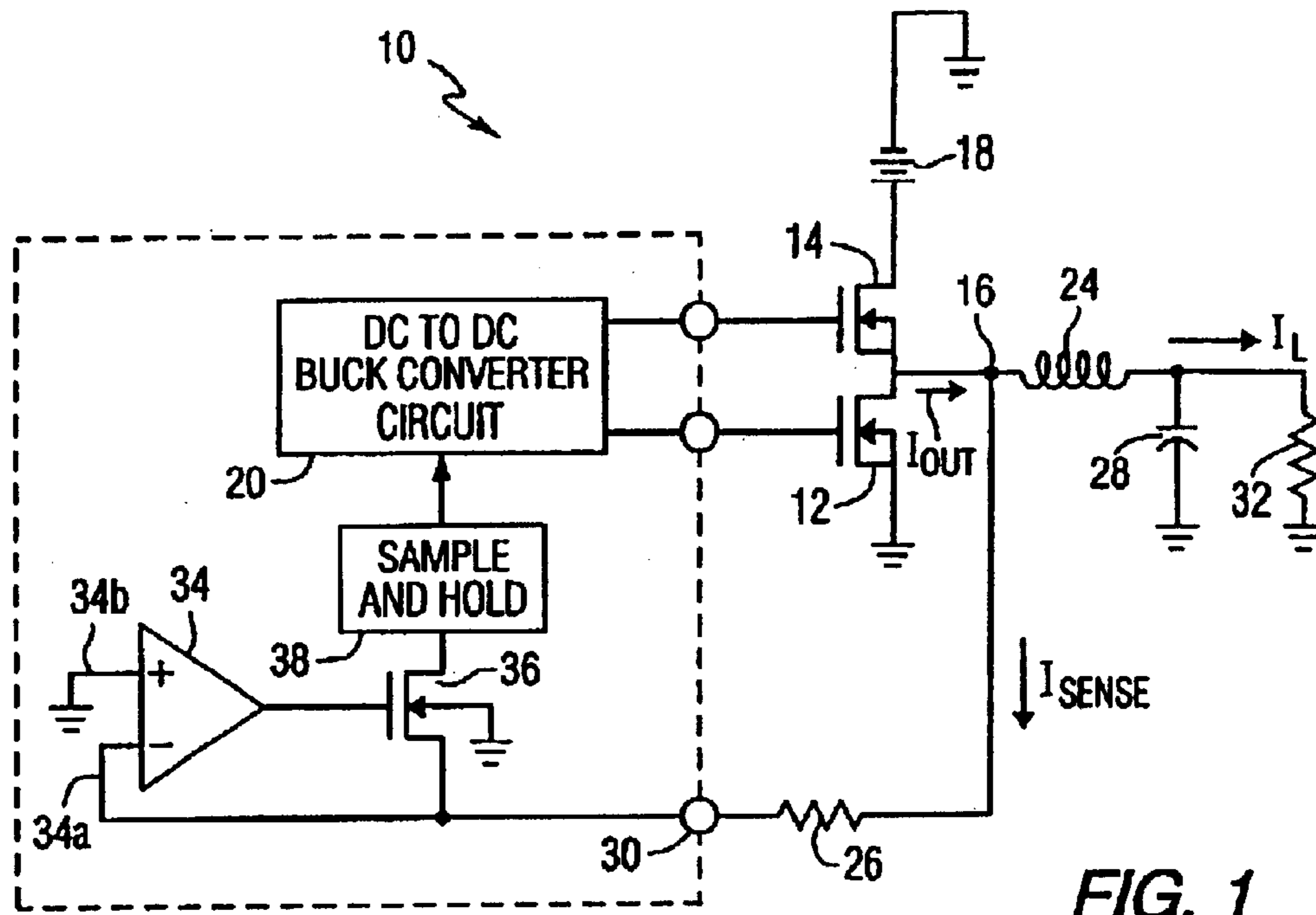
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(57) **ABSTRACT**

A DC to DC buck pulse width modulator converter circuit includes an input, a high side output and a low side output. A high side switch is electrically connected between a common output node and a voltage supply, and controls a flow of current therethrough dependent upon the high side output. A low side switch is electrically connected between the common output node and ground, and controls a flow of current therethrough dependent upon the low side output. A virtual ground amplifier includes a second input electrically connected to ground. A current feedback resistor is electrically connected intermediate the common output node and a first input of the virtual ground amplifier. A variable impedance component is electrically connected to an output of the virtual ground amplifier and to the first input of the virtual ground amplifier. The impedance of the variable impedance component is varied dependent upon the output of the virtual ground amplifier. A sample and hold circuit is electrically connected intermediate the input of the pulse width modulator converter circuit and the variable impedance component. The sample and hold circuit sources a virtual ground current through the variable impedance component, and samples the virtual ground current.

