United States Patent

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[54] **REGENERATIVE VOLTAGE REGULATORS**

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[52] **U.S. Cl.** .... **323/17,** 321/2, 323/22 T, 323/38, 323/DIG. 1

[51] **Int. Cl.** **G05f 1/56**

[58] **Field of Search** .... 321/2; 323/18, 22 T, 38, 17, 323/DIG. 1

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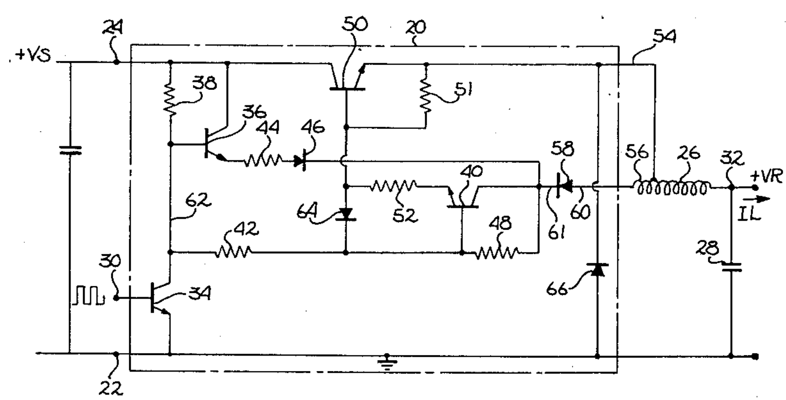
[57] **ABSTRACT**

Regenerative power switches for use in semiconductor circuits such as in voltage regulators having a DC or low-frequency output controlled by a high-frequency pulse input. The circuits are designed to minimize the power dissipation in the regulator circuit and to minimize the number of components, particularly inductive components required. The regulator circuit having a negative common uses a feedback voltage from a secondary coil on the output filter choke to create a voltage exceeding the supply voltage, which is used without rectification thereof to force a series transistor into saturation during the ON portion of the cycle, thereby minimizing the voltage drop across that transistor and maximizing power output capability of the voltage regulator or amplifier. The regulator circuit having a positive common uses a feedback voltage from a top on the output filter choke winding to force a series transistor into saturation. The use of the tap minimizes the power dissipation in the regulator during the ON portion of the cycle and further aids in a fast and complete turnoff.

