US00RE39065E

(19) **United States**
(12) **Reissued Patent**
Nelson

(10) **Patent Number: US RE39,065 E**
(45) **Date of Reissued Patent: Apr. 18, 2006**

(54) **SWITCHING VOLTAGE REGULATOR CIRCUIT**

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(21) Appl. No.: **08/794,374**

(22) Filed: **Dec. 10, 1996**

Related U.S. Patent Documents

Reissue of:
(64) Patent No.: **4,823,070**
Issued: **Apr. 18, 1989**
Appl. No.: **07/082,989**
Filed: **Aug. 3, 1987**

U.S. Applications:
(63) Continuation of application No. 08/558,204, filed on Nov. 16, 1995, which is a continuation of application No. 07/683,549, filed on Apr. 10, 1991, which is a continuation of application No. 06/932,158, filed on Nov. 18, 1986, now abandoned.

(51) **Int. Cl.**
G05F 1/40 (2006.01)

(52) **U.S. Cl.** **323/284**

(58) **Field of Classification Search** 323/284, 323/282, 287, 285, 267, 299; 363/20, 97, 363/13, 21, 131; H02M 3/335, 7/537; G05F 1/40, G05F 1/44, 1/46, 1/56, 5/00
See application file for complete search history.

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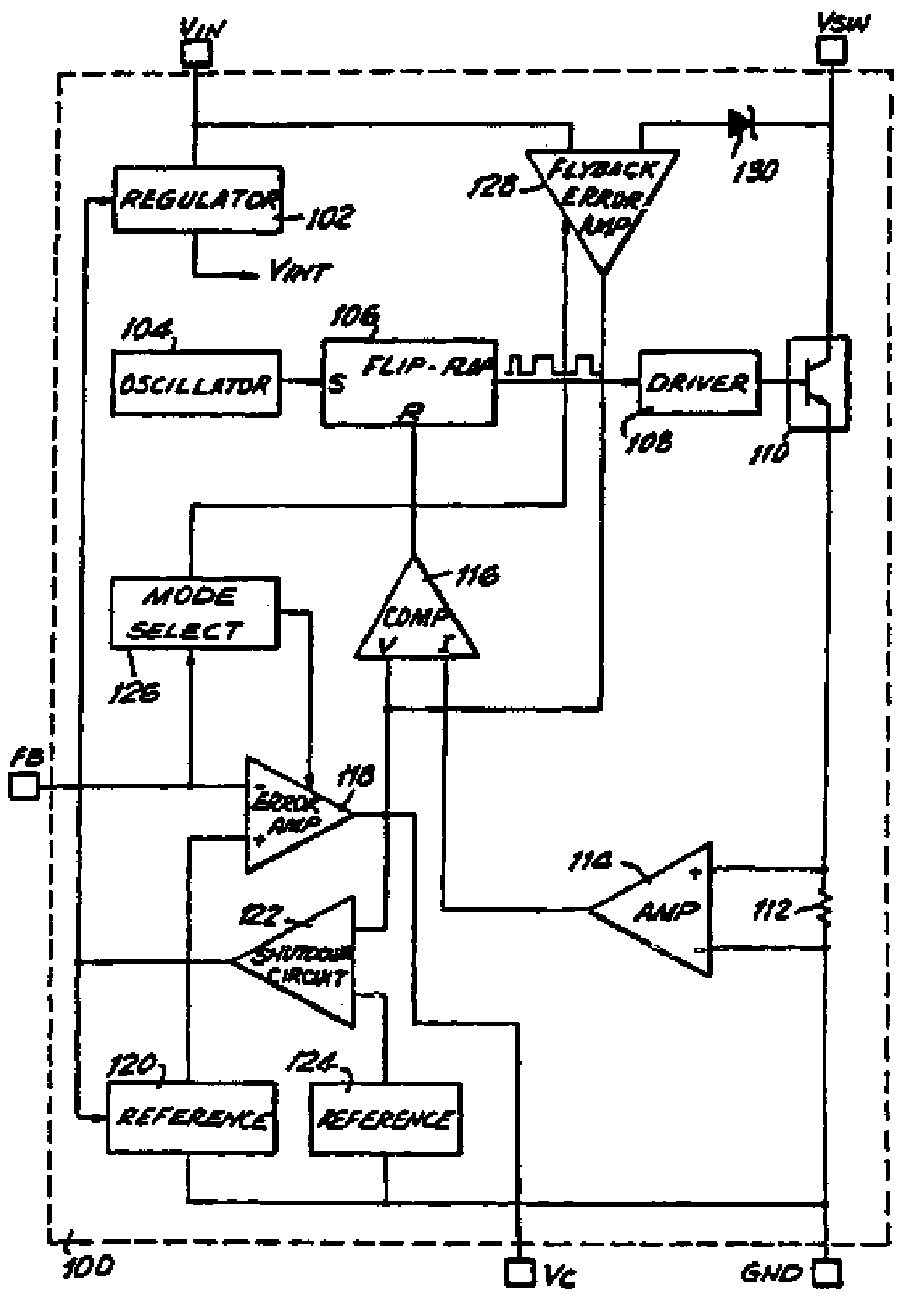
(57) **ABSTRACT**

An integrated circuit for use in implementing a switching voltage regulator, the integrated circuit including a power switching transistor, driver circuitry and control circuitry, which is operable in a normal feedback mode or an isolated flyback mode. The integrated circuit includes shutdown circuitry for placing the regulator in a micro-power sleep mode, and can be packaged in a five-pin conventional power transistor package. The terminals of the integrated circuit regulator perform multiple functions. A compensation terminal is used for frequency compensation, current limiting, soft-start operation and shutdown. A feedback terminal is used as a feedback input when the integrated circuit is in feedback mode, and as a logic pin to program the regulator for isolated flyback operation. The feedback terminal is also used to trim the flyback reference voltage.

91 Claims, 8 Drawing Sheets



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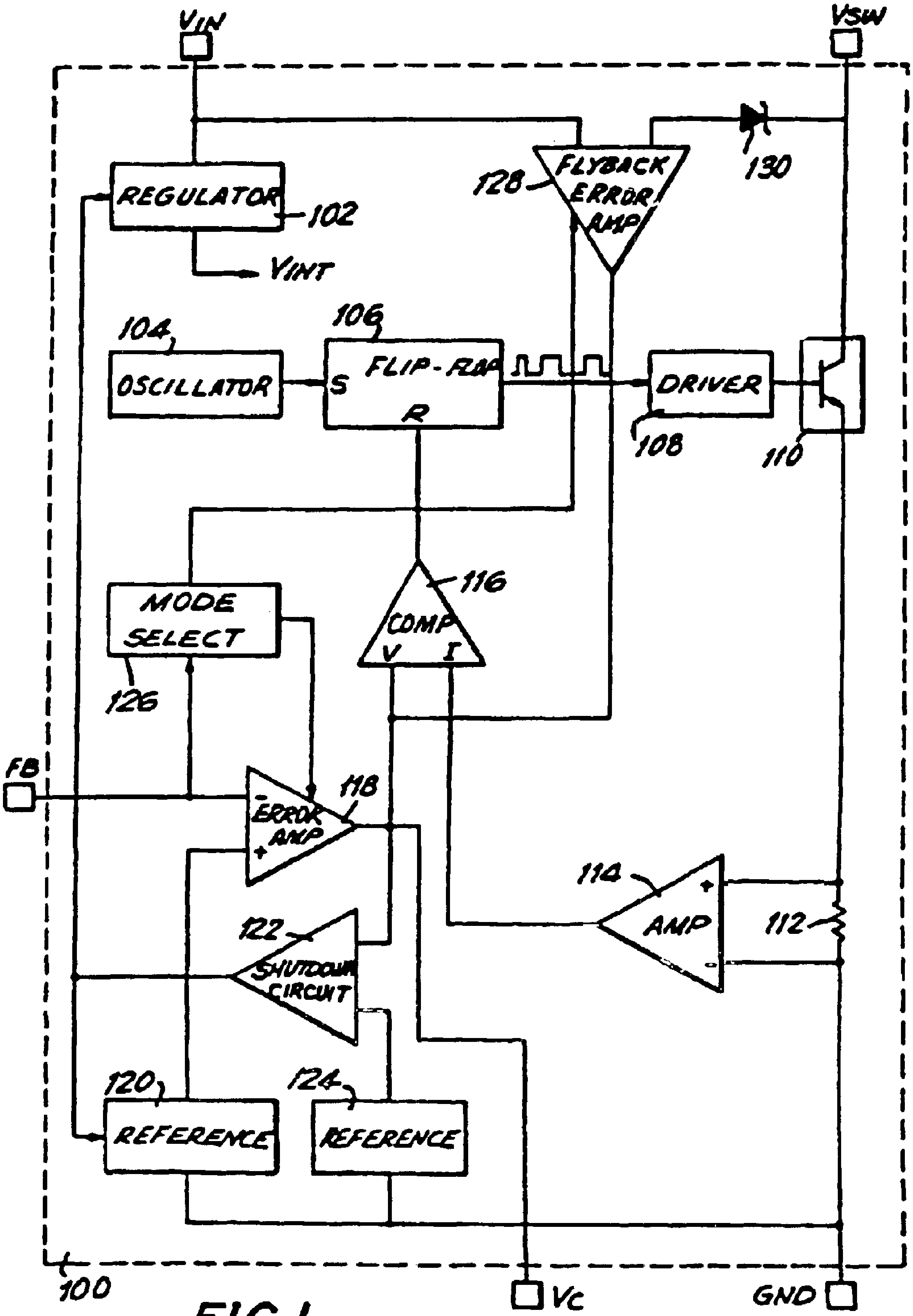
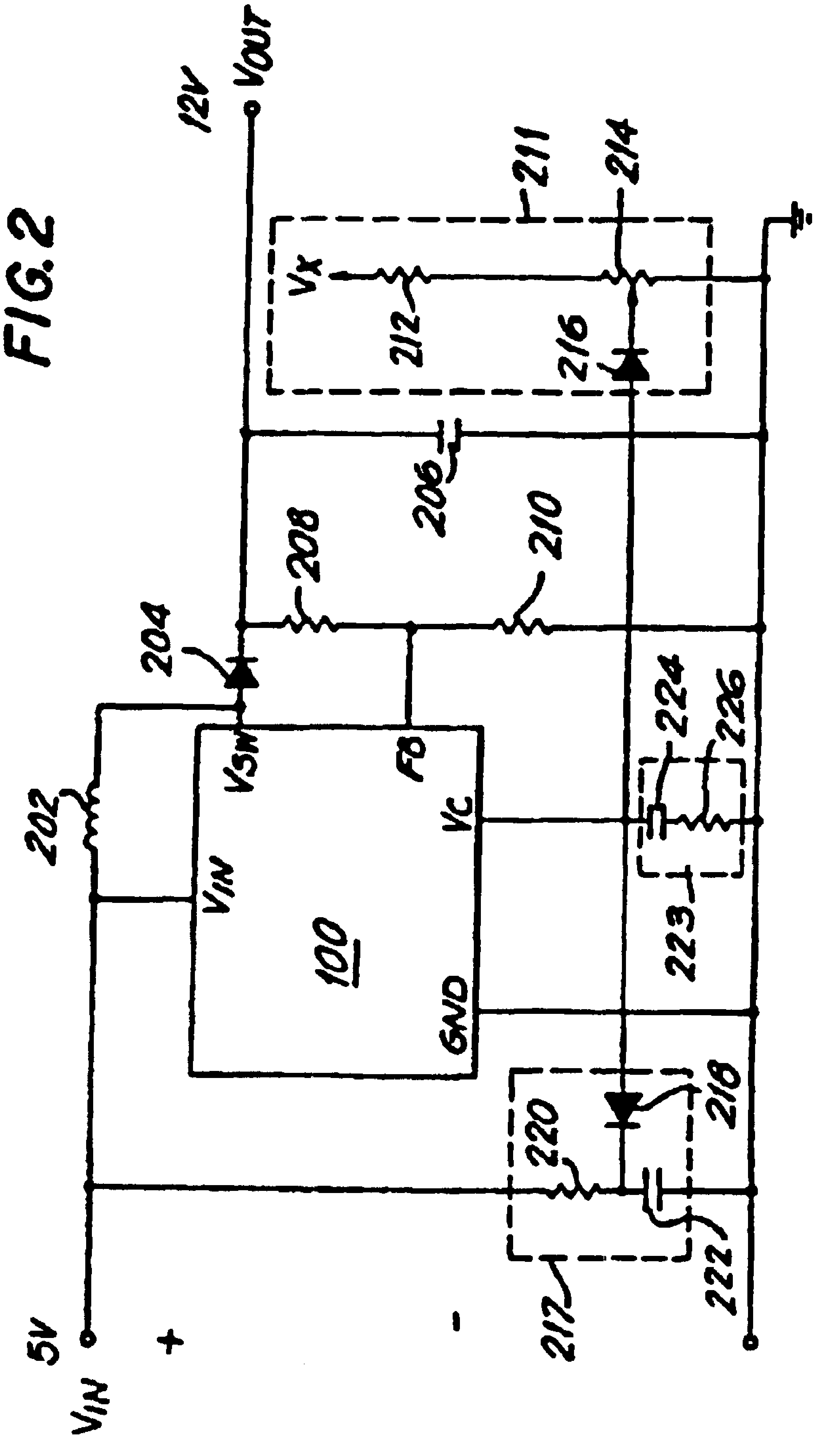

VIN
VSW
REGULATOR
102
VINT
128
FLYBACK ERROR AMP
130
104
OSCILLATOR
106
FLIP-FLOP
S
R
DRIVER
108
110
MODE SELECT
126
COMP
V
I
116
FB
ERROR AMP
118
114
AMP
112
122
SHUTDOWN CIRCUIT
120
REFERENCE
124
REFERENCE
100
Vc
GND