24 Claims, 5 Drawing Sheets





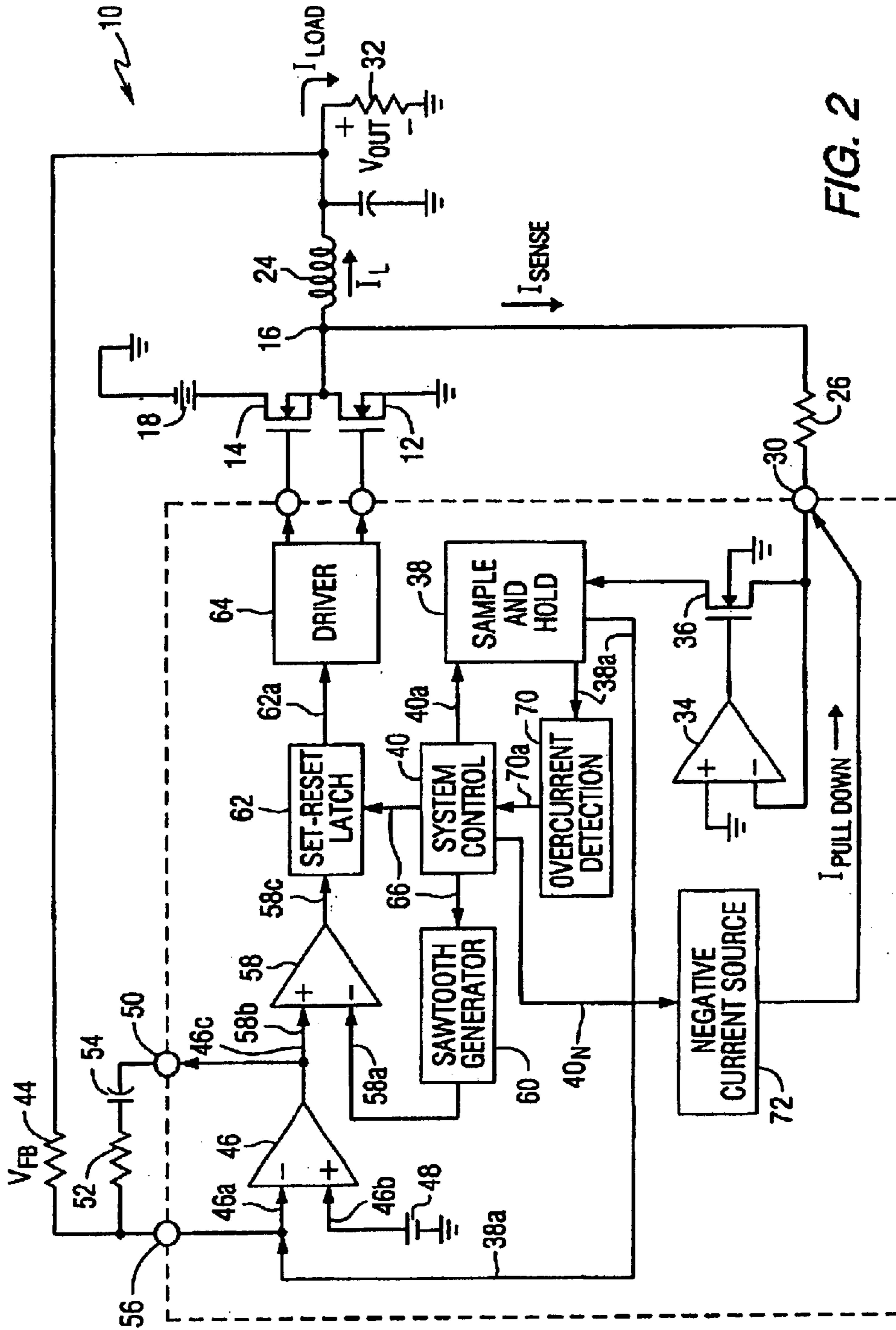


FIG. 2

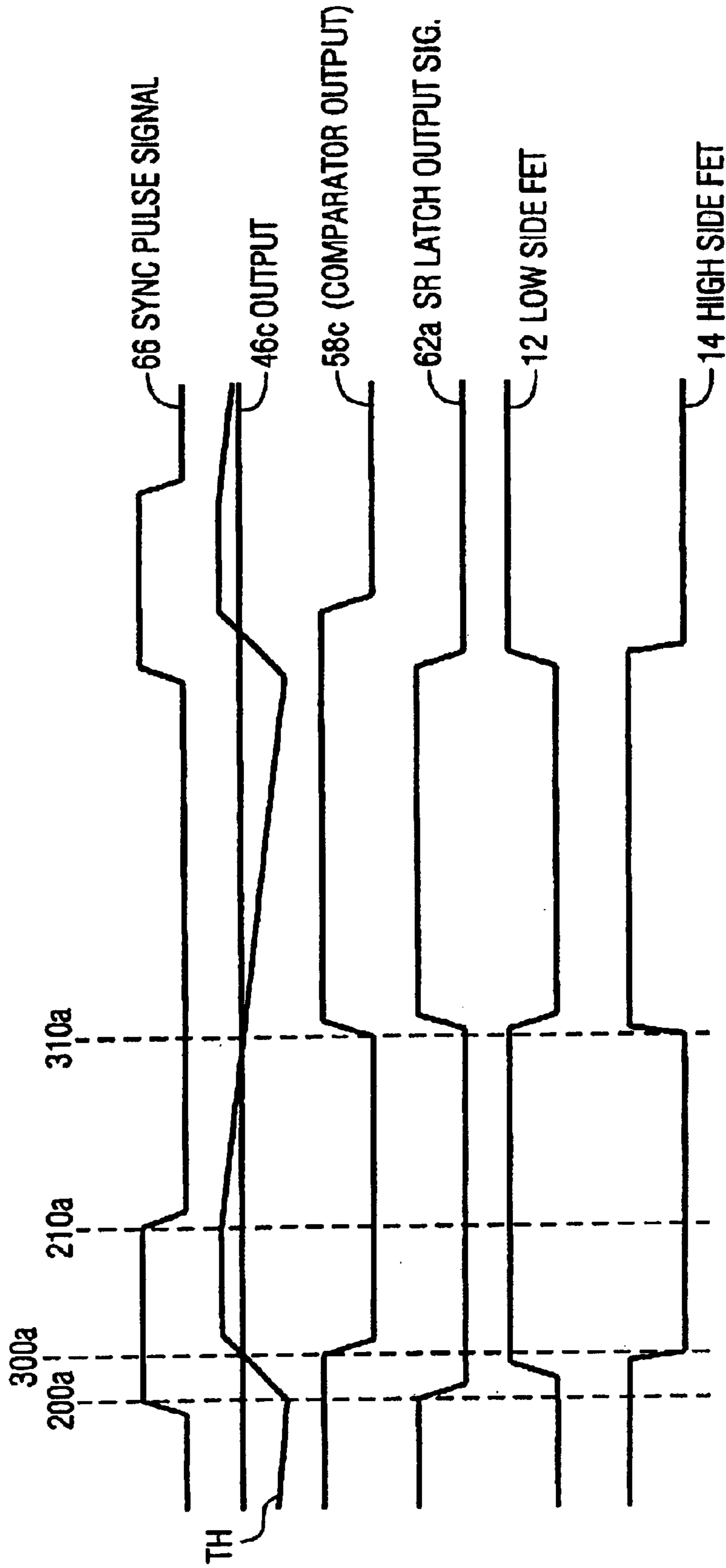


FIG. 3a

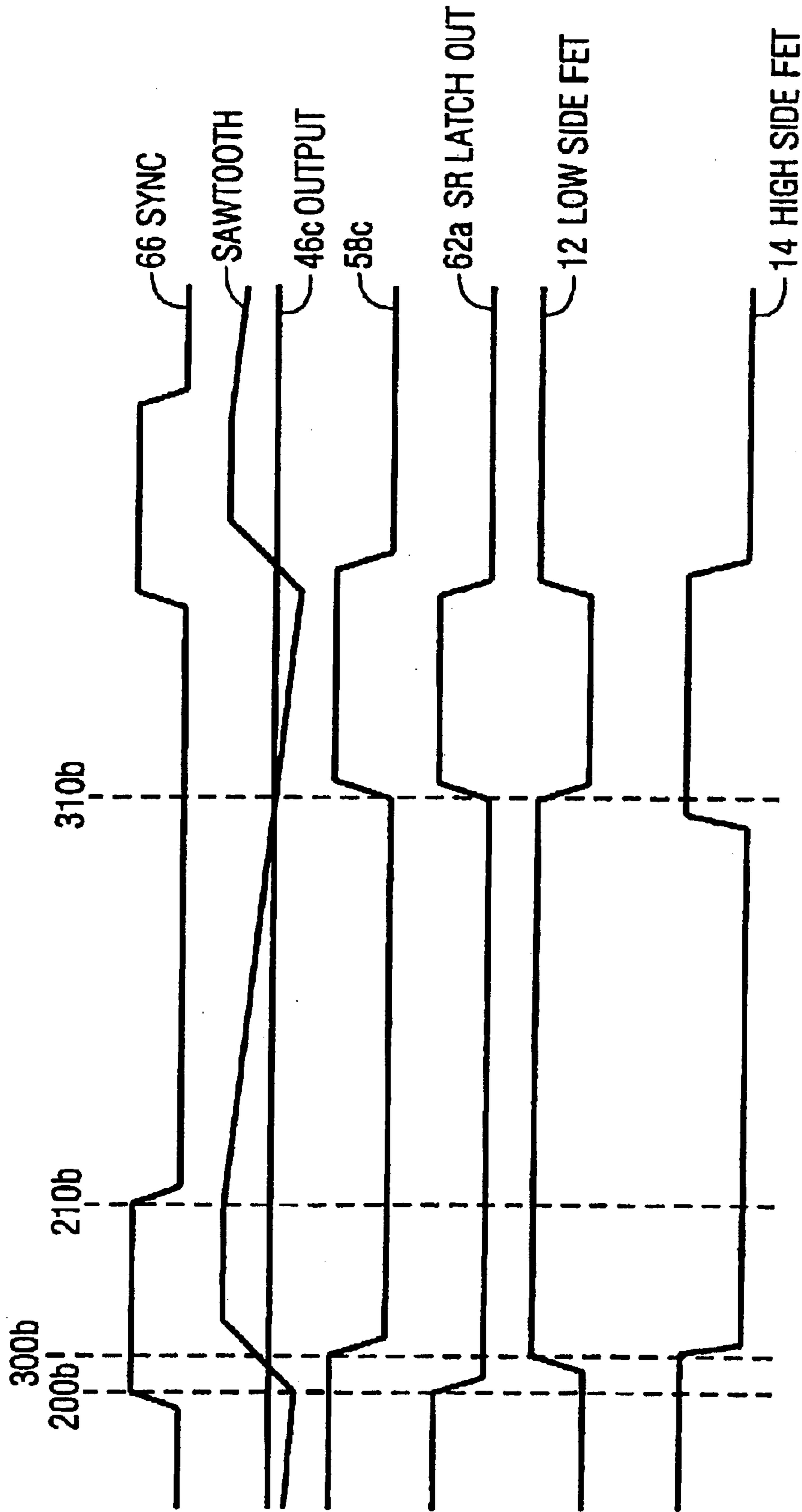


FIG. 3b

SYNCHRONOUS-RECTIFIED DC TO DC CONVERTER WITH IMPROVED CURRENT SENSING

Matter enclosed in heavy brackets [] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

CROSS REFERENCE TO RELATED APPLICATIONS

[This application claims the benefit of U.S. Provisional Patent Application Ser. No. 60/151,826, filed Sep. 1, 1999.] *Notice: More than one reissue application has been filed for the reissue of Pat. No. 6,246,220. The reissue applications are reissue application No. 10/044,506 (the parent reissue) and reissue application No. 10/282,753 (the present, continuation reissue application).* Both Reissue applications are reissues of the same U.S. Pat. No. 6,246,220.

This reissue Application claims the benefit of U.S. Provisional Patent Application Ser. No. 60/151,826, filed Sep. 1, 1999.

FIELD OF THE INVENTION

A synchronous buck DC to DC converter typically employs a pair of switches arranged to connect one end of an inductor to either an input supply voltage or to ground. The second end of the inductor is attached to a load. It is well known to use field effect transistors (FET's) as these switches. Load current flows from the supply through the upper FET and the inductor while the FET is on, and from ground through the lower FET and the inductor while that FET is on.

It is desirable to sense the value of the load current to perform various functions such as, for example, to deliberately decrease the output voltage as load current increases (i.e., output voltage "droop"), to provide for current limiting or over-current trip to protect the load and the converter components, and in order to balance the output current being sourced by each channel in a multi-channel or multi-phase converter. The load current can be sensed through determining the DC resistor of the inductor and sensing the voltage drop across that DC resistance, or by sensing the voltage drop across an added series sense resistor. The load current can also be detected by sensing the voltage drop caused by the load current flowing through the upper FET switch. However, each of these methods has their disadvantages. Sensing the load current by using the DC resistance of the inductor requires adding an R-C filter across the inductor to remove the AC component of the current. Thus, additional components are required and extra cost incurred. Adding a series sense resistor also requires an extra component, increase cost, and reduces system efficiency. Furthermore, sensing the voltage drop across the drain-to-source resistance of the upper FET when it is conducting has often proven to be impractical, since the "on" time of that switch is typically very short.

Therefore, what is needed in the art is a DC/DC converter with improved current sensing. Furthermore, what is needed in the art is an apparatus and method which enables the sensing of load current in a DC/DC converter by sensing the voltage drop across the drain-to-source resistance of a switching FET.

Moreover, what is needed in the art is an apparatus and method which enables sensing and detection of overcurrent in a DC/DC converter.

SUMMARY OF THE INVENTION

The present invention provides a power supply with improved current sensing.

The invention comprises, in one form thereof, a DC to DC buck pulse width modulator converter circuit having an input, a high side output and a low side output. A high side switch is electrically connected between a common output node and a voltage supply, and controls a flow of current therethrough dependent upon the high side output. A low side switch is electrically connected between the common output node and ground, and controls a flow of current therethrough dependent upon the low side output. A virtual ground amplifier includes a second input electrically connected to ground. A current feedback resistor is electrically connected intermediate the common output node and a first input of the virtual ground amplifier. A variable impedance component is electrically connected to an output of the virtual ground amplifier and to the first input of the virtual ground amplifier. The impedance of the variable impedance component is varied dependent upon the output of the virtual ground amplifier. A sample and hold circuit is electrically connected intermediate the input of the pulse width modulator converter circuit and the variable impedance component. The sample and hold circuit sources a virtual ground current through the variable impedance component, and samples the virtual ground current.

An advantage of the DC/DC converter or the present invention is that it provides an improved method and apparatus to measure the voltage drop across the drain-to-source resistance of a FET having a very brief "on" time.