FIG. 1

FIG. 2


12V
VOUT
211
214
VX
212
216
206
208
210
204
202
VIN
VSW
FB
VC
GND
100
224
226
223
218
220
217
222
5V
VIN
+
-

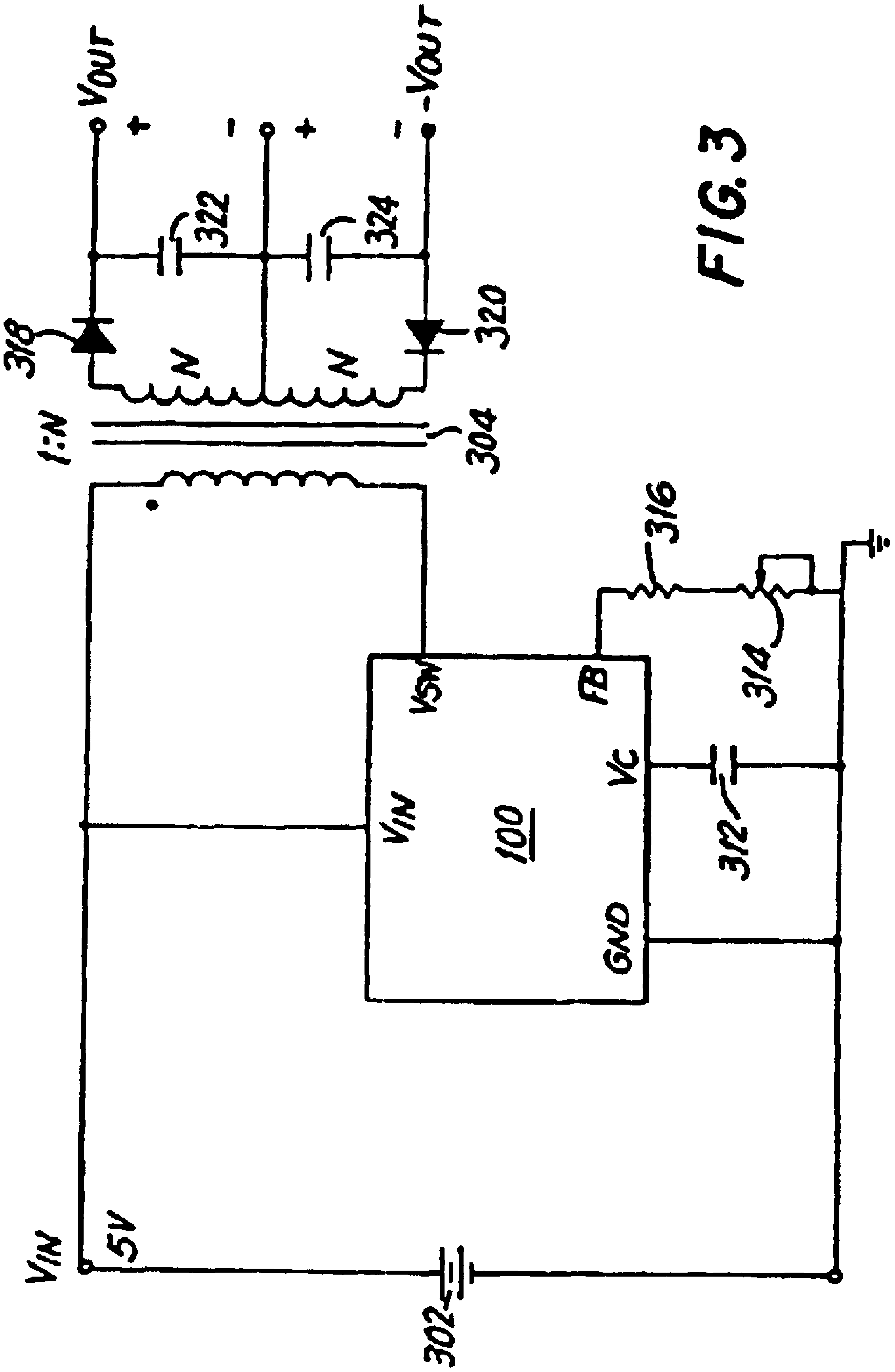
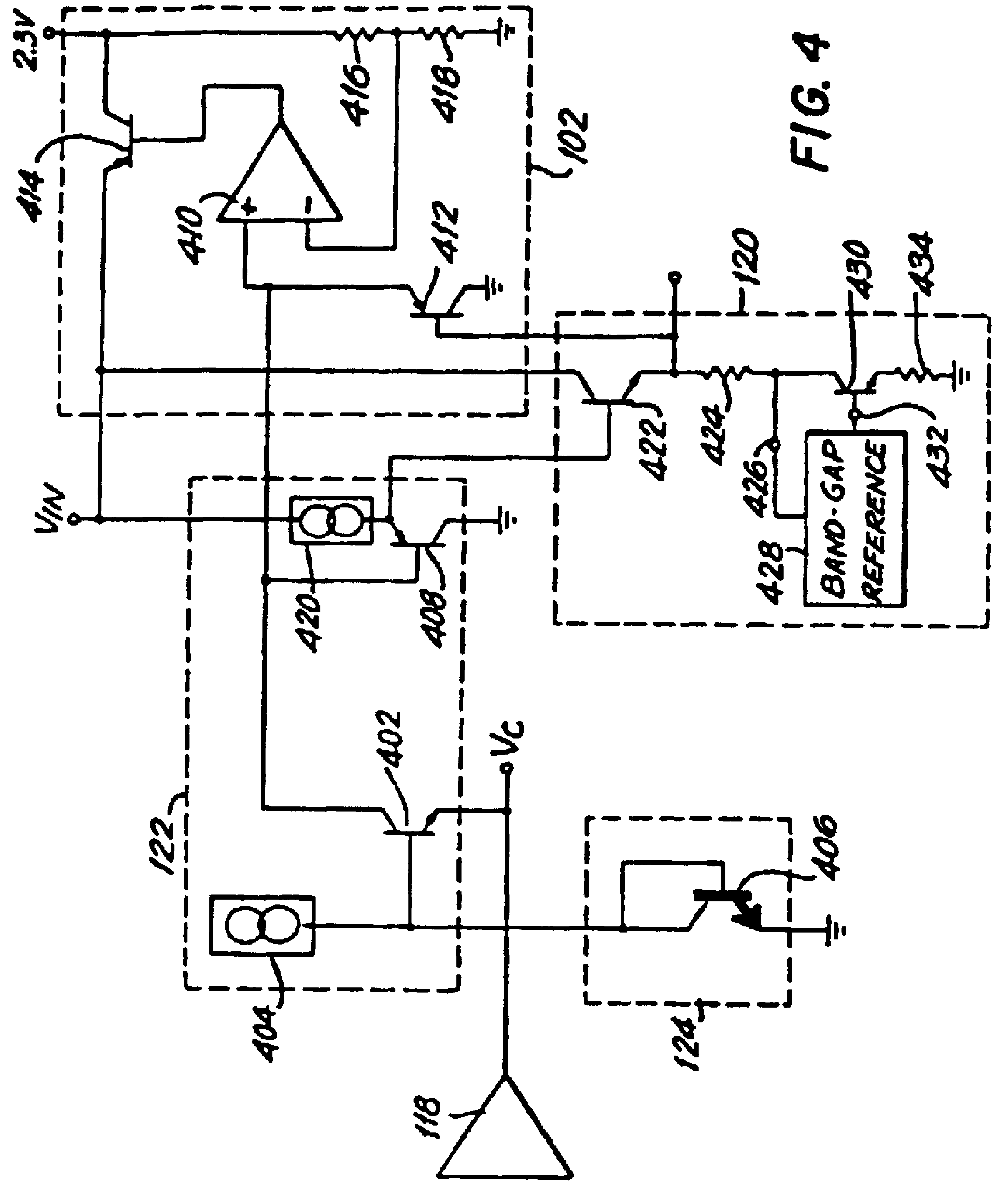

VOUT
+
-
+
-
-VOUT
322
324
318
320
N
N
1:N
304
316
314
VSW
FB
VC
VIN
100
GND
312
VIN
5V
302

FIG. 3



2.3V
414
410
416
418
102
412
120
430
434
VIN
422
424
426
428
BAND-GAP REFERENCE
432
420
408
402
122
VC
404
406
124
118

FIG. 4

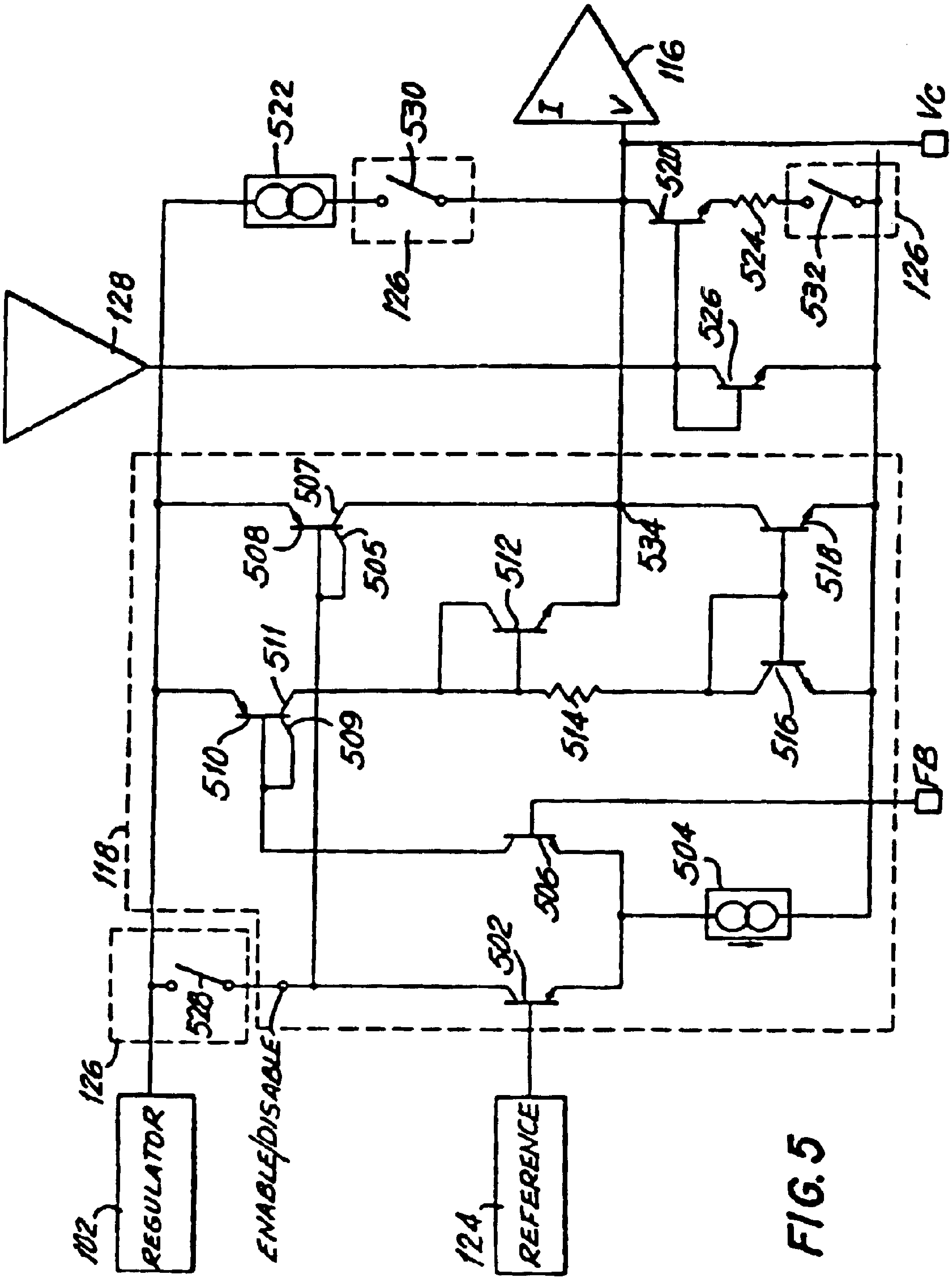

REGULATOR
102
ENABLE/DISABLE
REFERENCE
124
126
528
118
502
506
504
510
509
511
514
516
FB
508
507
505
512
534
518
128
526
532
126
524
520
522
530
126
116
I
V
Vc

FIG. 5

FIG. 6

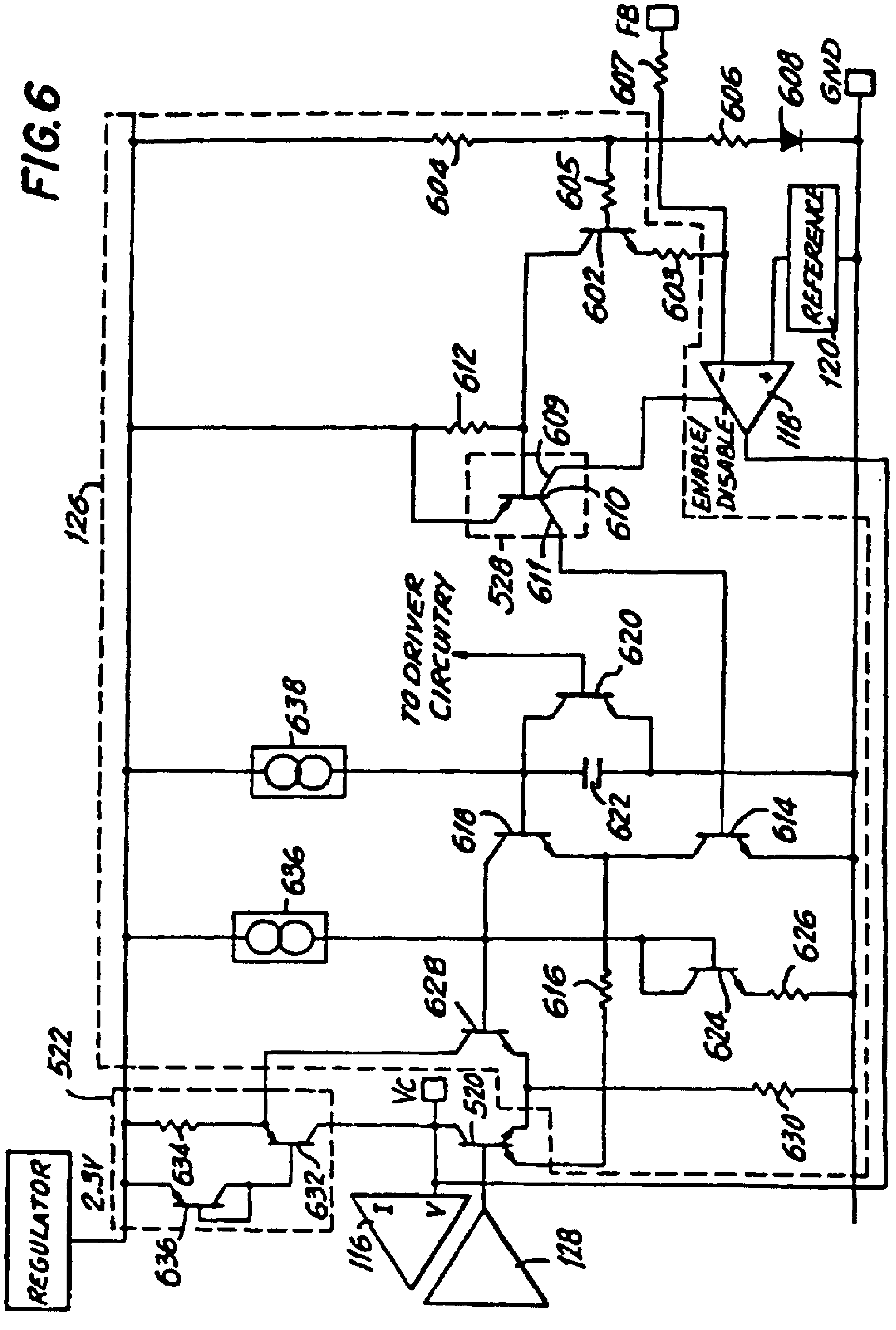
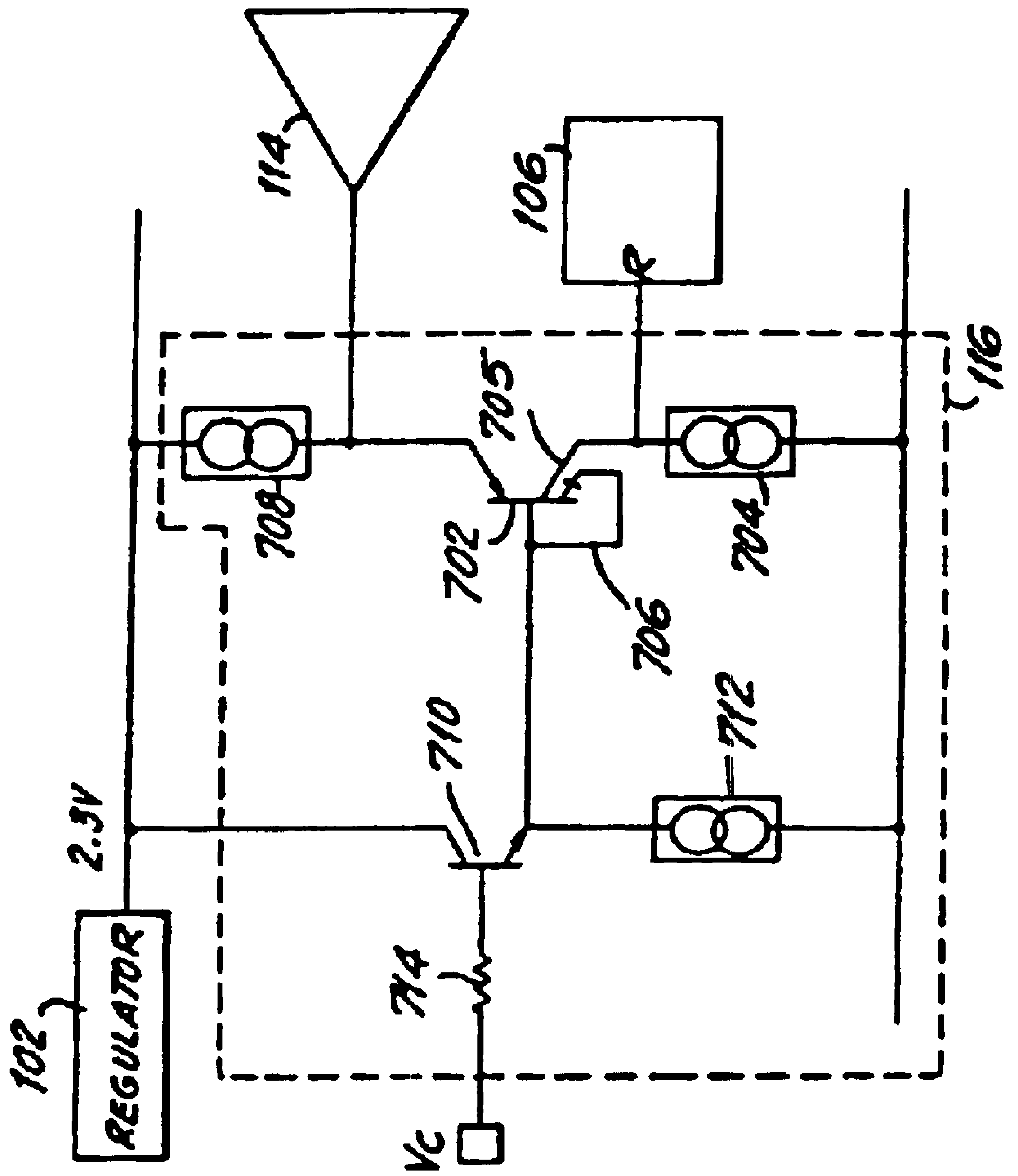