Another advantage of the DC/DC converter of the present invention is that the amount of droop in the output voltage in response to a change in load current is easily manipulated and scaled by selecting an appropriate value for the voltage feedback resistor.

Yet another advantage of the DC/DC converter of the present invention is that the sensitivity or magnitude of the current limiting or trip is easily manipulated or scaled by selecting an appropriate value for the voltage feedback resistor.

A still further advantage of the DC/DC converter of the present invention is that a broad range of load current and component values is accommodated by selecting an appropriate value for the current feedback resistor.

BRIEF DESCRIPTION OF THE DRAWINGS

The above-mentioned and other features and advantages of this invention, and the manner of attaining them, will become apparent and be better understood by reference to the following description of embodiments of the invention in conjunction with the accompanying drawings, wherein:

FIG. 1 is a high-level schematic and functional drawing of one embodiment of the DC/DC converter of the present invention;

FIG. 2 is a detailed schematic and functional diagram of the DC/DC converter of FIG. 1;

FIG. 3a and 3b are timing diagrams illustrating the operation of the DC/DC converter of FIG. 2;

FIG. 4 is a diagram of a node voltage versus load current of the DC/DC converter of FIG. 2;

FIG. 5 is a schematic of a negative current source for use with the DC/DC converter of FIG. 2; and

FIG. 6 is a detailed schematic of a second embodiment of a DC/DC converter of the present invention.

Corresponding reference characters indicate corresponding parts throughout the several views. The exemplifications set out herein illustrate one preferred embodiment of the invention, in one form, and such exemplifications are not to be construed as limiting the scope of the invention in any manner.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring now to the drawings, and particularly to FIG. 1, there is shown one embodiment of a DC/DC converter of the present invention. DC/DC converter 10 includes low side field effect transistor (FET) 12 and high side FET 14. The drain of low side FET 12 is electrically connected to the source of high side FET 14 at common output node 16. The drain of high side FET 14 is connected to power supply 18. The source of low side FET 12 is electrically connected to ground. Each gate terminal of low side FET 12 and high side FET 14 is electrically connected to a respective output (not referenced) of buck converter circuit 20. Inductor 24 and current feedback resistor 26 are each electrically connected to common output node 16, and thus to the drain of FET 12 and source of FET 14. More particularly, inductor 24 is electrically connected between common output node 16 and load reservoir capacitor 28, and current feedback resistor 26 is electrically interconnected between common output node 16 and virtual ground circuit node 30. A load 32, schematically represented as a resistor, is electrically connected in parallel with load reservoir capacitor 28.

Virtual ground amplifier 34 has its inverting input 34a electrically connected to virtual ground circuit node 30 and its non-inverting input 34b connected to ground. Output 34c of virtual ground amplifier 34 is electrically connected to and drives the gate of FET 36. The source of FET 36 is electrically connected to virtual ground circuit node 30. The drain of FET 36 is electrically connected to sample and hold circuit 38. Thus, as will be apparent to one skilled in the art, virtual ground amplifier 34 and FET 36 are configured to continuously drive virtual ground circuit node 30 toward ground potential. With virtual ground circuit node 30 being continuously driven towards ground potential, the end of current feedback resistor 26 that is connected to circuit node 30 will be at ground potential and the end connected to common output node 16 will have a negative voltage. This negative voltage at the end of current feedback resistor 26 that is connected to common output node 16 will be equal to the product of output current I_{OUT} and the on-state resistance that exists between the drain and source (RDS_{ON}) of low side FET 12. Current I_{SENSE} flows through current feedback resistor 26 and has a magnitude determined by the ratio of RDS_{ON} of low side FET 12 to the value of current feedback resistor 26. Thus, I_{SENSE} is the product of output current I_{OUT} and the ratio of RDS_{ON} of low side FET 12 to current feedback resistor 26, and as such is representative of output current I_{OUT} . Load current I_L is the current flowing through inductor 24 and is substantially equal to output current I_{OUT} minus I_{SENSE} . Typically, since the ratio of RDS_{ON} to the value of current feedback resistor 26 is relatively small, I_{SENSE} is substantially smaller than output current I_{OUT} . Therefore, output current I_{OUT} and load current I_L will be of substantially similar magnitudes and thus I_{SENSE} will also be representative of load current I_L .

The value of current feedback resistor 26 is selected to provide a convenient value of current flow for the values of load current I_L and/or the value of RDS_{ON} of low side FET 12. Thus, the sensitivity or magnitude of, for example, the voltage droop, current limiting or trip, and current balancing incorporated into DC/DC converter 10 is scaled by selecting

the value of current feedback resistor 26 relative to the value of RDS_{ON} of low side FET 12. Furthermore, the voltage drop across RDS_{ON} of low side FET 12, which is usually negative, is accommodated in DC/DC converter 10 without the need for a negative voltage supply.

Referring now to FIG. 2, system control circuit 40 is electrically connected to sample and hold circuit 38. As stated hereinabove, the drain of FET 36 connects the sample and hold circuit 38. The current supplied by the source of FET 36 flows from sample and hold circuit 38 into the drain of FET 36, out of the source of FET 36, and into virtual ground circuit node 30. Also flowing into virtual ground circuit node 30, from the opposite direction, is I_{SENSE} which, as stated above, is representative of load current I_L . In order to hold virtual ground circuit node 30 at ground potential, virtual ground amplifier 34, via output 34c, adjusts the current flowing through FET 36 and into virtual ground circuit node 30 to be substantially equal to $I_{L\ SENSE}$. Since I_{SENSE} is representative of the load current I_L , the current flowing through FET 36 and into virtual ground circuit node 30, as controlled by virtual ground amplifier 34 and FET 36, is also representative of load current I_L . System control circuit 40 periodically issues control signal 40a to sample and hold circuit 38. Control signal 40a is issued when FET 36 is in the on or conducting condition. In response to control signal 40a, sample and hold circuit 38 samples the current flowing through FET 36 when FET 36 is in the on condition and holds the sampled value. Thus, the sample value acquired by sample and hold circuit 38 is also representative of load current I_L . Sample and hold circuit 38 issues sample signal 38a which is representative of the sampled value of current flowing through FET 36.

DC/DC converter 10 monitors the voltage V_{OUT} across load 32 through voltage feedback resistor 44. Voltage feedback resistor 44 is connected at one end to load 32 and at the other end to inverting input 46a of error amplifier 46. V_{FB} is the voltage across voltage feedback resistor 44. The non-inverting input 46b of error amplifier 46 is electrically connected to reference voltage supply 48, which provides a predetermined voltage that is substantially equal to the desired output voltage of DC/DC converter 10. Error amplifier 46 regulates the voltage of inverting input 46a to be substantially equal to the voltage from reference voltage supply 48. Since the voltage at inverting input 46a is substantially equal to the sum of V_{OUT} and V_{FB} , error amplifier 46 acts to regulate the sum of V_{OUT} and V_{FB} to be substantially equal to the voltage from reference voltage supply 48. Output 46c of error amplifier 46 is electrically connected to compensation circuit node 50. A feedback path between output 46c and inverting input 46a of error amplifier 46 includes compensation resistor 52 and compensation capacitor 54. More particularly, connected to compensation circuit node 50 is one end of compensation capacitor 54 which, in turn, is connected at its other end to compensation resistor 52. Compensation resistor 52, at the end thereof opposite to compensation capacitor 54, is connected to summing node 56. Compensation resistor 52 and capacitor 54 in the voltage feedback path provide system stability and control system response.

Sample signal 38a, which is issued by sample and hold circuit 38 and is representative of load current I_L , is also connected to the inverting input of error amplifier 46. There is no other path for direct current at inverting input 46a of error amplifier 46 except through voltage feedback resistor 44. Thus, the voltage across voltage feedback resistor 44, i.e., V_{FB} , is modified by signal 38a. As stated above, error amplifier 46 regulates the voltage at its inverting input 46a,

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which is equal to the sum of V_{OUT} and V_{FB} , to be substantially equal to the reference voltage supply 48. Thus, for example, as sampling signal 38a increases, V_{FB} increases proportionally and error amplifier 46 reduces V_{OUT} to maintain the voltage at inverting input 46a to be equal to reference voltage supply 48. Since sampling signal 38a is representative of load current I_L , V_{OUT} is in effect modulated in an inversely proportional manner relative to load current I_L . Thus, as shown in FIG. 4, V_{OUT} is varied or droops dependent at least in part upon load current I_L . By selecting the value of feedback resistor 44, the amount of variation or droop in V_{OUT} relative to load current I_L is controlled.

Inverting input 58a of comparator 58 is electrically connected to sawtooth generator 60, and receives therefrom a sawtooth waveform having predetermined characteristics. Output 58c of comparator 58 is electrically connected to set-reset (SR) latch 62. Output 62a of SR latch 62 is electrically connected to and buffered by driver 64 which, in turn, drives low side FET 12 and high side FET 14. DC/DC converter 10 is configured, for example, such that a high-level signal at output 62a of SR latch 62 turns low side FET 12 off and turns on high side FET 14. Sawtooth generator 60 receives sync pulse 66 from system control circuit 40. SR latch 62 also receives sync pulse 66.

Error amplifier 46 produces at output 46c a signal that is representative of the actual output voltage V_{OUT} relative to, such as, for example, subtracted from or added to, the voltage of reference voltage supply 48, which represents the desired output voltage of DC/DC converter 10. For example, output 46c of error amplifier 46 produces a signal that is more negative, or increases in a negative direction, as V_{OUT} increases above the voltage of reference voltage supply 48. Conversely, and as a further example, error amplifier 46 produces at output 46c a signal having a decreasingly negative magnitude (i.e., a more positive magnitude) as V_{OUT} decreases below the voltage of reference voltage supply 48. Output 46c of error amplifier 46 is electrically connected to the non-inverting input of comparator 58. Comparator 58 compares the sawtooth waveform electrically connected to its inverting input 58a with output 46c of error amplifier 46 which is electrically connected to its noninverting input 58b. Output 58c of comparator 58 is active, such as, for example, high during the time that the sawtooth waveform generated by sawtooth generator 60 is less positive than output 46c of error amplifier 46.

Referring to FIG. 3a, the condition of output voltage V_{OUT} being less than the desired output voltage, or less than the voltage of reference voltage supply 48, is illustrated. Thus, output 46c of error amplifier 46 is relatively high, thereby placing a relatively high signal at noninverting input 58b of comparator 58. At least a substantial portion of the period of the sawtooth waveform will be less positive than the relatively high-level signal present at noninverting input 58b. Output 58c of comparator 58 is active, such as, for example, high, during that substantial portion of the period for which the sawtooth waveform has a value that is less positive than the relatively high signal present at noninverting input 58b. Thus, the pulse width of output 58c will be relatively wide, or alternatively the active period of output 58c will be relatively long in duration, when V_{OUT} is less than the voltage of reference voltage supply 48.

Conversely, and with particular reference to FIG. 3b output 46c of error amplifier 46 is relatively low when V_{OUT} is greater than the voltage of reference voltage supply 48. This condition places a relatively low-level signal at non-inverting input 58a of comparator 58. A relatively small portion of the period of the sawtooth waveform will be less

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positive than the relatively low-level signal present at non-inverting input 58b. Output 58c of comparator 58 will be active during only that relatively small portion, if any, of the period of the sawtooth waveform (e.g., the lowest points or bottom peaks) which is less positive than the relatively low signal at noninverting input 58b. Thus, the pulse width of output 58c will be relatively narrow, or alternatively the active period of output 58c will be relatively short in duration, when V_{OUT} is greater than the voltage of reference voltage supply 48.

When output 58c is active, output 62a of SR latch 62 is set, such as, for example, high. Conversely, when output 58c is not active, output 62a of SR latch 62 is reset, such as, for example, low. Thus, when the sawtooth waveform is more positive than the voltage level of reference voltage supply 48, output 62a of SR latch 62 is reset, i.e., low. Output 62a of SR latch 62 is set, i.e., high, when the sawtooth waveform drops below the predetermined voltage. Output 62a of SR latch 62 is electrically connected to and buffered by driver 64 which, in turn, drives low side FET 12 and high side FET 14. DC/DC converter 10 is configured such that, for example, a high or set condition on output 62a of SR latch 62 results in driver 64 turning off low side FET 12 and turning on high side FET 14.

Current tripping or over current protection is provided by overcurrent detection circuit 70. Overcurrent detection circuit 70 compares the sample signal 38a to a reference current (not shown) and issues overnight signal 70a to system control circuit 40 when sample signal 38a exceeds the reference current. System control 40 responds to overcurrent signal 70a by shutting down DC/DC converter 10. System control 40 is configured, for example, to restart the operation of DC/DC converter 10 after a predetermined amount of time.