REGULATOR
2.5V
522
634
636
632
116
I
V
128
VC
520
628
616
624
630
626
636
638
618
622
614
620
TO DRIVER CIRCUITRY
528
611
610
609
612
126
602
603
605
604
ENABLE/DISABLE
118
120
REFERENCE
607
FB
606
608
GND

FIG.7


114
106
116
705
708
702
704
706
710
712
2.5V
714
102
REGULATOR
Vc

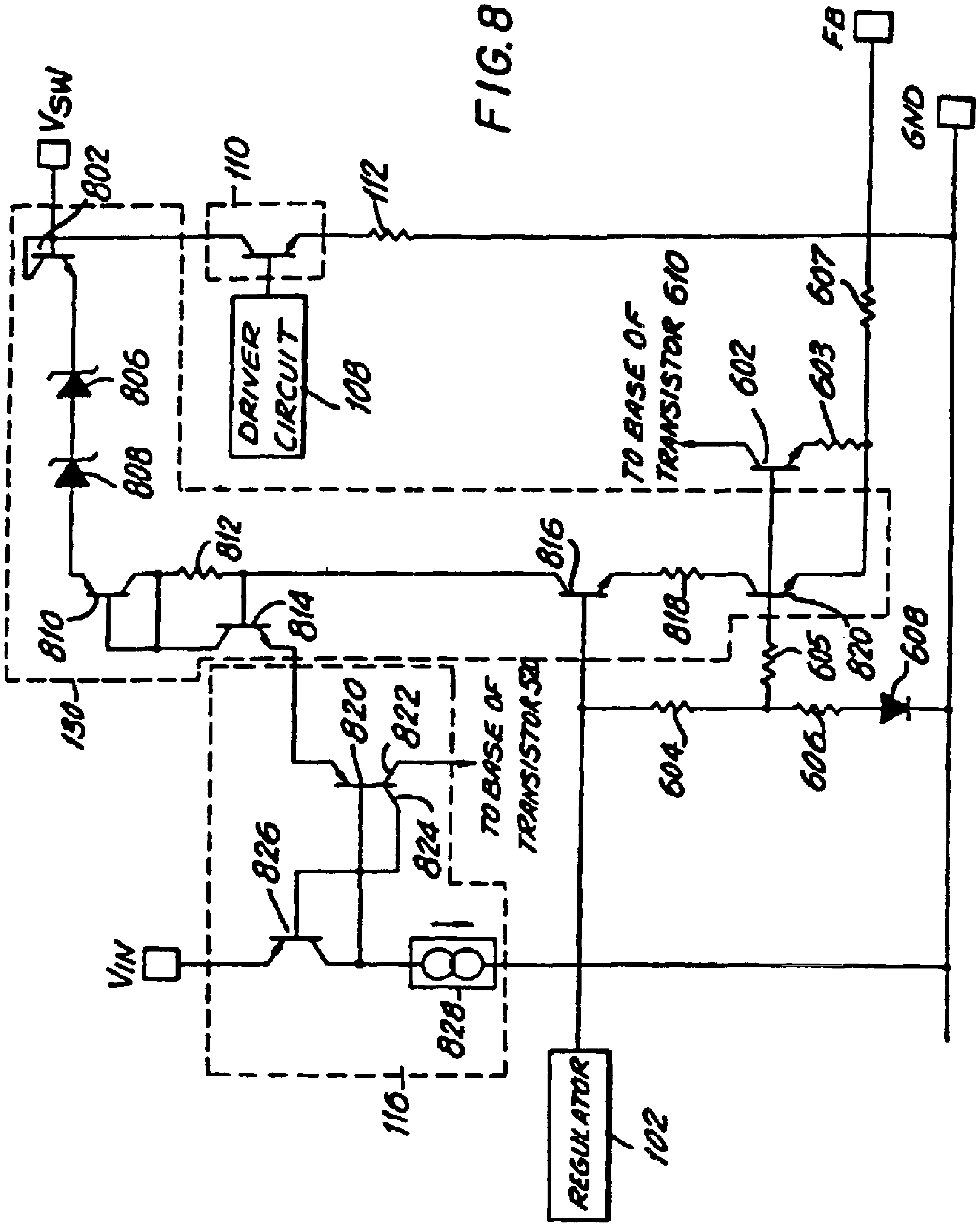


FIG.8

VSW
802
806
808
810
812
814
816
818
820
822
824
826
828
130
110
112
108
DRIVER CIRCUIT
TO BASE OF TRANSISTOR 610
602
603
607
FB
GND
604
605
606
608
TO BASE OF TRANSISTOR 52
VIN
116
REGULATOR
102

SWITCHING VOLTAGE REGULATOR CIRCUIT

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.

This is a continuation of application Ser. No. 08/558,204, filed Nov. 16, 1995, which is a continuation of application Ser. No. 07/683,549, filed Apr. 10, 1991, entitled Switching Voltage Regulator Circuit.

This is a continuation of application Ser. No. 932,158, filed Nov. 18, 1986, entitled "SWITCHING VOLTAGE REGULATOR CIRCUIT", now abandoned.

BACKGROUND OF THE INVENTION

The present invention relates to an integrated circuit switching voltage regulator circuit having multi-function terminals. More particularly, the present invention relates to an integrated circuit for use in implementing a switching voltage regulator circuit, the integrated circuit requiring only five terminals, operable in both feedback and isolated flyback mode, and including a power switching element, a driver network, and control circuitry which sets the duty cycle of the switching element.

The function of a voltage regulator is to provide a predetermined and substantially constant output voltage level from an unregulated input voltage. Two types of voltage regulators are commonly used today: linear regulators and switching regulators.

A linear regulator controls output voltage by controlling the voltage drop across a power transistor which is connected in series with a load. The power transistor is operated in its linear region and conducts current continuously.

A switching regulator controls output voltage by using a power transistor as a switch to provide a pulsed flow of current to a network of inductive and capacitive energy storage elements which smooth the switched current pulses into a continuous and regulated output voltage. The power transistor is operated either in a cutoff or saturated state at a duty cycle required by the voltage differential between the input and output voltages. Varying the duty cycle varies the regulated output voltage of the switching regulator.

The duty cycle of a switching regulator is controlled by monitoring output voltage or current through the switch. The latter type of switching regulator is known as a current-mode switching regulator, and is easier to frequency stabilize and has better response to transients than does a switching regulator in which the duty cycle is controlled directly by output voltage.

Switching regulators have at least two advantages over linear regulators. First, switching regulators typically operate with greater efficiency than linear regulators, a particularly important factor in high current regulators. Second, switching regulators are more versatile than linear regulators. Switching regulators can provide output voltages which are less than, greater than, or of opposite polarity to the input voltage, depending on the mode of operation of the switching regulator, whereas linear regulators can only provide output voltages which are less than the input voltage.

Further, switching regulators can be configured to drive current through the primary winding of a transformer, the secondary winding of which simultaneously provides current to the load. The transformer provides current gain, the amount of which is determined by the turns ratio of the transformer. Multiple outputs are possible, each output typically requiring two steering diodes, an inductor and a capacitor. Alternatively, the transformer may be configured such that current provided to the primary winding of the transformer by the regulator switch is stored as energy in the primary winding and is transferred to the secondary winding only after the switch driving the primary winding is opened. This configuration, known as flyback operation, allows multiple regulated output voltages and requires only one steering diode and one capacitor for each output.

In either of the above transformer configurations, the isolation provided by the transformer between input and output circuits is limited by the need to regulate the output voltage by sensing the output voltage of the regulator circuit and providing a feedback voltage signal to the control circuitry of the circuit. The output circuit driven by the secondary winding of the transformer thus remains electrically connected to the input circuit driving the primary winding. Voltage regulator configurations which sense output voltage of the circuit for use as a feedback signal are referred to herein as normal feedback mode regulators. Another configuration, known as an isolated flyback mode regulator, allows a transformer secondary winding to be totally isolated from the input circuit connected to the primary winding by regulating the peak voltage developed across the primary winding when the secondary winding provides current to the output circuit.

Switching regulators, although more flexible than linear regulators in circuit applications, are typically more complex than linear regulators. Although several integrated circuits in the past have been commercially available for implementing the control, driver and power switch functions of switching regulators, switching regulators utilizing such integrated circuits have required substantial engineering expertise and numerous discrete components to make them operational. Also, integrated circuits heretofore available typically required 8–14 terminals for connection to external discrete components, and could not be configured into a very low current (shutdown) mode. This quantity of terminals prevented such integrated circuits from being packaged in low-cost power transistor packages such as the conventional 5-pin TO-3 type metal can or the TO-220 type molded plastic packages, and thus limited the power handling capability of the integrated circuit. Further, heretofore available integrated circuits for use in implementing switching voltage regulators have not been capable of use both in normal feedback mode switching regulator circuits and isolated flyback mode regulator circuits.

In view of the foregoing, it would be desirable to be able to provide a switching voltage regulator circuit which is simple to implement and which is capable of versatile and efficient operation.

It would further be desirable to be able to provide a switching regulator circuit, having a very low current sleep mode which can be implemented as an integrated circuit which includes the power switch, and which can be packaged in a conventional TO-3 or TO-220 power transistor package.

It would also be desirable to be able to provide an integrated circuit which can be utilized to implement both normal feedback mode and isolated flyback mode regulator circuit topologies.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an integrated circuit for use in implementing a switching voltage regulator circuit, the integrated circuit being simple to implement and capable of efficient operation in numerous switching regulator configurations.

It is a further object of the present invention to provide an integrated circuit capable of implementing a switching voltage regulator circuit, and capable of operating in both normal feedback mode and isolated flyback mode voltage regulator configurations.

It is yet a further object of the present invention to provide an integrated circuit, for use in implementing a switching regulator, which includes control circuitry, driver circuitry and the power switch, which can be packaged in conventional 5-pin TO-3 or TO-220 power packages, and which is capable of operating in a very low current sleep mode.

These and other objects of the present invention are accomplished by a novel switching regulator circuit which can be packaged as an integrated circuit requiring only five external terminals for connection to discrete external components. The low number of terminals is achieved by assigning several functions to individual terminals. One terminal is used for soft starting, frequency compensation, switch current limiting and shutdown. Another terminal is used to receive a feedback signal when the integrated circuit is operated in a normal feedback mode switching voltage regulator circuit, and alternatively to place the integrated circuit into an isolated flyback mode and to vary the flyback reference voltage in an isolated flyback voltage regulator circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other objects and advantages of the invention will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout, and in which:

FIG. **1** is a block diagram of a five-terminal current-mode switching voltage regulator integrated circuit of the present invention;

FIG. **2** is a schematic diagram of the switching voltage regulator integrated circuit of FIG. **1** connected in a normal feedback mode boost regulator configuration and including a soft-start circuit, a frequency compensation circuit, and an external current limiting circuit;

FIG. **3** is a schematic diagram of the switching voltage regulator integrated circuit of FIG. **1** connected in an isolated flyback mode switching regulator configuration;

FIG. **4** is a schematic diagram of a preferred embodiment of shutdown circuit **122** and reference voltage generator **124**, as well as reference **120** and regulator **102**, of the switching voltage regulator integrated circuit of FIG. **1**;

FIG. **5** is a schematic diagram of a preferred embodiment of error amplifier **118** and its interconnection with mode select circuit **126** of the switching voltage regulator integrated circuit of FIG. **1**;

FIG. **6** is a schematic diagram of a preferred embodiment of switches **528**, **530** and **532** and mode select circuit **126** of FIGS. **1** and **5**;

FIG. **7** is a schematic diagram of a preferred embodiment of comparator **116** of the switching voltage regulator integrated circuit of FIG. **1**; and

FIG. **8** is a schematic diagram of a preferred embodiment of variable zener diode **130** of the switching voltage regulator of FIG. **1**.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **1** shows a five-terminal integrated circuit **100** of the present invention capable of implementing a current-mode switching voltage regulator circuit, and capable of being packaged in a conventional 5-pin power package. Five terminals are shown, labeled as V_{IN} (input supply), V_{SW} (output), FB (feedback), V_C (compensation) and GND (ground).

Terminal V_{IN} provides a connecting point for input voltage, and is used to supply power to the internal circuitry of integrated circuit **100**. Terminal V_{SW} is the output terminal of circuit **100**. It provides a connecting point between power switch **110** of regulator **100** and external components configured to implement a number of switching regulator topologies, to convert the pulsed current flowing through switch **110** into a regulated output voltage. Further, when regulator **100** is operated in an isolated flyback mode, as discussed further herein, terminal V_{SW} provides a flyback reference voltage point which is held to a peak voltage level which exceeds the voltage at terminal V_{IN} by a predetermined amount.

Terminal FB provides three functions. First it serves as an input for feedback voltage when integrated circuit **100** is operated in a feedback mode. Second, terminal FB acts as a logic pin for programming integrated circuit **100** for normal feedback or isolated flyback operation. As further discussed below, integrated circuit **100** is converted from normal feedback operation to isolated flyback operation when a current exceeding a predetermined threshold level is conducted out of terminal FB by connecting terminal FB to ground through a resistor. Third, terminal FB is used to establish the relative value (to voltage at V_{IN}) of the flyback reference voltage at terminal V_{SW}. The different functions of terminal FB, and their implementation, are discussed in greater detail below.