Negative current source 72 is electrically connected intermediate system control 40 and virtual ground circuit node 30. Load current I_L becomes negative under certain operating conditions, such as, for example, when load current I_L has a low average value and the sawtooth waveform created due to the switching of voltage across inductor 24 dips to a negative value. During such operating conditions, i.e., when I_L is negative, the voltage at the drain of low side FET 12 is positive. The positive voltage on the drain of low side FET 12 results in the sourcing of current through resistor 26 and into virtual ground circuit node 30, thereby driving virtual ground circuit node 30 to a positive potential. Negative current source 72 sources $I_{PULL\ DOWN}$ into virtual ground circuit node 30 in response to signal 40_N, and thereby maintains virtual ground node 30 at ground potential under the conditions when I_L is negative. Thus, virtual ground amplifier 46, variable impedance component 36 and sample and hold circuit 38 are not required to operate in a bi-directional manner (i.e., they source current is one direction only) and the need to include a negative voltage supply in DC/DC converter 10 is eliminated.

As best shown in FIG. 5, negative current source 72 includes switches 80, 82 and 84. Each of switches 80, 82 and 84 are, for example, MOS transistors. Current source 86 is a pull down current source, such as, for example, an NMOS mirror, and is electrically connected intermediate ground and node 90. Switch 80 is electrically connected intermediate node 90 and voltage supply 88, and selectively connects node 90 to voltage supply 88. Capacitor 92 is electrically interconnected between node 90 and node 94. Each of switch 82 and 84 have a first side electrically connected to node 94. The other side of switch 82 is electrically connected to ground, while the other side of switch 84 is electrically

connected to virtual ground circuit node **30**. Switches **80** and **82** are closed and switch **84** is open when the reverse current sourced by current source **86** is not required to maintain virtual ground circuit node **30** at ground potential, such as, for example, when low side FET **12** is off. The supply voltage of voltage supply **88** is thus stored across capacitor **92**, with node **90** having a positive potential and node **94** having a negative potential. In order to source pull down current from current source **86**, switches **80** and **82** are each opened and switch **84** is closed. Thus, $I_{PULL\ DOWN}$ flows into virtual ground node **30** in the same direction as normal forward current induced by the voltage drop on low side FET **12**. The addition of current $I_{PULL\ DOWN}$ maintains virtual ground circuit node **30** at ground potential, and is optionally subtracted out later so as not to affect subsequent circuit operation, such as, for example, the current limit trip point.

In use, and with continued reference to FIGS. **3a** and **3b**, the sequence of operation DC/DC converter **10** is as follows. Sawtooth generator **60** receives sync pulse **66** from system control circuit **40**. SR latch **62** also receives sync pulse **66**. Sync pulse resets both the sawtooth waveform and output **62a** of SR latch **62** to low levels. SR latch **62** is configured to reset output **62a** based upon sync pulse **66**, regardless of the condition or state of the output of comparator **58**. Thus, if the output of comparator **58** is, for example, continuously higher than the sawtooth waveform, output **62a** of SR latch **62** will be low during a high level of sync pulse **66**. As shown in FIGS. **3a** and **3b** at points **200a** and **200b**, respectively, sync pulse **66** resets the sawtooth waveform generated by sawtooth generator **60** to a low level, and resets output **62a** of SR latch **62**. DC/DC converter **10** is configured such that, for example, when output **62a** of SR latch **62** is low, high side FET **14** is off and low side FET **12** is on. Thus, the resetting of output **62a** of SR latch **62** by sync pulse **66** turns on low side FET **12**. During this time period, i.e., when low side FET **12** is on, RDS_{ON} of low side FET **12** is measured. At the trailing edge of sync pulse **66**, at points **210a** and **210b**, respectively, the sawtooth waveform begins to slope downward (i.e. has a negative slope).

Referring now particularly to FIG. **3a**, the condition of DC/DC converter **10** having an output voltage V_{OUT} that is lower than the desired or target level is illustrated. Thus, the voltage across load **32** is lower than desired. This condition results in output **46c** of error amplifier **46** having a high level relative to the sawtooth waveform. At point **300a**, the leading, or positively sloped, edge of the sawtooth waveform crosses above the output level of output **46c** of error amplifier **46**, thereby sending output **58c** of comparator **58** low. This particular transition in output **58c** does not affect output **62a** of SR latch **62** since sync pulse **66** is still active, and thus output **62a** remains reset or low.

At point **310a**, the trailing, or negatively sloped, edge of the sawtooth waveform crosses below the output level of output **46c** of error amplifier **46**, thereby sending output **58c** of comparator **58** high. This transition in output **58c** to a high level, in turn, sets output **62a** of SR latch **62** high thereby turning high side FET **14** on and turning off low side FET **12**. The high level of output **46c** relative to the sawtooth waveform results in the sawtooth waveform dropping below the level of output **46c** (at point **310a**) relatively early in the period of the sawtooth waveform. Thus, points **300a** and **310a** are relatively close in time, and, therefore, the period of time during which low side FET **12** is off is corresponding brief. Conversely, the period of time during which high side FET **14** is on and sourcing current is relatively long. Thus, high side FET **14** is on for a relatively long period of time

and sources a greater amount of current to load **32** when V_{OUT} is less than the desired output voltage.

Referring now FIG. **3b**, the condition of DC/DC converter **10** having an output voltage that is higher than the desired or target voltage level is shown. Thus, the voltage across load **32** is greater than desired. The output of error amplifier **46** is therefore low relative to the sawtooth waveform. At point **300b**, the leading, or positively sloped, edge of the sawtooth waveform crosses above the output level of output **46c** of error amplifier **46**, thereby sending output **58c** of comparator **58** low. Output **62a** of SR latch **62** has previously been reset by sync pulse **66**.

At point **310b**, the trailing, or negatively sloped, edge of the sawtooth waveform crosses below the output level of output **46c** of error amplifier **46**, thereby sending output **58c** of comparator **58** high. This transition in output **58c** to a high level, in turn, sets output **62a** of SR latch **62** high thereby turning high side FET **14** on and turning off low side FET **12**. The low level of output **46c** relative to the sawtooth waveform results in the sawtooth waveform dropping below the level of output **46c** (at point **310b**) relatively late in the period of the sawtooth waveform. Thus, points **300a** and **310a** are separated by a substantially greater amount of time relative to the situation illustrated in FIG. **3a** (i.e., when output **46c** is high relative to the sawtooth waveform and/or when V_{OUT} is less than the target value). Therefore, the period of time during which low side FET **12** is on is of a correspondingly longer duration. Conversely, the period of time during which high side FET **14** is on and sourcing current is relatively brief. Therefore high side FET **14** sources a lesser amount of current to load **32** when V_{OUT} is greater than the desired output voltage.

In both cases, i.e., whether the voltage across load **32** is higher or lower than desired, output **62a** of SR latch **62** goes low based upon sync pulse **66** rather than dependent upon the relative value of the voltage across load **32**. Output **62a** of SR latch **62** remains low at least during the duration of sync pulse **66**. When output **62a** of SR latch **62** is in the low state, high side FET **14** is in the off condition and low side FET **12** is in the on condition, and the voltage drop across RDS_{ON} of low side FET **12** is sampled and held. However, when low side FET **12** is in the on condition the direction of load current I_L is toward load **32**. Thus, load current I_L flows from ground through the source to the drain of low side FET **12** when low side FET **12** is in the on condition. This direction of current flow through low side FET **12** develops a negative voltage on the drain of low side FET **12**. The magnitude of this negative voltage is the product of I_L and the RDS_{ON} of low side FET **12**.

In the embodiment shown, the source of low side FET **12** is electrically connected to ground. However, it is to be understood that low side FET **12** can be alternately configured such as, for example, having its source tied through a resistor to ground, and electrically connecting sensing resistor **26** to the source of low side FET **12**. The net effect is the same, and the virtual ground amplifier continues to drive virtual ground node **30** to virtual ground. In this alternative configuration, current from Sample and Hold circuit **38** is still representative of load current I_L except the load-current-induced voltage drop across the added sense resistor is measured rather than the voltage drop across RDS_{ON} of low side FET **12**. This alternative embodiment is best shown in FIG. **6**.

In the embodiment shown, reference voltage supply **48** is described as a fixed voltage supply. However, it is to be understood that reference voltage supply **48** can be alterna-

tively configured, such as, for example, as a bandgap or other fixed voltage source, or may be configured as a Digital to Analog converter or other variable voltage source.

In the embodiment shown, FET **36** is configured as an FET. However, it is to be understood that FET **36** can be alternately configured, such as, for example, an NPN transistor, with Base substituted for Gate, Emitter for Source, and Collector for Drain.

In the embodiment shown, virtual ground amplifier **34** is configured for continuous operation. However, it is to be understood that virtual ground amplifier **34** can be alternately configured, such as, for example, an auto-zeroed amplifier or other non-continuously operating amplifier, as it is needed only when low side FET **12** is in the on state.

In the embodiment shown, DC/DC converter **10** is configured such that a high-level signal at output **62a** of SR latch **62** turns low side FET **12** off and turns on high side FET **14**. However, it is to be understood that DC/DC converter **10** can be alternately configured such that the operational polarity of FET **12** and FET **14** is reversed.

In the embodiment shown, system control circuit **40** is configured to restart the operation of DC/DC converter **10** after a predetermined amount of time following the detection of an overcurrent condition. However, it is to be understood that system control circuit **40** may be alternately configured, such as, for example, to issue a visual or audible warning signal or to completely shut down DC/DC converter **10**.

In the embodiment shown, DC/DC converter **10** is configured with indicator **24**, load capacitor **28** and load **32** connected to node **16**. However, it is to be understood that DC/DC converter **10** can be alternately configured, such as, for example, without interface **24**, load capacitor **28** and load **32** such that a user, designer, or manufacturer can choose and customize circuitry attached to node **16** of DC/DC converter **10**.

While this invention has been described as having a preferred design, the present invention can be further modified within the spirit and scope of this disclosure. This application is therefore intended to cover any variations, uses, or adaptations of the present invention using the general principles disclosed herein. Further, this application is intended to cover such departures from the present disclosure as come within the known or customary practice in the art to which this invention pertains and which fall within the limits of the appended claims.

What is claimed is:

[1. A power supply, comprising:

a DC to DC buck pulse width modulator converter circuit having an input, a high side output and a low side output;

a high side switch electrically connected intermediate a common output node and a voltage supply, said high side switch configured for controlling a flow of current therethrough dependent at least in part upon said high side output;

a low side switch electrically connected intermediate said common output node and ground, said low side switch configured for controlling a flow of current therethrough dependent at least in part upon said low side output;

a virtual ground amplifier having a first input, a second input and an output, said second input electrically connected to ground potential;

a current feedback resistor electrically connected intermediate said common output node and said first input of said virtual ground amplifier;

a variable impedance component electrically connected to said output of said virtual ground amplifier and to said first input of said virtual ground amplifier, said variable impedance component configured to vary in impedance dependent at least in part upon said output of said virtual ground amplifier; and

a sample and hold circuit electrically connected intermediate said DC to DC buck pulse width modulator converter circuit and said variable impedance component, said sample and hold circuit configured to source a virtual ground current through said variable impedance component and to sample and hold said virtual ground current.]

[2. The power supply of claim **1**, further comprising a system control circuit, said system control circuit electrically coupled to said sample and hold circuit, said system control circuit issuing a first control signal, said sample and hold circuit being configured to sample and hold said virtual ground current in response to said first control signal, said sample and hold circuit issuing a sample signal dependent at least in part upon said virtual ground current, said system control circuit selectively activating and deactivating at least one of said high side switch and said low side switch dependent at least in part upon said sample signal.]

[3. The power supply of claim **2**, wherein said system control circuit issues a sync signal, said sync signal resetting at least one of said high side switch and said low side switch.]

[4. The power supply of claim **2**, further comprising an overcurrent detector circuit electrically coupled to said sample and hold circuit and to said system control circuit, said overcurrent detector circuit configured for issuing an overcurrent signal when said sample signal exceeds a predetermined threshold.]

[5. The power supply of claim **4**, wherein said system control circuit is configured for shutting down said DC to DC buck pulse width modulator converter circuit in response to said overcurrent signal.]

[6. The power supply of claim **5**, wherein said system control circuit is configured to restart said DC to DC buck pulse width modulator converter circuit a predetermined period of time after receiving said overcurrent signal.]

[7. The power supply of claim **2**, further comprising a power supply output, a voltage feedback resistor electrically connected intermediate said power supply output and said input of said DC to DC buck pulse width modulator converter circuit.]

[8. The power supply of claim **7**, wherein said system control circuit includes a current mirror, said current mirror sourcing a droop current, said droop current being dependent at least in part upon said virtual ground current, said droop current being electrically coupled to said input of said DC to DC buck pulse width modulator converter circuit to modify a feedback voltage across said voltage feedback resistor and thereby adjust an output voltage of said power supply dependent at least in part upon said droop current.]

[9. The power supply of claim **1**, further comprising a negative current source, said system control circuit issuing a second control signal, said second control signal being electrically coupled to said negative current source, said negative current source sourcing a negative current in response to said second control signal, said negative current flowing into said first input of said virtual ground amplifier to thereby connect said current feedback resistor to ground when current through said current feedback resistor is negative.]

[10. The power supply of claim **1**, wherein said variable impedance component comprises one of a field effect transistor and an NPN-type transistor.]