Terminal V_C provides access to a point in the internal circuitry of integrated circuit **100** to provide several functions. First, a frequency compensation circuit may be connected to terminal V_C to control the closed loop response of integrated circuit **100**. Second, a current limit circuit may be connected to terminal V_C to limit the peak current through switch **110**. Third, a soft-start circuit may be connected to terminal V_C to ensure that the width of the initial current pulse flowing through switch **110** starts from zero and builds up to a proper level gradually when regulator **100** is first powered up, thereby avoiding sudden current surges upon start-up of the circuitry. Fourth, a shutdown circuit may be connected to terminal V_C for placing regulator **100** into an inactive sleep mode in which the current drawn by regulator **110** is reduced to a very low value. These different functions, and their implementation, are described in greater detail below.

Referring now to the circuitry internal to switching regulator circuit **100**, connected to terminal V_{IN} is a linear voltage regulator **102** which regulates the supply voltage applied to terminal V_{IN} to provide a substantially constant voltage for use by the internal circuitry of regulator **100**. Voltage regulator **102** may be substantially any conventional voltage regulator circuit which provides a regulated output voltage of about 2.3V (this voltage is not critical, and may be varied as desired). Voltage regulator **102** is discussed in more detail below.

Conventional oscillator **104** is connected to the set input of conventional set/reset flip-flop **106** to provide flip-flop **106** with a digital clocking signal. The output of flip-flop **106** is connected to driver circuitry **108**, which in turn is connected to switch **110**. Substantially any conventional driver circuitry may be used to provide sufficient base drive current to switch transistor **110**. Alternatively, a driver circuit may be used of the type disclosed in co-pending patent application Ser. No. 932,014 (*now U.S. Pat. No. 4,755,741*) filed Nov. 18, 1986, entitled “Adaptive Transistor Drive Circuit”, filed in the name of Carl T. Nelson, the disclosure of which is incorporated herein by reference.

The digital clocking signal provided by oscillator **104**, which preferably has a frequency of approximately 40 kHz, is used to turn on switch **110** via flip-flop **106** and driver circuitry **108**. Switch **110** is a power transistor having a base connected to driver circuitry **108**, a collector connected to terminal V_{SW} and an emitter connected to one end of sense resistor **112**, the other end of which is connected to terminal GND.

Flip-flop **106** supplies a signal to driver circuitry **108** in response to the clock signal provided by oscillator **104**. The signal provided by flip-flop **106** in response to the clock signal causes driver circuitry **108** to turn on switch **110**. When regulator **100** is configured in a switching regulator with external components as described below, the current flows between terminal V_{SW} and terminal GND as a consequence of the turning on of switch **110** and through sense resistor **112**, which causes a voltage to be generated across sense resistor **112**. Sense resistor **112** in FIG. **1** has a value of approximately 0.02 ohms, although other values may be used. The inputs of a conventional common base differential amplifier **114**, preferably having a differential voltage gain of approximately **6**, are connected across sense resistor **112**. The output of amplifier **114** is connected to one input (I) of comparator circuit **116** (the details of which are further discussed with reference to FIG. **7**). Amplifier **114** detects the voltage generated across sense resistor **112** when power transistor **110** conducts, and responsively provides an amplified signal to input I of comparator **116**. The second input (V) of comparator **116** is connected to the output of an error amplifier **118** (the details of which also are discussed below with reference to FIG. **5**). The inverting input of error amplifier **118** is connected to terminal FB. The noninverting input of error amplifier **118** is connected to an internal reference voltage generator **120**. Reference voltage generator **120** is a temperature compensated band-gap reference voltage circuit (e.g., a Brokaw Cell) having a voltage output of approximately 1.24V. Error amplifier **118** has a differential voltage gain of approximately 800–1000, and provides a maximum output voltage of approximately 2.0V.

Error amplifier **118** detects the difference in voltage between the voltage at terminal FB and the reference voltage provided by reference generator **120**, and responsively provides an error signal to the V input of comparator **116**. The output of error amplifier **118** is also connected to terminal V_C and to one input of shutdown circuit **122**, a second input of which is connected to reference voltage generator **124**. Reference voltage generator **124**, the details of which are further discussed herein, preferably provides a reference voltage of approximately 0.15V. The output of shutdown circuit **122** is connected to regulator **102** and reference voltage generator **120**. As will be explained in greater detail below with reference to FIG. **4**, shutdown circuit **122** provides a shutdown signal to regulator **102** and reference generator **120** when the voltage at terminal V_C is externally pulled down below the 0.15V reference voltage provided by reference generator **124**.

The on/off duty cycle of switch **110** is determined by the output of comparator **116**, which is connected to the reset input of flip-flop **106**. The output state of comparator **116** at any time depends on the instantaneous values of the voltages at its two inputs. When integrated circuit **100** is operated in its normal feedback mode, as described below, a voltage proportional to the regulated output voltage is applied to terminal FB. Typically the voltage applied to terminal FB is set by a voltage divider resistor network comprising two resistors connected in series between the regulated output of the voltage regulator circuit and ground. Terminal FB is connected between the two resistors, and the ratio of the resistance values of the two resistors determines the proportional relationship of the feedback voltage applied to terminal FB to the regulated output voltage. The ratio is chosen such that the voltage applied to terminal FB equals the output voltage of reference generator **120** when the regulated output voltage is at a desired value. Error amplifier **118** produces a voltage output which changes in proportion to any difference in voltage between the voltage at terminal FB and the reference voltage provided by reference generator **120**. If the voltage at terminal FB exceeds the reference voltage, the output voltage of error amplifier **118** drops proportionally, and if the voltage at terminal FB falls below the reference voltage, the output voltage of error amplifier **118** increases proportionally.

This voltage output is applied to input V of comparator **116**. The voltage output of amplifier **114**, which is proportional in magnitude to the current through switch **110**, is applied to input I of comparator **116**. As long as the voltage at input V remains higher than the voltage at input I, comparator **116** remains in an output state which causes flip-flop **106** to remain set and to thereby maintain the on condition of switch **110** which was initiated by oscillator **104**. On the other hand, if the voltage at input V becomes lower than the voltage at input I, comparator **116** changes its output state to cause flip-flop **106** to reset, thereby causing driver circuitry **108** to turn off switch **110**.

During normal feedback operation, therefore, switch **110** is turned off when switch current reaches a predetermined level set by the output of error amplifier **118**. If the regulated output voltage rises above a predetermined steady-state value set by the voltage divider network and reference voltage generator **120**, the duty cycle of switch **110** is shortened, because the voltage at input V drops as a result of the voltage differential at the inputs of error amplifier **118**. The voltage at input I reflecting the switch current crosses the lowered threshold value set by the voltage at input V earlier in the switch cycle than during steady-state operation. The shortened duty cycle causes the regulated output voltage to drop until it reaches its previous steadystate value. If the regulated voltage falls below the predetermined steady-state value, the duty cycle of switch **110** is lengthened because error amplifier **118** causes the voltage at input V to increase above its steady-state value such that the voltage at input I crosses the threshold value set by the voltage at input V later in the switch cycle than during steady-state operation. The lengthened duty cycle causes the regulated output voltage to increase until it reaches its previous steady-state value.

The voltage V_c at input V of comparator **116** varies between 0.9 and 2.0 volts during normal feedback operation. For a voltage at input V below 0.9V, the duty cycle of switch **110** is zero. Above 0.9V, and up to 2.0V, switch **110** closes (turns on) at the beginning of each cycle of oscillator **104** and opens (turns off) when the switch current (collector current through transistor **110**) reaches a trip level set by the voltage at input V of comparator **116**. The switch current trip level increases from zero, when input V is at a voltage approximately equal to 0.9V, to approximately 9.0A when the voltage at input V reaches its maximum value of 2.0V. Because this voltage appears at terminal V_c, the peak current through switch **110** can be limited by externally clamping the voltage of terminal V_c to a set value below the internal clamp value of 2.0V. External current limiting is but one of several functions of terminal V_C. Other possible functions include frequency compensation, soft starting, and total regulator shutdown into a micro-power sleep mode. The implementation of these functions will be further discussed below.

Terminal FB also serves multiple purposes. During normal feedback operation of integrated circuit **100**, terminal FB acts as the input point for feedback voltage from the voltage regulator output, as previously discussed. Terminal FB further acts as a logic pin for programming regulator **100** for feedback or fully-isolated flyback operation. Terminal FB is connected to the input of mode select circuitry **126**. Mode select circuitry **126** has an output connected to error amplifier **118** and to flyback error amplifier **128**. Flyback error amplifier **128** has two inputs, one connected to terminal V_{IN}, and the other connected to the anode of a variable zener diode **130**. The cathode of variable zener diode **130** is connected to terminal V_{SW}. The output of flyback error amplifier **128** is connected to the V input of comparator **116**.

By connecting terminal FB to ground through an external resistor, current having a value determined by the resistance value of the external resistor is drawn out of terminal FB. As a result of the flow of this current, mode select circuitry **126** disables error amplifier **118** to effectively remove it from the circuit, and enables flyback error amplifier **128** to effectively connect its output to the V input of comparator **116**, thereby placing regulator **100** into its isolated flyback mode of operation. A preferred embodiment of mode select circuitry **126** is discussed below.

In an isolated flyback regulator circuit, discussed in more detail below with reference to FIG. **3**, terminal V_{SW} is connected to one end of the primary winding of a transformer, the other end of which is connected to terminal V_{IN}. When switch **110** is closed, current is drawn through the inductive primary winding of the transformer and energy is stored. This energy is transferred to the secondary winding when switch **110** opens. Upon the opening of switch **110**, a voltage is developed across the primary winding of the transformer which is proportionally related to the output voltage of the circuit by the turns ratio of the transformer (ignoring the offset in output voltage introduced by the forward-voltage drop of steering diodes connected between the secondary winding and the output of the circuit).

Flyback error amplifier **128** regulates the voltage differential developed when switch **110** is opened between terminals V_{IN} and V_{SW}, and consequently that developed across the primary winding of the transformer, to a value equal to the breakdown voltage of variable zener diode **130**.

On each switch cycle, if the voltage at terminal V_{SW} rises to a value which exceeds the voltage at terminal V_{IN} by more than the breakdown voltage of variable zener diode **130**, a voltage differential is established at the inputs of flyback error amplifier **128** which causes the voltage output of flyback error amplifier **128** to decrease. This in turn lowers the switch current trip level voltage at input V of comparator **116**. Consequently, the duty cycle of switch **110** is shortened in response to an increase in the voltage at terminal V_{SW} above the reference voltage set by the voltage at terminal V_{IN} and the breakdown voltage of variable zener diode **130**. Conversely, if the voltage at terminal V_{SW} does not reach a value equal to the sum of the voltage at terminal V_{IN} and the breakdown voltage of variable zener diode **130**, the voltage at the output of flyback error amplifier **128** increases, which in turn raises the switch current trip level voltage at input V of comparator **116**. The duty cycle of switch **110** is thereby increased until the voltage at terminal V_{SW} during the open condition of switch **110** exceeds the voltage at V_{IN} by the breakdown voltage of variable zener diode **130**. During the period when switch **110** is closed, the voltage at the output of flyback error amplifier **128** is held substantially constant by a resistance/capacitance network externally connected to terminal V_C, as described more fully below. In this manner, integrated circuit **100**, when connected in an isolated flyback regulator circuit, maintains the peak voltage across the primary winding of a transformer connected between terminals V_{IN} and V_{SW} at the breakdown voltage of variable zener diode **138**, and thereby regulates the output voltage of the isolated flyback regulator circuit.

Variable zener diode **130** has a minimum breakdown voltage of approximately 16V. The actual value of the breakdown voltage is dependent on the value of the external resistor connecting terminal FB to the ground, as will be further discussed below. Terminal FB thus provides a third function in that it permits the regulated flyback voltage to be trimmed by varying the value of the resistor connected thereto.

FIGS. **2** and **3** show illustrative application circuits in which integrated circuit **100** is operated in its normal feedback mode (FIG. **2**) and in its isolated flyback mode (FIG. **3**).

Referring first to FIG. **2**, a typical implementation of a boost regulator using integrated circuit **100** in its normal feedback mode and connected to discrete external components is shown. The boost regulator provides a regulated output voltage V_{OUT} which is higher than the voltage applied at terminal V_{IN}.

Terminal V_{IN} of integrated circuit **100** is connected to one end of inductor **202**, the other end of which is connected to terminal V_{SW} and to the anode of diode **204**. The cathode of diode **204** is connected to one end of capacitor **206** and to one end of resistor **208**. The other end of resistor **208** is connected to one end of resistor **210** and to terminal FB. The other end of resistor **210** is connected to ground, to the other end of capacitor **206**, and to terminal GND.

The values of resistors **208** and **210** determine the regulated output voltage V_{OUT}. Error amplifier **118** operates in conjunction with comparator **116**, as previously described with respect to FIG. **1**, to cause the on/off duty cycle of switch **100** to adjust to that necessary to establish the voltage at terminal FB to equal the reference voltage out of reference generator **120**. Resistors **208** and **210** comprise a voltage divider circuit which sets output voltage V_{OUT} equal to 1.24 (R1+R2)/R2, where R1 is the value of resistor **208** and R2 is the value of resistor **210**. Resistor **210** is preferably given the value 1.24 k ohms to set the current through resistor **210** at 1 mA, but this value can vary from 300 ohms to 10 k ohms with negligible effect on regulator performance. The value of resistor **208** is then selected to set V_{OUT} to a desired value. To produce an output voltage V_{OUT} equal to 12V, for example, resistor **208** has a value of 10.7 k ohms. For an input voltage of 5V and a switching frequency of 40 k Hz, the value of inductor **202** is 150 μH. Capacitor **206** has a capacitance of approximately 1000 μF. to ensure an effective series resistance of less than 0.04 ohms, which in turn produces a low output voltage ripple. The foregoing values for the external components shown in FIG. **2** are provided for purposes of illustration, and not of limitation. Other values may be used if desired.

FIG. **2** further shows simplified circuits for implementing current limiting, soft starting, frequency compensation, and shutdown of integrated circuit **100** to a micro-power sleep mode. As discussed above, terminal V_C may be used to provide external current limiting. The peak current through switch **110** can be externally limited to any value less than 9A by clamping terminal V_C to a voltage less than 2V. A circuit **211** for externally limiting the peak current through switch **110**, by clamping the voltage at terminal V_C to a value less than 2.0 volts, is shown in FIG. **2**. Current limit circuit **211** is connected to terminal V_C of regulator **100** via diode **216**. Voltage V_x is provided by a separate regulated voltage or the unregulated input voltage. Resistor **212** is connected between voltage V_x and one end of variable resistor **214**, and is selected to drop approximately 2V across variable resistor **214**. The value of variable resistor **214** is preferably kept to 500 ohms or less to maintain a sharp knee in the current limit curve, although a greater value of resistance may be used if desired. The current limit can be fixed by replacing variable resistor **214** with a fixed resistor. Diode **216**, connected between variable resistor **214** and terminal V_C, prevents current from flowing into terminal V_C. Other external clamp circuits may be used to provide more precise current limiting.

Terminal V_C also may be used to provide a soft start operation. This ensures that the switch current is near zero when supply voltage is first applied to terminal V_{IN}, and that the output current rises gradually with time until it reaches its final value. An implementation of a soft start circuit is shown in FIG. **2**. Soft start circuit **217** includes diode **218**, resistor **220** and capacitor **222**. The anode of diode **218** is connected to terminal V_C and its cathode is connected to one end of resistor **220** and to one end of capacitor **222**. The other end of resistor **220** is connected to terminal V_{IN}, and the other end of capacitor **222** is connected to terminal GND. Soft start circuit **217** provides a time-dependent external current limit which prevents regulator **100** from drawing large input currents or from overshooting the desired output voltage. During startup the voltage at terminal V_C is clamped by capacitor **222** to less than 0.9 volts and rises gradually when voltage is first applied to terminal V_{IN} at a rate determined by the value of resistor **220** and capacitor **222**, thereby gradually increasing the peak current allowed through switch **110**. Resistor **220** also resets the soft start circuit by providing a current path to discharge capacitor **222** when the circuit is turned off. Other soft-start circuits may of course be used.

Terminal V_C further provides a point for introducing frequency compensation into the negative feedback loop of the switching voltage regulator circuit. Like any control system incorporating negative feedback, switching voltage regulators need a frequency compensation network to ensure that loop gain drops below unity before excess loop phase shift exceeds 180°. Such compensation is important in feedback switching voltage regulators, because the inductive elements in such circuits insert a 90° phase shift and output capacitors add an additional 90° phase shift in the feedback loop. In integrated circuit **100**, the use of the output of error amplifier **118** at terminal V_C to sense current and to set a switch current trip level significantly reduces inductance-induced phase shift, thus permitting a simple pole-zero compensation scheme to ensure both loop stability and good transient response.

Frequency compensation is preferably performed with an RC network connected between terminals V_C and GND, as shown by frequency compensation circuit **223** in FIG. **2**. One end of capacitor **224** is connected to terminal V_C, and the other end of capacitor **224** is connected to one end of resistor **226**. The other end of resistor **226** is connected to terminal GND. The values of capacitor **224** and resistor **226** are determined by applying a square-wave generator to the regulator output and monitoring the voltage at the output. Initially, the circuit should be overcompensated with a large capacitor **224**, preferably having a capacitance of at least 2 μF, and a small resistor **226**, preferably having a value of approximately 1 k ohm, to produce a waveform which is single-pole overdamped. The value of capacitor **224** is then reduced until the response becomes slightly underdamped, and the value of resistor **226** is increased to introduce a zero into the loop and to thereby improve damping. Preferably, the smallest value for capacitor **224** and the largest value for resistor **226** which result in no loop oscillations and rapid loop settling are chosen.

Terminal V_C additionally functions to provide a means for reducing the current drawn by integrated circuit **100** when it is desired to deactivate the regulator. As previously discussed with reference to FIG. **1**, this function is implemented in integrated circuit **100** by shutdown circuit **122** and reference voltage generator **124**. When the voltage at terminal V_C is externally clamped to a value less than the 0.15V reference voltage provided by generator **124**, shutdown circuit **122** provides a signal to regulator **102** and to generator **120** which deactivates both so that the only current drawn by regulator **100** is a current of 50 μA–100 μA necessary to bias shutdown circuit **122**. The voltage at terminal V_C can be externally pulled below 0.15V to activate shutdown circuit **122**, the details of which are discussed below, by connecting terminal V_C to a conventional relay or saturated transistor (not shown in FIG. **2**).

FIG. **3** shows a fully-isolated flyback regulator configuration employing integrated circuit **100** in its isolated flyback mode to provide output voltages of ±15V from an input voltage of 5V. Terminal V_{IN} is connected to a 5V voltage source **302**, and to one end of the primary winding of transformer **304**, the other end of which is connected to terminal V_{SW}. Transformer **304** has a turns ratio N equal to 0.875, where N is the ratio of secondary winding turns to primary winding turns for each output of transformer **304**. Terminal GND is connected to the negative side of voltage source **302**, to one end of frequency compensation capacitor **312**, and to one end of variable resistor **314**. The other end of frequency compensation capacitor **312** is connected to terminal V_c, and the other end of variable resistor **314** is connected to one end of resistor **316**, the other end of which is connected to terminal FB. Frequency compensation capacitor **312** has a value of 0.01 μF. Variable resistor **314** and resistor **316** have values of 5 K ohms and 400 ohms, respectively.

Integrated circuit **100** is converted from normal feedback mode to isolated flyback mode when the current drawn from terminal FB by resistors **314** and **316** exceeds approximately 10 μA at 25° C. Terminal FB has a voltage of approximately 0.4V when this current is drawn out of the terminal, although the actual voltage depends on the value of resistors **314** and **316** because terminal FB has an output impedance of approximately 200 ohms. For example, a current of 400 μA in resistors **314** and **316** will reduce the voltage at terminal FB from 0.4V to 0.3V.

Resistors **314** and **316** also serve to adjust the regulated output voltage V_{OUT}. Regulator **100** regulates the voltage (V_{PRI}) across the primary of transformer **304** during the off time of switch **110** to $V_{PRI}=16V+7000(V_{FB}/R)$, where V_{SB} is the voltage at terminal FB and R is the sum of the values of resistors **314** and **316**. The regulated output voltage V_{OUT} is determined by $V_{OUT}=N[16+7000\ (V_{FB}/R)]-V_f$, where V_f is the forward voltage of diodes **318** and **320** connected to the secondary winding of transformer **304**. Preferably, the term 7000 (V_{FB}/R) is set to approximately 2V to permit some adjustment range in V_{OUT}.

Connected between the cathode of diode **318** and a center tap of the secondary winding of transformer **304** is an output capacitor **322**, and connected between the anode of diode **320** and the center tap is an output capacitor **324**. The output capacitors **322** and **324** are responsible for filtering the output of the flyback regulator circuit because the flyback converter does not use the inductance of the transformer as a filter. Preferably, capacitors **322** and **324** have low effective series resistance to minimize output ripple. As this may require large capacitors, a conventional LC filter (not shown) also may be used at the output to provide low output ripple.

FIGS. **2** and **3** illustrate two applications of integrated circuit **100**. They are provided only for illustration, and are not limitations of the present invention. Numerous other switching voltage regulator topologies may be implemented using integrated circuit **100**. Further details concerning the application of integrated circuit **100** and such other topologies may be found in "LT1070 Design Manual, Application Note 19," dated June 1986, published by Linear Technology Corporation.

FIGS. **4**–**8** show preferred circuit embodiments for implementing components of integrated circuit **100** of FIG. **1**. Referring first to FIG. **4**, schematic diagrams are shown for shutdown circuit **122**, regulator **102** and reference voltage generators **120** and **124**. The output of error amplifier **118** is connected to terminal V_C and to the emitter of transistor **402** of shutdown circuit **122**. Connected to the base of transistor **402** is a conventional current source **404** and the base and collector of a transistor diode connected transistor **406**. The emitter of transistor diode **406** is connected to ground. Transistor **406** is a high V_{BE} transistor having a forward voltage which is approximately 0.15 V greater than the forward base-emitter voltage of transistor **402**. The collector of transistor **402** is connected to the base of transistor **408**, to the non-inverting input of conventional differential error amplifier **410** of regulator **102** and to the emitter of transistor **412**. The collector of transistor **412** is connected to ground and its base is connected to the output of reference voltage generator **120**. Error amplifier **410**, reference generator **120**, and resistors **416** and **418** regulate the voltage drop across transistor **414** to provide a regulated output voltage of approximately 2.3V. Regulator **102** thus is configured as a conventional linear regulator having a reference voltage provided by reference voltage generator **120** and employing a PNP pass transistor to provide low drop-out, although regulator **102** may be any other conventional linear voltage regulator.

The emitter of transistor **408** is connected to conventional current source **420** and to the base of transistor **422** in reference voltage, generator **120**. The emitter of transistor **422** is connected to one end of resistor **424**, the other end of which is connected to the reference voltage output **426** of conventional Brokaw-cell band-gap voltage reference circuit **428**, and to the collector of transistor **430**. The base of transistor **430** is connected to a point **432** within band gap circuit **428** which has a positive temperature coefficient of approximately 2mV/° C., and to one end of resistor **434**, the other end of which is connected to ground.

Band-gap reference circuit **428** provides a voltage of approximately 1.24V at reference output **426** having negative a temperature coefficient over at least a portion of the range of operating temperatures of integrated circuit **100** which causes the voltage at reference output **426** to decrease with increasing temperature. To increase the temperature stability of the output voltage of reference voltage generator **120**, a voltage having a positive temperature coefficient is applied to the base of transistor **430**. At a predetermined operating temperature, determined by the values of resistors **424** and **434**, this voltage becomes sufficiently high to turn on transistor **430** and to thereby cause current to flow through resistors **424** and **434**. The current flowing through resistor **424** causes a voltage drop across resistor **424** which increases the voltage at the output of reference voltage generator **120** over the output voltage of band-gap reference circuit **428**. The voltage drop across resistor **424** has a positive temperature coefficient set by the values of resistors **424** and **434** which is used to offset the negative temperature coefficient of the output voltage of band-gap reference circuit **428**. Resistors **424** and **434** have values of 200 ohms and 7.9 kilohms, respectively.

Current source **404** provides current to forward bias transistor diode **406**. Because the forward voltage drop across transistor diode **406** is approximately 0.15V greater than the forward base-emitter voltage drop of transistor **402**, transistor **402** remains in an off condition during normal operation of regulator **100** as the voltage at terminal V_C varies between 0.9V and 2.0V. However, if the voltage at terminal V_C is caused to drop below a value equal to the difference in the forward voltage of transistor diode **406** and the forward base-emitter voltage of transistor **402**, which means that terminal V_C is pulled down to a voltage level below 0.15V, the base-emitter junction of transistor **402** becomes forward biased and transistor **402** is turned on. The current drawn by transistor **402** pulls current out of the base of transistor **408**, thereby causing the emitter of transistor **408** to draw current which turns off transistor **422**. This disables reference voltage generator **120**. Likewise, when transistor **402** conducts, the non-inverting input of error amplifier **410** is pulled low, thereby disabling regulator **102**. In the micropower sleep shutdown mode, no current flows in integrated circuit **100** with the exception of the current necessary to bias transistors **402**, **406** and **408**. Typically, this current has a value in the range of 40 μA–100 μA.

FIG. **5** shows a preferred implementation of mode select circuitry **126** and error amplifier **118** of FIG. **1**. Reference voltage generator **124** is connected to the base of transistor **502** of error amplifier **118**, and provides to the base a voltage of approximately 1.24V. The emitter of transistor **502** is connected to a conventional current source **504**, and to the emitter of transistor **506**, the base of which is connected to terminal FB.

The bases of transistors **502** and **506** act as the inputs of error amplifier **118**. Current source **504** causes a current of approximately 50 μA to flow from the junction of the emitters of transistors **502** and **506**. The collector of transistor **502** is connected at a node to one end of switch **528**, and to the base and collector **505** of transistor **508**. That node is labelled in FIG. **5** "enable/disable". The other end of switch **528** is connected to the output of regulator **102**, as are the emitters of transistors **508** and **510**. The collector of transistor **506** is connected to the base and collector **509** of transistor **510**, collector **511** of which is connected to the base and collector of transistor **512** and to one end of resistor **514**. The other end of resistor **514** is connected to the base and collector of transistor **516** and to the base of transistor **518**. Collector **507** of transistor **508** and the collector of transistor **518** are connected to the emitter of transistor **512**, the collector of transistor **520**, one end of switch **530**, and terminal V_C. The areas of collectors **507** and **511** are respectively four times greater than the areas of collectors **505** and **509**.

Transistors **502** and **506** form a differential input stage. The collector currents are inverted and multiplied by a factor of four by transistors **508** and **510**, the current gains of which are set by the collector area ratio. The collector current of transistor **508** is further inverted by transistors **516** and **518** to generate a current fed balanced output at node **534** which can swing from a maximum voltage of approximately 2.3V set by regulator **102**, when the voltage at terminal FB is pulled low, to a clamp level of approximately 0.4V set by resistor **514** and transistor **512**, when the voltage at terminal FB rises above the voltage applied to the base of transistor **502** by generator **124**. Resistor **514** has a value of approximately 3 k ohms although other values may be used to set different clamp levels.

The other end of switch **530** is connected to conventional current source **522**, which provides a current of approximately 30 μA. The emitter of transistor **520** is connected to one end of resistor **524**, the other end of which is connected to one end of switch **532**. The other end of switch **532** is connected to the emitters of transistor diode **526** and transistors **516** and **518**, and to current source **504**. The collector and base of transistor diode **526** are connected to the output of flyback error amplifier **128**.

During the normal feedback mode of operation of integrated circuit **100**, switches **528**, **530** and **532** are open and a feedback voltage is applied to terminal FB. Error amplifier **118** is enabled while switch **528** is open, and an output voltage therefrom is applied to the V input of comparator **116**. At the same time, the output voltage of flyback error amplifier **128** is applied to the base of transistor **520**. However, because switches **530** and **532** are open, the output of flyback error amplifier **128** is isolated from terminal V_C during feedback operation of integrated circuit **100** and effectively disabled.

In the isolated flyback mode of integrated circuit **100**, terminal FB is pulled low by an external resistor connected to ground and switch **528** is closed, thus turning off transistor **507** and disabling error amplifier **118**. Switches **530** and **532** are closed only after a delay of 1.5 microseconds, as discussed below, following the closing of switch **110**. This prevents the flyback error amplifier **128** from attempting to regulate the voltage at terminal V_{SW} during any overvoltage spikes caused by the leakage inductance of the transformer in the flyback regulator circuit. When switches **530** and **532** are closed, the output of flyback amplifier **128** drives transistor **520**, which in turn controls the voltage at terminal V_C. The current through switch **530** is fixed at 30 μA by current source **522**. The current through switch **532** can rise to a maximum of approximately 70 μA, allowing terminal V_C to source current up to 30 μA, or to sink current up to 40 μA, in the flyback mode. The gm of flyback error amplifier **128** is typically 300 micromhos. Current source **504** sets the gm of error amplifier **118** at 4400 micromhos.

Switches **528**, **530** and **532**, and mode select circuitry **126**, are shown in FIG. **6** in greater detail. The emitter of transistor **602** is connected to one end of resistor **603**, the other end of which is connected to the inverting input of error amplifier **118**. The other end of resistor **607** is connected to terminal FB. Resistor **603** has a value of 5 kohms, resistor **605** a value of 1.3 kohms, and resistor **607** a value of 30 ohms. The non-inverting input of error amplifier **118** is connected to the output of reference voltage generator **120** and is provided thereby with a reference voltage of approximately 1.24V. The base of transistor **602** is connected to one end of resistor **605**, the other end of which is connected between resistors **604** and **606**. The other end of resistor **604** is connected to the output of regulator **102** (hereinafter referred to as the 2.3V line). The other end of resistor **606** is connected through diode **608** to terminal GND. The collector of transistor **602** is connected to the base of transistor **610** and to one end of resistor **612**, the other end of which is connected to the 2.3V line and to the emitter of transistor **610**. Collector **609** of transistor **610** is connected to the collector of transistor **502**, shown in FIG. **5**, and collector **611** of transistor **610** is connected to the base of transistor **614**.

The emitter of transistor **614** is connected to terminal GND, and its collector is connected to one end of resistor **616**, the other end of which is connected to one emitter of transistor **520**, and to the emitter of transistor **618**. Resistor **616** has a value of approximately 24 kilohms. The base of transistor **618** is connected to current source **638**, to the collector of transistor **620** and to one end of capacitor **622**, the other end of which is connected to the emitter of transistor **620**. Current source **638** provides a current of approximately 20 μA. The base of transistor **620** is connected to driver circuitry **108** and is turned on and off by driver circuitry **108** in phase with the turning on and off of power switch transistor **110**. The collector of transistor **618** is connected to current source **636**, to the base and collector of transistor diode **624**, the emitter of which is connected to terminal GND through resistor **626**, and to the base of transistor **628**. Current source **636** provides a current of approximately 100 μA. The emitter of transistor **628** is connected to an emitter of transistor **520**, and to terminal GND through resistor **630**, which has a value of 1.0 kilohms. The collector of transistor **628** is connected to the emitter of transistor **632**, and to the 2.3V line through resistor **634**, which has a value of approximately 1.3 kilohms. The collector of transistor **632** is connected to the collector of transistor **520**, to the V input of comparator **115** and to terminal V_C. The base of transistor **632** is connected to the base and collector of transistor diode **636**, the emitter of which is connected to the 2.3V line. Transistors **632** and **636**, and resistor **634**, correspond to current source **522** of FIG. **5**, and provide a 30 μA current to the collector of transistor **520**.