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[11. The power supply of claim 1 further comprising an inductor having a first end and a second end, said first end electrically connected to said common output node, said second end configured for being electrically connected to a load.]

12. A method of sensing an output current in a power supply, said power supply comprising a DC to DC buck pulse width modulator converter circuit having an input, a high side output and a low side output, said method comprising the steps of:

electrically connecting a high side switch intermediate a common output node and a voltage supply, said high side switch configured for controlling a flow of current therethrough dependent at least in part upon said high side output;

a low side switch electrically connected intermediate said common output node and ground, said low side switch configured for controlling a flow of current therethrough dependent at least in part upon said low side output;

directing a sensed current to a virtual ground node, said sensed current comprising a known portion of the output current when said low side switch is in an on condition, said sensed current flowing into said virtual ground node in a first direction;

sourcing a virtual ground current into said virtual ground node, said virtual ground current flowing into said virtual ground node in a second direction, said second direction being opposite to said first direction, said virtual ground current being substantially equal to said sensed current and thereby canceling said sensed current at said virtual ground node; and

sampling and holding a value of said virtual ground current.

13. The method of claim 12, comprising the further step of selectively activating and deactivating at least one of said high side switch and said low side switch dependent at least in part upon said sampling and holding step.

14. The method of claim 12, comprising the further step of selectively activating and deactivating at least one of said high side switch and said low side switch on at least one of a periodic and a random basis.

15. The method of claim 12, comprising the further steps of:

comparing said sampled and held value of said virtual ground current to a predetermined maximum limit; and shutting down said power supply when said virtual ground current exceeds said predetermined maximum limit.

16. The method of claim 15, comprising the further step of restarting said power supply a predetermined period of time after said shutting down step.

17. The method of claim 12, comprising the further step of adjusting an output voltage of said power supply dependent at least in part upon said sampled and held value of said virtual ground current.

[18. A power supply, comprising:

ADC to DC buck pulse width modulator converter circuit having an input, a high side output and a low side output;

a high side switch electrically connected intermediate a common output node and a voltage supply, said high side switch configured for controlling a flow of current therethrough dependent at least in part upon said high side output;

a low side switch electrically connected to said common output node and to ground through a sense resistor, said

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low side switch configured for controlling a flow of current therethrough dependent at least in part upon said low side output;

a virtual ground amplifier having a first input, a second input and an output, said second input electrically connected to ground potential;

a current feedback resistor electrically connected intermediate said sense resistor and said first input of said virtual ground amplifier;

a variable impedance component electrically connected to said output of said virtual ground amplifier and to said first input of said virtual ground amplifier, said variable impedance component configured to vary in impedance dependent at least in part upon said output of said virtual ground amplifier; and

a sample and hold circuit electrically connected intermediate said DC to DC buck pulse width modulator converter circuit and said variable impedance component, said sample and hold circuit configured to source a virtual ground current through said variable impedance component and to sample and hold said virtual ground current.]

19. A method for controlling a DC/DC converter having an output voltage and sourcing an output current to a load, the method comprising:

receiving a sensed current at a node, the sensed current representative of the output current when a low side circuit is in an on condition, the sensed current flowing into the node in a first direction;

sourcing a current into the node, the sourced current flowing into the node in a second direction, the second direction being opposite to the first direction, the sourced current also representative of the output current;

sampling and holding a value of the sourced current; receiving a signal representative of the output voltage; issuing an error signal dependent at least in part upon the signal representative of the output voltage, the sampled and held value of the sourced current and a first reference signal;

issuing a comparison signal, the comparison signal based at least in part upon the error signal and a second reference signal; and

issuing a control signal based at least in part upon the comparison signal, wherein the control signal selectively controls the DC/DC converter.

20. The method of claim 19, wherein receiving a sensed current comprises receiving a current through a sense resistor.

21. The method of claim 19, wherein receiving a sensed current comprises receiving a current through a sense resistor coupled between a node of the low side circuit and the node receiving the sensed current.

22. The method of claim 19, wherein sourcing a current into the node comprises sourcing a current through a variable impedance component.

23. The method of claim 19, wherein the second reference signal is a ramp signal.

24. The method of claim 19, wherein issuing a control signal comprises issuing a control signal with an SR latch.

25. The method of claim 19, and further including summing at least two of the signal representative of the output voltage, the sampled and held value of the sourced current and the first reference signal prior to issuing an error signal.

26. A method of sensing an output current in a power supply, the power supply comprising a DC to DC converter

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circuit having an input, a high side output and a low side output, the method comprising:

receiving a sensed current at a node, the sensed current representative of the output current when a low side circuit is in an on condition, the sensed current flowing into the node in a first direction;

sourcing a current into the node, the sourced current flowing into the node in a second direction, the second direction being opposite to the first direction, the sourced current also representative of the output current; and

sampling and holding a value of the sourced current.

27. The method of claim 26, wherein receiving a sensed current comprises receiving a current through a sense resistor.

28. The method of claim 26, wherein receiving a sensed current comprises receiving a current through a sense resistor coupled between a node of the low side circuit and the node receiving the sensed current.

29. The method of claim 26, wherein sourcing a current into the node comprises sourcing a current through a variable impedance component.

30. A method of controlling an output current in a power supply, the power supply comprising a converter circuit having an input, a high side output coupled to a high side switch and low side output coupled to a low side switch, the method comprising:

generating a sensed current that is representative of the load current;

directing the sensed current to a current sense node in a first direction;

sourcing a current into the current sense node, the sourced current flowing into the current sense node in

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a second direction, the second direction being opposite to the first direction, the sourced current being substantially equal to the sensed current and thereby canceling the sensed current at the current sense node;

sampling and holding a value of the sourced current; and generating control signals for the high side and low side outputs based on the sourced current.

31. The method of claim 30, wherein generating a sensed current comprises generating a sensed current when the low side switch is in an on condition.

32. The method of claim 30, wherein generating control signals comprises generating signals for activating and deactivating at least one of the high side switch and the low side switch dependent at least in part upon the value of the sampling and holding of the sourced current.

33. The method of claim 30, wherein generating control signals comprises activating and deactivating at least one of the high side switch and the low side switch on at least one of a periodic and a random basis.

34. The method of claim 30, further comprising:

comparing the sampled and held value of the sourced current to a selected value; and

shutting down the power supply when the sourced current exceeds the selected value.

35. The method of claim 34, further comprising restarting the power supply a selected period of time after shutting down the power supply.

36. The method of claim 30, wherein generating control signals comprises generating control signals to adjust an output voltage of the power supply dependent at least in part upon the sampled and held value of the sourced current.

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