The base of transistor **520** is connected to the output of flyback error amplifier **128** and to the base and collector of transistor diode **526**, the emitter of which is connected to terminal GND as shown in FIG. **5**.

Resistors **604** and **606**, which have values of approximately 5.8 kilohms and 500 ohms, respectively, and diode **608** bias the base of transistor **602** at a voltage of approximately 1V. When an external resistor is connected between terminal FB and ground, such that current is drawn out of terminal FB, the voltage at terminal FB is clamped to approximately 0.4V by transistor **602**. The current drawn through transistor **602** causes transistor **610** to turn on, thereby providing current to the collector of transistor **502** (shown in FIG. **5**) and the base of transistor **614**. In this manner, transistor **610** acts as switch **528** in FIG. **5**, disabling error amplifier **118** as before described when an external resistor is connected between terminal FB and ground.

Driver circuitry **108** provides a drive current to the base of transistor **620** when switch **110** is closed which forward biases transistor **620** into saturation. The current drawn by transistor **620** holds transistor **618** in an off condition, which in turn allows transistor **628** to conduct. The on condition of transistor **628** pulls the emitter of transistor **632** low, turning off transistor **632**. Transistor **628** acts as switch **530**, disabling current source **522** while switch **110** is closed. The on condition of transistor **628** also holds the emitter of transistor **520** at a sufficiently high voltage to maintain transistor **520** in an off condition, thereby isolating the output of flyback amplifier **128** from input V of comparator **116**. In this manner, transistor **628** also acts as switch **532**, preventing flyback error amplifier **128** from regulating the voltage at terminal V_{SW} while switch **110** is closed.

Upon the opening of switch **110**, driver circuitry **108** causes transistor **620** to turn off. Capacitor **622**, which has a capacitance of 40 pF, is charged by the current from current source **638**. After approximately 1.5 microseconds, the voltage across capacitor **622** causes transistor **618** to conduct, which in turn forces transistor **628** into an off condition. This permits transistors **520** and **632** to turn on and enables flyback error amplifier **128** to regulate the voltage at terminal V_{SW}. The 1.5 microsecond delay between the closing of switch **110** and the enabling of flyback amplifier **128** prevents overvoltage spikes from degrading the regulation of the flyback converter. While regulator **100** is in its flyback mode, and during the periods when flyback error amplifier **128** is disabled, the voltage at terminal V_C is held to its previous value by the frequency compensation network connected to terminal V_C.

FIG. **7** shows a preferred embodiment for implementing comparator **116** of FIG. **1**. Transistor **702** has a first collector **705** connected to the reset input of flip-flop **106** and to current source **704**, and remote collector **706** which is connected to the base of transistor **702**. Current source **704** provides a current of approximately 50 μA. The emitter of transistor **702** is connected to the output of amplifier **114** and to current source **708**, which provides a current of approximately 330 μA. The base and remote collector **706** of transistor **702** are connected to the emitter of transistor **710**, and to current source **712**, which provides a current of approximately 50 μA. The collector of transistor **710** is connected to the output of regulator **102**, which provides a voltage of approximately 2.3V. The base of transistor **710** is connected to terminal V_C through resistor **714**.

The voltage at the base of transistor **702** is approximately equal to the voltage at terminal V_C minus the base-emitter voltage drop of transistor **710**. When the voltage at terminal V_C is higher than the voltage at the output of amplifier **114**, the base-emitter junction of transistor **702** is reverse-biased, and the reset input of flip-flop **106** is held low by current source **704**, maintaining flip-flop **106** in the set condition initiated by oscillator **104**. When the voltage at terminal V_C drops below the voltage at the output of amplifier **114**, indicating that the current passing through switch **110** has reached the switch current trip level, transistor **702** turns on and activates the reset input of flip-flop **106**, thereby causing switch **110** to open.

As transistor **702** saturates, collector **706** begins to conduct current. This prevents current source **712** from pulling the base of transistor **702** to ground, and thereby prevents the deactivation of the reset input of flip-flop **106** which might otherwise result from the saturation of transistor **702**.

FIG. **8** shows a preferred embodiment of flyback error amplifier **128** and variable zener diode **130**. Referring first to variable zener diode **130**, terminal V_{SW} is connected to the base and collector of transistor diode **802** of zener diode **130**, and to the collector of power switch transistor **110**. The base of power switch transistor **110** is connected to the output of driver circuitry **108**, and its emitter is connected to one end of sense resistor **112**, the other end of which is connected to terminal GND as before described. The emitter of transistor diode **802** is connected to the cathode of zener diode **806**, the anode of which is connected to the cathode of zener diode **808**. Zener diodes **806** and **808** each have a breakdown voltage of approximately 7.0V, although zener diodes having other values of breakdown voltage may be used, as will be appreciated. The anode of zener diode **808** is connected to the emitter of transistor diode **810**, the collector and base of which are connected to one end of resistor **812** and to the collector of transistor **814**. Resistor **812** has a value of approximately 7 kilohms.

Resistor **812** is also connected to the collector of transistor **816**, the base of which is connected to the output of regulator **102**, and the emitter of which is connected to one end of resistor **818**. The other end of resistor **818**, which preferably has a value of approximately 200 ohms, is connected to the collector of transistor **820**, the base of which is connected to one end of resistor **605** and to the base of transistor **602** of mode select circuitry **126**. The emitter of transistor **820** is connected to one end of resistor **603** and to one end of resistor **607**. The connection of transistor **602**, resistors **603**, **604**, **605**, **606** and **607**, and diode **608** is the same as discussed for the mode select circuit of FIG. **6**.

The emitter of transistor **814** is connected to the emitter of transistor **820** of flyback amplifier **128**. Collector **822** of transistor **820** of flyback amplifier **128** is connected to the base of transistor **520**, shown in FIG. **5**. Collector **824**, which has an area approximately four times less than that of collector **822**, and the base of transistor **820** are connected to the base and collector of transistor diode **826**, and to current source **828**, which provides a current of 75 μA to bias transistor **820**. The emitter of transistor diode **826** is connected to terminal V_{IN}.

As discussed in connection with FIG. **6**, integrated circuit **100** is placed into its flyback mode by pulling a threshold current ranging from 3 μA to 30 μA out of terminal FB. This current is drawn through the emitters of transistors **602** and **820**, which conduct substantially equal amounts of current up to a value of approximately 1 μA, at which point resistor **603** begins to reduce the percentage of current conducted by transistor **602**. Resistor **603** limits the maximum current conducted by transistor **602** to approximately 30 μA, forcing any additional current drawn out of terminal FB to be conducted by transistor **820**. The current conducted by transistor **820** flows through resistor **812**, creating a proportional voltage drop from the collector to the base of transistor **814**. This voltage drop increases the effective breakdown voltage of variable zener diode **130**, which is comprised by transistor diodes **802** and **810**, zener diodes **806** and **808**, and transistor **814**. The effective breakdown voltage is determined by summing the voltage drops across the base-emitter junctions of transistor **814** and transistor diodes **802** and **810**, the breakdown voltages of zener diodes **806** and **808**, and the voltage across resistor **812**, and is approximately equal to 16V+7000 (V_{FB}/R), where 7000 is the value of resistor **812**, V_{SB} is the voltage at terminal FB, R is the value of the external resistor tying terminal FB to ground, and the term 7000 (V_{FB}/R) represents the voltage across resistor **812**. The voltage at terminal FB is approximately 0.4V when a current of 30 μA is pulled out of terminal FB. Due to the output impedance of terminal FB, which is approximately 200 ohms, this voltage drops to approximately 0.3V when a current of 500 μA is pulled out of terminal FB. Neglecting the variation in voltage V_{SB} due to output impedance, it can be seen that the effective breakdown voltage of variable zener diode **130** is dependent on the value of the resistor connected to terminal FB. For example, a 1.0 kohm resistor tied between terminal FB and ground results in an effective breakdown voltage of approximately 18.5V. Thus, the flyback reference voltage set by the effective breakdown voltage of variable zener diode **130** can be trimmed by varying the value R of the external resistor tying terminal FB to ground.

Current source **828**, transistor diode **826** and transistor **820** comprise flyback error amplifier **128**. When the voltage at terminal V_{SW} exceeds the voltage at terminal V_{IN} by more than the effective breakdown voltage of variable zener diode **130**, zener diodes **806** and **808** conduct, causing transistor **820** to turn on. Transistor **820** provides current to the base of transistor **520** causing it to turn on and to pull down the voltage at the V input of comparator **116**, thereby lowering the switch current trip level and shortening the duty cycle of switch **110**. When the voltage at terminal V_{SW} does not exceed the voltage at V_{IN} by at least the effective breakdown voltage of variable zener diode **130**, transistor **820** does not conduct, and transistor **520** is turned off. At the same time, current source **522**, shown in FIG. **5**, provides a current of approximately 30 μA to the V input of comparator **116** which causes the voltage at the V input to increase, thereby raising the switch current trip level and consequently lengthening the duty cycle of switch **110**.

While preferred embodiments of the invention have been set forth for purposes of the disclosure, modification of the disclosed embodiments may occur to those of skill in the art. For example, while the multi-function terminal feature of the present invention has been disclosed in the context of an integrated circuit for use in implementing a current-mode switching voltage regulator, it will of course be understood by those of skill in the art that the invention may be employed to implement a 5-terminal integrated circuit for use with voltage-mode switching voltage regulator topologies having a micro-power sleep mode capability.

Thus, a switching voltage regulator circuit including control circuitry, driver circuitry and a power switching device, capable of being implemented as an integrated circuit requiring only five terminals having multiple functions, including micro-power mode shutdown circuitry, and operable in a normal feedback mode as well as in an isolated flyback mode, has been disclosed. The invention can readily be packaged in a 5-pin power transistor integrated circuit package. One skilled in the art will appreciate that the present invention can be practiced by other than the described embodiments, which are presented for purposes of illustration and not of limitation, and the present invention is limited only by the claims which follow.

What is claimed is:

1. An integrated circuit for use in a switching voltage regulator circuit, the switching voltage regulator circuit providing a regulated voltage output at an output terminal, the integrated circuit including internal drive circuitry, a power switching transistor and control circuitry for varying the switching duty cycle of the switching transistor, the integrated circuit having at most five terminals including an input terminal, an output terminal a ground terminal and first and second function terminals for connection to discrete external components to implement the switching voltage regulator circuit, the integrated circuit comprising:

first means connected to one of the function terminals for accepting a feedback signal from the output of the switching voltage regulator circuit and for enabling the integrated circuit to operate in a first mode to regulate the output of the switching voltage regulator by varying the duty cycle of the switching transistor as a function of the magnitude of the feedback signal;

second means connected to the input and output terminals for enabling the integrated circuit to operate in an isolated flyback mode to regulate the output of the switching voltage regulator circuit as a function of a feedback voltage developed across a primary winding of a discrete external transformer; and

mode select means connected to one of the function terminals and to said first and second means to disable the first means and to enable the second means in response to a disable signal applied to that function terminal by the discrete components.

2. An integrated circuit for use in a switching voltage regulator circuit providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for varying the on and off switching duty cycle of the switching transistor, and further having an input terminal, an output terminal, a ground terminal and first and second function terminals for connection to external components, the integrated circuit comprising:

first means connected to the first function terminal and to the control circuitry for accepting a first feedback signal indicative of the regulated output voltage, and for enabling the integrated circuit to operate in a normal feedback mode to regulate the regulated output voltage by varying the duty cycle of the switching transistor as a function of the magnitude of the first feedback signal;

second means connected to the input and output terminals and to the control circuitry for accepting a second feedback signal between the input and output terminals indicative of a voltage developed across a winding of an external transformer, and for enabling the integrated circuit to operate in a fully isolated flyback mode to regulate the regulated output voltage as a function of the magnitude of the second feedback signal; and

third means connected to one of the function terminals and to said first and second means to disable one of the first and second means and to enable the other in response to a control signal applied to that function terminal by external components.

3. The integrated circuit of claim **2**, wherein said first means includes:

means for producing a first reference signal; and

means for detecting a difference between the first feedback signal and the first reference signal, and for generating an error signal indicative of that difference;

and wherein the control circuitry includes:

means for comparing the error signal to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the error signal.

4. The integrated circuit of claim **2**, wherein said second means includes:

means responsive to the second feedback signal for generating an error signal indicative of a difference between the second feedback signal and a predetermined threshold signal level;

and wherein the control circuitry includes:

means for comparing the error signal to a signal indicative of the magnitude of current conducted by the switching transistor, and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the error signal.

5. The integrated circuit of claim **2**, wherein said first means includes:

means for producing a first reference signal; and

means for detecting a difference between the first feedback signal and the first reference signal, and for generating a first error signal indicative of that difference;

wherein said second means includes:

means responsive to the second feedback signal for generating a second error signal indicative of a difference between the second feedback signal and a predetermined threshold signal level;

and wherein the control circuitry includes:

means for receiving the first and second error signals, for comparing at any given time one of the first and second error signals to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the compared one of the first and second error signals.

6. The integrated circuit of claim **3**, wherein said means for generating an error signal includes a differential amplifier having a first input for receiving the feedback signal and a second input for receiving the first reference signal.

7. The integrated circuit of claim **4**, wherein said means for generating the second feedback error signal includes:

an amplifier having a first input connected to one of the input and output terminals; and

means connected to a second input of said amplifier and to the other of the input and output terminals for establishing a threshold voltage, whereby a voltage differential is established across the inputs of the amplifier when a voltage difference between the input and output terminals exceeds the threshold voltage.

8. The integrated circuit of claim **7**, wherein said means for establishing a threshold voltage includes a zener diode.

9. The integrated circuit of claim **8**, wherein said zener diode has a zener breakdown voltage, and wherein said means for establishing a threshold voltage further includes:

means for establishing a trimming voltage in series with the zener breakdown voltage such that at least a part of the threshold voltage is comprised of the sum of the trimming and zener breakdown voltages; and

means connected to said means for establishing a trimming voltage, and to one of the function terminals, for varying the trimming voltage in response to a signal at that function terminal, thereby varying the threshold voltage.

10. The integrated circuit of claim **9**, wherein said means for varying the trimming voltage is connected to the first function terminal.

11. The integrated circuit of claim **10**, wherein:

said means for establishing a trimming voltage comprises a resistor; and wherein

said means for varying the trimming voltage varies a current conducted by said trimming voltage resistor as a function of a current conducted by the first function terminal.

12. The integrated circuit of claim **11**, wherein the current conducted by the first function terminal is established at least in part by external components connected to the first function terminal.

13. The integrated circuit of claim **12**, wherein the external components connected to the first function terminal includes a resistor connected to ground.

14. The integrated circuit of claim **2**, wherein said third means is connected to the first function terminal.

15. The integrated circuit of claim **14**, wherein the control signal is a current, and wherein said third means includes:

means for sensing the current conducted by the first function terminal; and

means responsive to said sensing means for disabling said first means and enabling said second means when the current sensed by said sensing means exceeds a predetermined threshold current.

16. The integrated circuit of claim **2**, wherein said third means is connected to the first function terminal, and wherein the integrated circuit further comprises:

fourth means connected to the control circuitry and to the second function terminal for performing at least two of:

(a) frequency compensating the integrated circuit,

(b) limiting the peak current conducted by the switching transistor,

(c) variably limiting the current conducted by the switching transistor as a function of time, and

(d) shutting down the integrated circuit, whereby the current drawn by the integrated circuit is reduced.

17. The integrated circuit of claim **16**, wherein said fourth means includes:

means for generating a signal indicative of the magnitude of current conducted by the switching transistor;

means connected to at least one terminal of the integrated circuit for sensing a feedback signal from the discrete components indicative of the magnitude of at least one of the regulated output voltage and the voltage developed across the winding of the external transformer, and for generating an error signal indicative of the difference between the feedback signal and a reference signal;

means for comparing the error signal to the current magnitude signal, and for turning off the switching transistor when the current magnitude signal exceeds the error signal; and

means for applying the error signal to the second function terminal, whereby the magnitude of the error signal may be controlled by a network of one or more external components connected to the second function terminal.

18. The integrated circuit of claim **17**, wherein the network of external components connected to the second function terminal includes a frequency compensating capacitor.

19. The integrated circuit of claim **17**, wherein the network of external components connected to the second function terminal includes a frequency compensation capacitor in series with a resistor.

20. The integrated circuit of claim **17**, wherein the network of external components connected to the second function terminal prevents the error signal at the second function terminal from exceeding a predetermined maximum level, thereby limiting to a maximum peak value the magnitude of current conducted by the switching transistor.

21. The integrated circuit of claim **20**, wherein the network of external components establishes a predetermined maximum voltage at the second function terminal.

22. The integrated circuit of claim **17**, wherein the network of external components connected to the second function terminal variably controls the voltage at the second function terminal as a function of time, thereby variably limiting as a function of time the current conducted by the switching transistor.

23. The integrated circuit of claim **22**, wherein the network of external components for variably controlling the voltage at the second function terminal includes:

a resistor connected between a first node and a second node;

a capacitor connected between the second node and the ground terminal; and

means connected between the second node and the second function terminal for applying at least a portion of a voltage at the second node to the second function terminal, such that the voltage at the second function terminal upon application of a voltage at the first node gradually increases with time to gradually increase the current conducted by the switching transistor.

24. The integrated circuit of claim **17**, the integrated circuit further having voltage regulator circuitry for providing a regulated voltage to at least portions of the internal drive circuitry, and wherein said fourth means further includes:

means for producing second reference signal;

means for comparing the second reference signal to a shutdown control signal applied to the second function terminal by the external components, and for generating a shutdown signal when the second reference signal and the shutdown control signal differ by a predetermined amount; and

means responsive to the shutdown signal for disabling at least the voltage regulator circuitry, thereby shutting down and reducing the current drawn by the integrated circuit.

25. The integrated circuit of claim **24**, wherein the shutdown control signal is a voltage, and wherein:

said means for producing a second reference signal includes a diode having a first forward voltage drop; and wherein

said means for comparing the second reference signal to the shutdown control signal includes a transistor having a base-emitter circuit connected between said diode and the second function terminal, the base-emitter circuit having a second forward voltage drop which differs from the first forward voltage drop, and said transistor being adapted to disable the voltage regulator circuitry when the shutdown control signal voltage at the second function terminal is less than the difference between the first and second forward voltage drops.

26. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having a power switching transistor, circuitry for driving the switching transistor and control circuitry for varying the on and off switching duty cycle of the switching transistor, and further having for connection to external components an input terminal, an output terminal, a ground terminal and a function terminal, the integrated circuit comprising:

first means connected to the function terminal and to the control circuitry for accepting a first feedback signal indicative of the regulated output voltage, and for enabling the integrated circuit to operate in a normal feedback mode to regulate the regulated output voltage by varying the duty cycle of the switching transistor as a function of the magnitude of the first feedback signal;

second means connected to at least one of the terminals and to the control circuitry for accepting a second feedback signal indicative of a voltage developed across a winding of an external transformer, and for enabling the integrated circuit to operate in a fully isolated flyback mode to regulate the output voltage as a function of the magnitude of the second feedback signal; and

mode select means connected to the function terminal and to said first and second means to disable one of the first and second means and to enable the other in response to a mode select control signal applied to the function terminal by external components.

27. The integrated circuit of claim **26**, wherein said first means includes:

means for producing a first reference signal; and

means for detecting a difference between the first feedback signal and the first reference signal, and for generating an error signal indicative of that difference;

and wherein the control circuitry includes:

means for comparing the error signal to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the error signal.

28. The integrated circuit of claim **26**, wherein said second means includes:

means responsive to the second feedback signal for generating an error signal indicative of a difference between the second feedback signal and a predetermined threshold signal level;

and wherein the control circuitry includes:

means for comparing the error signal to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the error signal.

29. The integrated circuit of claim **26**, wherein said first means includes:

means for producing a first reference signal; and

means for detecting a difference between the first feedback signal and the first reference signal, and for generating a first error signal indicative of that difference;

wherein said second means includes:

means responsive to the second feedback signal for generating a second error signal indicative of a difference between the second feedback signal and a predetermined threshold signal level;

and wherein the control circuitry includes:

means for receiving the first and second error signals, and for comparing at any given time one of the first and second error signals to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the compared one of the first and second error signals.

30. The integrated circuit of claim **27**, wherein said means for generating an error signal includes a differential amplifier having a first input for receiving the first feedback signal and a second input for receiving the first reference signal.

31. The circuit of claim **28**, wherein said means for generating the second feedback error signal includes:

an amplifier having a first input connected to one of the input and output terminals; and

means connected to a second input of said amplifier and to the other of the input and output terminals for establishing a threshold voltage, whereby a voltage differential is established across the inputs of the amplifier when a voltage difference between the input and output terminals exceeds the threshold voltage.

32. The circuit of claim **31**, wherein said means for establishing a threshold voltage includes a zener diode.

33. The circuit of claim **32**, wherein said zener diode has a zener breakdown voltage, and wherein said means of establishing a threshold voltage further includes:

means for establishing a trimming voltage in series with the zener breakdown voltage such that at least a part of the threshold voltage is comprised of the sum of the trimming and zener breakdown voltages; and

means connected to said means for establishing a trimming voltage, and to the function terminal, for varying the trimming voltage in response to a signal at the function terminal, thereby varying the threshold voltage.

34. The circuit of claim **33** wherein:

said means for establishing a trimming voltage comprises a resistor; and wherein

said means for varying the trimming voltage varies a current conducted by said trimming voltage resistor as a function of a current conducted by the function terminal.

35. The circuit of claim **34**, wherein the current conducted by the function terminal is established at least in part by external components connected to the function terminal.

36. The circuit of claim **35**, wherein the external components connected to the function terminal include a resistor connected to ground.

37. The circuit of claim **26**, wherein said mode select means is connected to the function terminal.

38. The circuit of claim **37**, wherein said mode select means includes:

means for sensing current conducted by the function terminal; and

means responsive to said sensing means for disabling said first means and enabling said second means when the current sensed by said sensing means exceeds a predetermined threshold current.

39. The circuit of claim **38**, wherein the function terminal is connected to external components adapted to conduct a current which exceeds the threshold current.

40. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having a power switching transistor, circuitry for driving the switching transistor and control circuitry for varying the on and off switching duty cycle of the switching transistor, and further having at most five terminals for connection to external components consisting of an input terminal, an output terminal, a ground terminal and first and second function terminal, the integrated circuit comprising:

first means connected to the first function terminal and to the control circuitry for accepting a first feedback signal indicative of the regulated output voltage, and for enabling the integrated circuit to operate in a normal feedback mode to regulate the regulated output voltage by varying the duty cycle of the switching transistor as a function of the magnitude of the first feedback signal;

second means connected to at least one of the input and output terminals and to the control circuitry for accepting a second feedback signal indicative of a voltage developed across a winding of an external transformer, and for enabling the integrated circuit to operate in a fully isolated flyback mode to regulate the regulated output voltage as a function of the magnitude of the second feedback signal;

mode select means connected to the first function terminal and to said first and second means to disable one of the first and second means and to enable the other in response to a mode select control signal applied to the first function terminal by external components; and

means connected to the control circuitry and to the second function terminal for enabling the switching voltage regulator circuit in response to signals applied to the second function terminal by a network of external components to be frequency compensated.

41. The integrated circuit of claim **40**, wherein said first means includes:

means for producing a first reference signal; and

means for detecting a difference between the first feedback signal and the first reference signal, and for generating an error signal indicative of that difference;

and wherein the control circuitry includes:

means for comparing the error signal to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the error signal.

42. The integrated circuit of claim **40**, wherein said second means includes:

means responsive to the second feedback signal for generating an error signal indicative of a difference between the second feedback signal and a predetermined threshold signal level;

and wherein the control circuitry includes:

means for comparing the error signal to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the error signal.

43. The integrated circuit of claim **40**, wherein said first means includes:

means for producing a first reference signal; and

means for detecting a difference between the first feedback signal and the first reference signal, and for generating a first error signal indicative of that difference;

wherein said second means includes:

means responsive to the second feedback signal for generating a second error signal indicative of a difference between the second feedback signal and a predetermined threshold signal level;

and wherein the control circuitry includes:

means for receiving the first and second error signals, for comparing at any given time one of the first and second error signals to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the compared one of the first and second error signals.

44. The integrated circuit of claim **40**, wherein said means for generating an error signal includes a differential amplifier having a first input for receiving the first feedback signal and a second input for receiving the first reference signal.

45. The circuit of claim **42**, wherein said means for generating the second feedback error signal includes:

an amplifier having a first input connected to one of the input and output terminals; and

means connected to a second input of said amplifier and to the other of the input and output terminals for establishing a threshold voltage, whereby a voltage differential is established across the inputs of the amplifier when a voltage difference between the input and output terminals exceeds the threshold voltage.

46. The circuit of claim **45**, wherein said means for establishing a threshold voltage includes a zener diode.

47. The circuit of claim **46**, wherein said zener diode has a zener breakdown voltage, and wherein said means for establishing a threshold voltage further includes:

means for establishing a trimming voltage in series with the zener breakdown voltage such that at least a part of the threshold voltage is comprised of the sum of the trimming and zener breakdown voltages; and

means connected to said means for establishing a trimming voltage, and to one of the function terminals, for varying the trimming voltage in response to a signal at that function terminal, thereby varying the threshold voltage.

48. The circuit of claim **47**, wherein said means for varying the trimming voltage is connected to the first function terminal.

49. The circuit of claim **48**, wherein:

said means of establishing a trimming voltage comprises a resistor; and wherein

said means for varying the trimming voltage varies a current conducted by said trimming voltage resistor as a function of a current conducted by the first function terminal.

50. The circuit of claim **49**, wherein the current conducted by the first function terminal is established at least in part by external components connected to the first function terminal.

51. The circuit of claim **50**, wherein the external components connected to the first function terminal include a resistor connected to ground.

52. The circuit of claim **40**, wherein said mode select means is connected to the first function terminal.

53. The circuit of claim **40**, wherein said mode select means includes:

means for sensing current conducted by the first function terminal; and

means responsive to said sensing means for disabling said first means and enabling said second means when the current sensed by said sensing means exceeds a predetermined threshold current.

54. The integrated circuit of claim **39**, wherein the network of external components connected to the second function terminal includes a frequency compensating capacitor.

55. The integrated circuit of claim **40**, wherein the network of external components connected to the second function terminal includes a frequency compensation capacitor in series with a resistor.

56. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, and further having input and ground terminals for connection to a source of input power, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals, the integrated circuit comprising:

first means responsive to control signals applied to the first multi-function terminal, said first means including at least two of:

(a) means for controlling the duty cycle of the switching transistor when the integrated circuit is operating in a normal feedback mode,

(b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode, and

(c) means for trimming a flyback voltage developed across a winding of an external transformer when the integrated circuit operates in a fully-isolated flyback mode; and

second means responsive to control signals applied to the second multi-function terminal for performing at least two of:

(a) frequency compensating the integrated circuit,

(b) limiting peak current conducted by the switching transistor,

(c) variably limiting current conducted by the switching transistor as a function of time, and

(d) shutting down the integrated circuit, whereby current drawn by the integrated circuit is reduced.

57. The integrated circuit of claim **56**, wherein said normal feedback mode controlling means includes:

means for producing a first reference signal;

means for generating a feedback mode error signal indicative of a difference between the first reference signal and a feedback signal applied to the first multi-function terminal indicative of the magnitude of the regulated output voltage;

means for comparing the feedback mode error signal to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to said comparing means for turning off the switching transistor when the current magnitude signal exceeds the error signal, whereby the duty cycle of the switching transistor is controlled as a function of the feedback signal.

58. The integrated circuit of claim **56**, wherein said programming means includes:

means for controlling the duty cycle of the switching transistor when the integrated circuit operates in a fully-isolated flyback mode; and

means connected to the first multi-function terminal for sensing a mode-select signal at the first multi-function terminal and for responsively disabling said normal feedback mode controlling means and enabling said flyback mode controlling means.

59. The integrated circuit of claim **58**, wherein said flyback mode controlling means includes:

means connected to the input and output terminals for receiving a flyback signal indicative of a voltage developed across the winding of the external transformer, and for generating a flyback mode error signal indicative of a difference between the flyback signal and a threshold signal level;

means for comparing the flyback mode error signal to a signal indicative of the magnitude of current conducted by the switching transistor; and

means responsive to the output of said comparing means for turning off the switching transistor when the current magnitude signal exceeds the error signal, whereby the duty cycle of the switching transistor is controlled as a function of the flyback signal.

60. The integrated circuit of claim **59**, wherein said trimming means includes:

means connected to the first multi-function terminal for sensing a trimming control signal; and means connected to said trimming control signal sensing means and to said flyback mode error signal generating means for trimming the magnitude of the threshold signal in response to the trimming control signal, thereby trimming the flyback voltage.

61. The integrated circuit of claim **56**, wherein said second means includes:

means for generating a signal indicative of the magnitude of current conducted by the switching transistor;

means connected to at least one terminal of the integrated circuit for sensing a feedback signal indicative of the magnitude of at least one of the regulated output voltage and the voltage developed across the winding of the external transformer, and for generating an error signal indicative of the difference between the feedback signal and a reference signal;

means for comparing the error signal to the current magnitude signal, and for turning off the switching transistor when the current magnitude signal exceeds the error signal; and

means for applying the error signal to the second multi-function terminal, whereby the magnitude of the error signal may be controlled by a network of one or more external components connected to the second multi-function terminal.

62. The integrated circuit of claim **61**, wherein the network of external components connected to the second multi-function terminal includes a frequency compensating capacitor.

63. The integrated circuit of claim **61**, wherein the network of external components connected to the second multi-function terminal includes a frequency compensation capacitor in series with a resistor.

64. The integrated circuit of claim **61**, wherein the network of external components connected to the second multi-function terminal prevents the error signal at the second multi-function terminal from exceeding a predetermined maximum level, thereby limiting to a maximum peak value the magnitude of current conducted by the switching transistor.

65. The integrated circuit of claim **62**, wherein the network of external components establishes a predetermined maximum voltage at the second multi-function terminal.

66. The integrated circuit of claim **61**, wherein the network of external components connected to the second multi-function terminal variably controls the voltage at the second multi-function terminal as a function of time, thereby variably limiting as a function of time the current conducted by the switching transistor.

67. The integrated circuit of claim **66**, wherein the network of external components for variably controlling the voltage at the second multi-function terminal includes:

a resistor connected between a first node and a second node;

a capacitor connected between the second node and the ground terminal; and

means connected between the second node and the second multi-function terminal for applying at least a portion of a voltage at the second node to the second multi-function terminal, such that the voltage at the second multi-function terminal upon application of a voltage at the first node gradually increases with time to gradually increase the current conducted by the switching transistor.

68. The integrated circuit of claim **56**, the integrated circuit further having voltage regulator circuitry for providing a regulated voltage to at least portions of the internal Circuitry, wherein said second means further includes:

means for producing a second reference signal;

means for comparing the second reference signal to a shutdown control signal applied to the second multi-function terminal by the external components, and for generating a shutdown signal when the second reference signal and the shutdown control signal differ by a predetermined amount; and

means responsive to the shutdown signal for disabling at least the voltage regulator circuitry, thereby shutting down and reducing the current drawn by the integrated circuit.

69. The integrated circuit of claim **68**, wherein the shutdown control signal is a voltage, and wherein:

said means for producing a second reference signal includes a diode having a first forward voltage drop; and wherein

said comparing means includes a transistor having a base-emitter circuit connected between said diode and the second multi-function terminal, the base-emitter circuit having a second forward voltage drop which differs from the first forward voltage drop, and said transistor being adapted to disable the voltage regulator circuitry when the shutdown control signal voltage at the second multi-function terminal is less than the difference between the first and second forward voltage drops.

70. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, and further having input and ground terminals for connection to a source of input voltage and current, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals, the integrated circuit comprising:

first means responsive to control signals applied to the first multi-function terminal, said first means including:

(a) means for controlling the duty cycle of the switching transistor when the integrated circuit operates in a normal feedback mode,

(b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode, and

(c) means for trimming a flyback voltage developed across a winding of an external transformer when the integrated circuit operates in a fully-isolated flyback mode; and

second means responsive to control signals applied to the second multi-function terminal for:

(a) frequency compensating the integrated circuit,

(b) limiting peak current conducted by the switching transistor,

(c) variably limiting current conducted by the switching transistor as a function of time, and

(d) shutting down the integrated circuit, whereby current drawn by the integrated circuit is reduced.

71. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, and further having input and ground terminals for connection to a source of input voltage and current, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals, the integrated circuit comprising:

first means responsive to control signals applied to the first multi-function terminal, said first means including:
  (a) means for controlling the duty cycle of the switching transistor when the integrated circuit operates in a normal feedback mode,
  (b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode, and
  (c) means for trimming a flyback voltage developed across a winding of an external transformer when the integrated circuit operates in a fully-isolated flyback mode; and

second means responsive to control signals applied to the second multi-function terminal for:
  (a) frequency compensating the integrated circuit,
  (b) limiting peak current conducted by the switching transistor, and
  (c) variably limiting current conducted by the switching transistor as a function of time.

72. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, and further having input and ground terminals for connection to a source of input voltage and current, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals, the integrated circuit comprising:

first means responsive to control signals applied to the first multi-function terminal, said first means including:
  (a) means for controlling the duty cycle of the switching transistor when the integrated circuit operates in a normal feedback mode, and
  (b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode; and

second means responsive to control signals applied to the second multi-function terminal for:
  (a) frequency compensating the integrated circuit,
  (b) limiting peak current conducted by the switching transistor,
  (c) variably limiting current conducted by the switching transistor as a function of time, and
  (d) shutting down the integrated circuit, whereby current drawn by the integrated circuit is reduced.

73. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, and further having input and ground terminals for connection to a source of input voltage and current, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second function terminals for connection to external components adapted to apply control signals to the function terminals, the integrated circuit comprising:

first means responsive to a control signal applied to the first function terminal for controlling the duty cycle of the switching transistor as a function of the magnitude of the regulated output voltage; and

second means responsive to control signals applied to the second function terminal for:
  (a) frequency compensating the integrated circuit,
  (b) limiting *peak* current conducted by the switching transistor,
  (c) variably limiting current conducted by the switching transistor as a function of time, and
  (d) shutting down the integrated circuit, whereby current drawn by the integrated circuit is reduced.

74. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, and further having input and ground terminals for connection to a source of input voltage and current, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals, the integrated circuit comprising:

first means responsive to control signals applied to the first multi-function terminal, said first means including:
  (a) means for controlling the duty cycle of the switching transistor when the integrated circuit operates in a normal feedback mode, and
  (b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode;

second means responsive to control signals applied to the second multi-function terminal for:
  (a) frequency compensating the integrated circuit,
  (b) limiting peak current conducted by the switching transistor, and
  (c) variably limiting current conducted by the switching transistor as a function of time.

75. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, the integrated circuit comprising:

at most five terminals for connection to external components, including input and ground terminals for connection to a source of input power, and output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals;

first means responsive to control signals applied to the first multi-function terminal, said first means including at least two of:
  (a) means for controlling the duty cycle of the switching transistor when the integrated circuit is operating in a normal feedback mode,

(b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode, and

(c) means for trimming a flyback voltage developed across a winding of an external transformer when the integrated circuit operates in a fully-isolated flyback mode; and

second means responsive to control signals applied to the second multi-function terminal for performing at least two of:

(a) frequency compensating the integrated circuit,

(b) limiting peak current conducted by the switching transistor,

(c) variably limiting current conducted by the switching transistor as a function of time, and

(d) shutting down the integrated circuit, whereby current drawn by the integrated circuit is reduced.

76. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, the integrated circuit comprising:

at most five terminals for connection to external components, including input and ground terminals for connection to a source of input power, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals;

first means responsive to control signals applied to the first multi-function terminal, said first means including:

(a) means for controlling the duty cycle of the switching transistor when the integrated circuit is operating in a normal feedback mode,

(b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode, and

(c) means for trimming a flyback voltage developed across a winding of an external transformer when the integrated circuit operates in a fully-isolated flyback mode, and

second means responsive to control signals applied to the second multi-function terminal for:

(a) frequency compensating the integrated circuit,

(b) limiting peak current conducted by the switching transistor,

(c) variably limiting current conducted by the switching transistor as a function of time, and

(d) shutting down the integrated circuit, whereby current drawn by the integrated circuit is reduced.

77. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, the integrated circuit comprising:

at most five terminals for connection to external components, including input and ground terminals for connection to a source of input power, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals;

first means responsive to control signals applied to the first multi-function terminal, said first means including:

(a) means for controlling the duty cycle of the switching transistor when the integrated circuit is operating in a normal feedback mode,

(b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode, and

(c) means for trimming a flyback voltage developed across a winding of an external transformer when the integrated circuit operates in a fully-isolated flyback mode; and

second means responsive to control signals applied to the second multi-function terminal for performing at least two of:

(a) frequency compensating the integrated circuit,

(b) limiting peak current conducted by the switching transistor, and

(c) variably limiting current conducted by the switching transistor as a function of time.

78. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, the integrated circuit comprising:

at most five terminals for connection to external components, including input and ground terminals for connection to a source of input power, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals;

first means responsive to control signals applied to the first multi-function terminal, said first means including at least two of:

(a) means for controlling the duty cycle of the switching transistor when the integrated circuit is operating in a normal feedback mode, and

(b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode; and

second means responsive to control signals applied to the second multi-function terminal for performing at least two of:

(a) frequency compensating the integrated circuit,

(b) limiting peak current conducted by the switching transistor,

(c) variably limiting current conducted by the switching transistor as a function of time, and

(d) shutting down the integrated circuit, whereby current drawn by the integrated circuit is reduced.

79. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, the integrated circuit comprising:

at most five terminals for connection to external components, including input and ground terminals for connection to a source of input power, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second function terminals for connection to external components adapted to apply control signals to the function terminals;

first means responsive to control signals applied to the first function terminal for controlling the duty cycle of the switching transistor as a function of the magnitude of the regulated output voltage; and

second means responsive to control signals applied to the second function terminal for:

(a) frequency compensating the integrated circuit,

(b) limiting peak current conducted by the switching transistor,

(c) variably limiting current conducted by the switching transistor as a function of time, and

(d) shutting down the integrated circuit, where*by* current drawn by the integrated circuit is reduced.

80. An integrated circuit for use in implementing a switching voltage regulator providing a regulated output voltage, the integrated circuit having internal drive circuitry, a power switching transistor and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, the integrated circuit comprising:

at most five terminals for connection to external components, including input and ground terminals for connection to a source of input power, an output terminal for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage, and first and second multi-function terminals for connection to external components adapted to apply control signals to the multi-function terminals;

first means responsive to control signals applied to the first multi-function terminal, said first means including:

(a) means for controlling the duty cycle of the switching transistor when the integrated circuit is operating in a normal feedback mode, and

(b) means for programming the integrated circuit to operate in one of a normal feedback mode and a fully-isolated flyback mode; and

second means responsive to control signals applied to the second multi-function terminal for performing at least two of:

(a) frequency compensating the integrated circuit,

(b) limiting peak current conducted by the switching transistor, and

(c) variably limiting current conducted by the switching transistor as a function of time.

81. An integrated circuit capable of implementing a current-mode normal feedback switching voltage regulator and a current-mode fully isolated flyback switching voltage regulator, the integrated circuit having a switching transistor, circuitry for driving the switching transistor, and control circuitry for controlling the on and off duty cycle of the switching transistor to produce a pulsed output, the integrated circuit comprising:

at most five terminals for connection to external components, including:

(a) input and ground terminals, connected to the integrated circuitry, for connection to a source of input voltage and current;

(b) an output terminal, connected to the switching transistor, for connection to external components adapted to convert the pulsed output of the switching transistor into the regulated output voltage;

(c) a first multi-function terminal responsive to control signals applied by external components connected to the first multi-function terminal for performing at least two functions selected from the group of:

(1) controlling the duty cycle of the switching transistor when the integrated circuit is operating in a normal feedback mode,

(2) programming the integrated circuit to operate in one of a normal feedback mode and fully-isolated flyback mode, and

(3) trimming a flyback voltage developed across a winding of an external transformer when the integrated circuit operates in a fully-isolated flyback mode; and

(d) a second multi-function terminal, responsive to control signals applied by external components connected to the second multi-function terminal, for performing at least two functions selected from the group of:

(1) frequency compensating the integrated circuit,

(2) limiting peak current conducted by the switching transistor,

(3) variably limiting current conducted by the switching transistor as a function of time, and

(4) shutting down the integrated circuit, whereby current drawn by the integrated circuit is reduced.

82. An integrated circuit for implementing a current-mode switching voltage regulator circuit by connecting the integrated circuit to external components, the integrated circuit comprising:

at most five terminals, the terminals comprising input and ground terminals for connecting the integrated circuit to a source of input voltage and current, an output terminal for connecting the integrated circuit to an external inductive or transformer load, a feedback terminal for receiving an external feedback signal proportional to the regulated output voltage of the switching regulator, and a compensation terminal for connection to an external frequency compensation network;

a power switching transistor having its collector-emitter circuit coupled to conduct a current between the output terminal and the ground terminal;

means coupled to the switching transistor for varying the on and off duty cycle of the switching transistor in response to a control signal;

means including a resistive element coupled in series with the collector-emitter circuit of the switching transistor, and an amplifier coupled to the resistive element for generating a current sense signal indicative of the current conducted by the switching transistor;

means for generating an error signal indicative of a difference between the feedback signal and a reference signal;

means for coupling the error signal to the compensation terminal; and

means for comparing the current sense signal to the error signal and for generating the control signal to turn off the switching transistor when the current sense signal compares in a predetermined manner to the error signal to vary the duty cycle of the switching transistor to produce the regulated output voltage.

83. The integrated circuit of claim 82 further comprising:

means responsive to control signals applied to the compensation terminal for performing at least one of:

(a) limiting peak current conducted by the switching transistor,

(b) variably limiting current conducted by the switching transistor as a function of time, and

(c) shutting down the integrated circuit, whereby current drawn by the integrated circuit is reduced.

84. The integrated circuit of claim 82, wherein the control signal is generated when the current sense signal exceeds the error signal.

85. An integrated circuit for implementing a current-mode switching voltage regulator circuit by connecting the integrated circuit to external components, the integrated circuit comprising:

at least an input terminal and a ground terminal for connecting the integrated circuit to a source of input voltage and current, an output terminal for connecting the integrated circuit to an external inductive or transformer load, a feedback terminal for receiving an external feedback signal proportional to the regulated output voltage of the switching regulator, and a compensation terminal for connection to an external frequency compensation network;

a power switching transistor structure coupled to conduct current between the output terminal and the ground terminal;

a driver circuit coupled to provide a base drive current to the switching transistor;

a circuit coupled to the driver circuit for varying the on and off duty cycle of the switching transistor in response to a control signal;

a circuit including a resistive element coupled in series with the current path in the switching transistor between the output terminal and the ground terminal and an amplifier coupled to the resistive element for generating a current sense signal indicative of the current conducted by the switching transistor;

a circuit for generating an error signal indicative of a difference between the feedback signal and a reference signal, and for coupling the error signal to the compensation terminal and to the driver circuit;

a reference circuit coupled to provide the reference signal to the circuit for generating an error signal;

a circuit for comparing the current sense signal to the error signal and for generating the control signal to turn off the switching transistor when the current sense signal compares in a predetermined way to the error signal to vary the duty cycle of the switching transistor to produce the regulated voltage, the comparing circuit further being responsive to control signals externally applied to the compensation terminal for performing at least one of (a) limiting peak current conducted by the switching transistor, and (b) variably limiting current conducted by the switching transistor as a function of time; and

a circuit for placing the integrated circuit into a shutdown state where the current drawn by the integrated circuit is reduced, including by deactivating the reference circuit; wherein:

the driver circuit is responsive at least in part to the error signal for causing the base drive current provided to the switching transistor to vary so as to increase the efficiency of operation of the switching transistor.

86. The integrated circuit of claim 85, wherein the circuit for placing the integrated circuit into a shutdown state is responsive to a signal externally applied to the compensation terminal.

87. The integrated circuit of claim 86, wherein the switching transistor structure is a bipolar transistor.

88. An integrated circuit for implementing a current-mode switching regulator circuit by connecting the integrated circuit to external components, the integrated circuit comprising:

at least an input terminal and a ground terminal for connecting the integrated circuit to a source of input voltage and current, an output terminal for connecting the integrated circuit to an external inductive or transformer load, a feedback terminal for receiving an external feedback signal proportional to the regulated output voltage of the switching regulator, and a compensation terminal for connection to an external frequency compensation network;

a power switching transistor structure coupled to conduct current between the output terminal and the ground terminal;

a circuit coupled to the switching transistor structure for varying the on and off duty cycle of the switching transistor in response to a control signal;

a circuit, including a resistive element coupled in series with a current path in the switching transistor structure between the output terminal and the ground terminal and an amplifier coupled to the resistive element, for generating a curernt sense sigal indicative of the current conducted by the switching transistor;

a circuit for generating an error signal indicative of a difference between the feedback signal and a reference signal, and for coupling the error signal to the compensation terminal; and

a circuit for comparing the current sense signal to the error signal and for generating the control signal to turn off the switching transistor when the current sense signal compares in a predetermined way to the error signal to vary the duty cycle of the switching transistor to produce the regulated voltage, said comparing circuit further being responsive to control signals externally applied to the compensation terminal for (a) limiting peak current conducted by the switching transistor and (b) variably limiting current conducted by the switching transistor as a function of time,

wherein the integrated circuit terminals require connection to no more than five different nodes among the external components to implement a current-mode switching regulator circuit.

89. The integrated circuit of claim 88, further comprising a circuit for reducing the current drawn by the integrated circuit to place the integrated circuit into a shutdown state.

90. The integrated circuit of claim 89, wherein the circuit for reducing the current drawn by the integrated circuit is responsive to a signal externally applied to the compensation terminal.

91. The integrated circuit of claim 89, wherein the switching transistor structure is a bipolar transistor.

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