6 Claims, 9 Drawing Figures



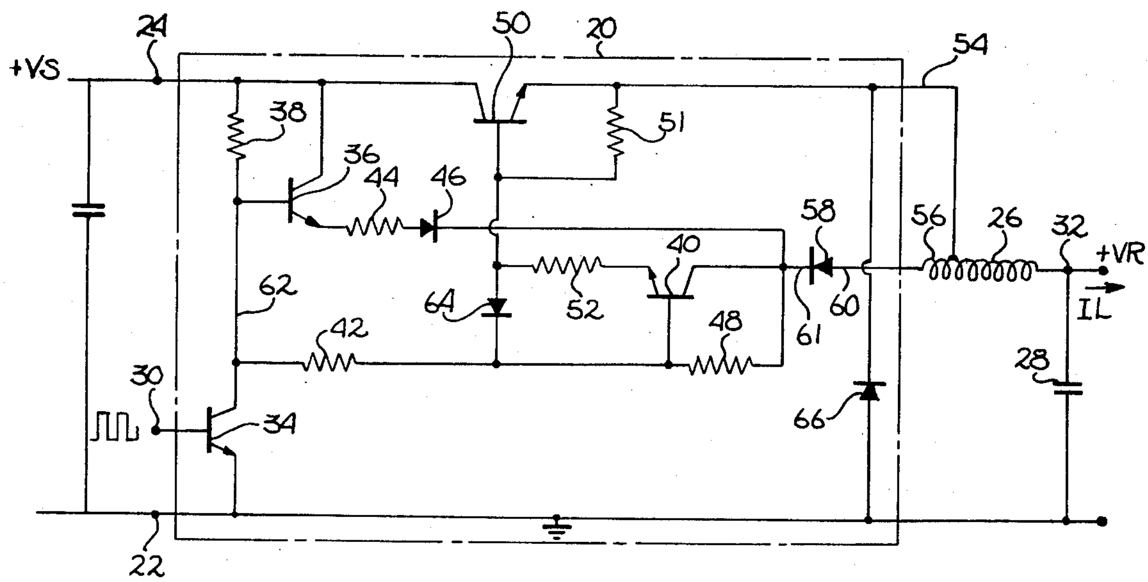


Fig. 1

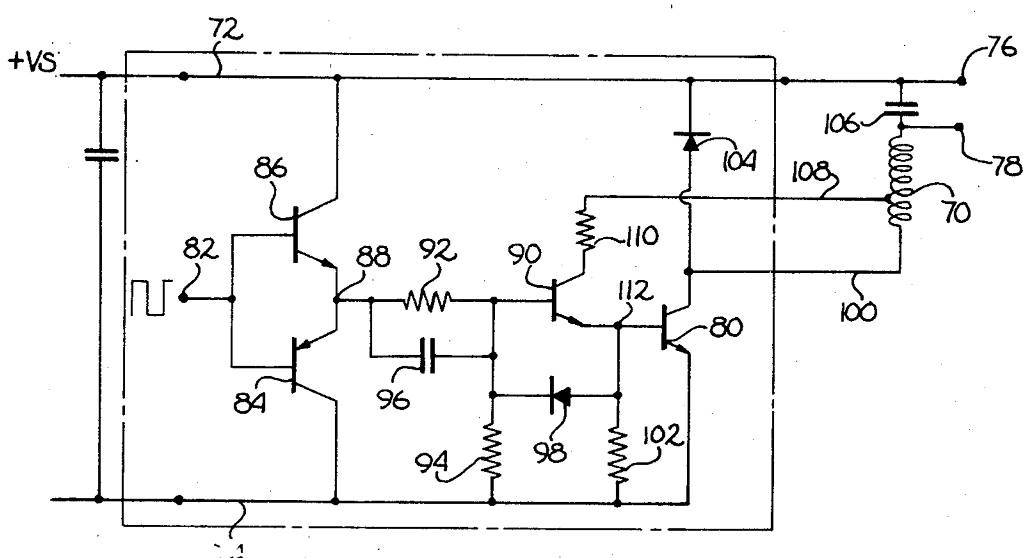


Fig. 2

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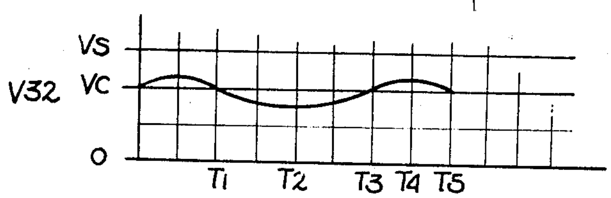

Fig. 3a

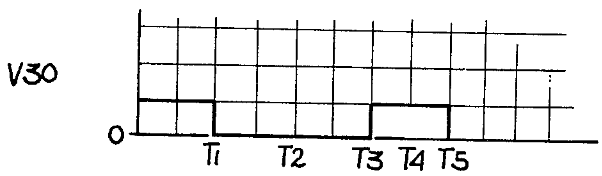

Fig. 3b

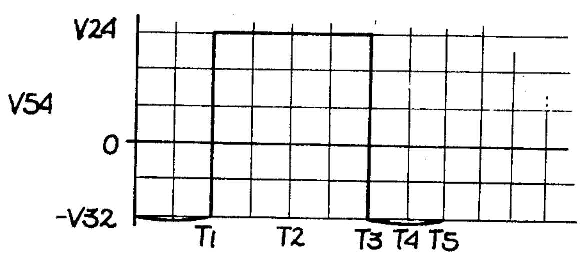

Fig. 3c

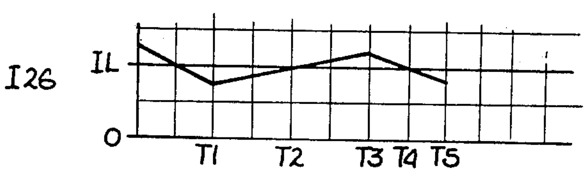

Fig. 3d

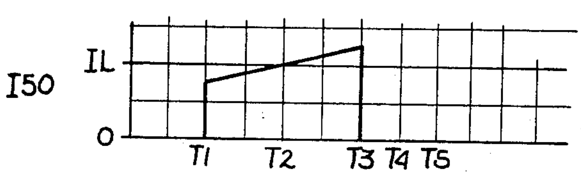

Fig. 3e

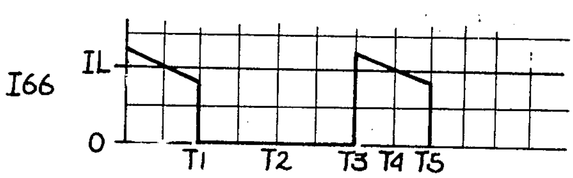

Fig. 3f

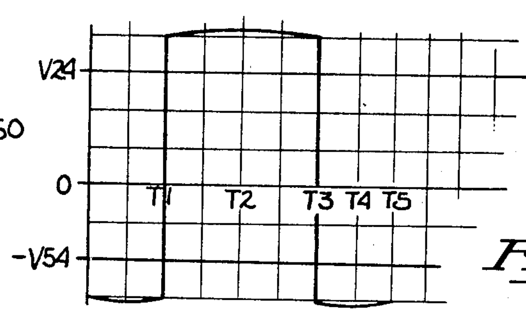

Fig. 3g

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REGENERATIVE VOLTAGE REGULATORS

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to the field of electronic voltage regulators and amplifiers.

2. Prior Art

Various types of voltage regulators, and particularly semiconductor device voltage regulators, are well known in the prior art. These voltage regulators are primarily of two types. The earlier regulator is a nonswitching type, which characteristically has a relatively high power dissipation within the regulator as compared with the output power derived therefrom. The second type of regulator is a switching regulator, wherein a series transistor is switched on and off at a high frequency in a controlled manner so as to deposit an incremental charge into an output capacitor, thereby maintaining the charge on the output capacitor and, therefore, the output voltage, within a desired voltage band.

The nonswitching regulator is characterized by a series transistor connected between an unregulated power supply and the regulated output, and a control circuit for controlling the base current in the series transistor to thereby control the voltage drop across the transistor in the required manner to achieve the regulated output. Since the series transistor delivers the output current with a substantial voltage drop across the transistor, there is a large power dissipation in the transistor. By way of example, if a 75-volt regulated output is desired, the minimum input voltage to the regulator must be somewhat higher than 75 volts. This is because since normally no voltage is available which is higher than the unregulated supply voltage (e.g., the regulator input), and as a result, the base current required to put the series transistor into full saturation cannot be supplied. Therefore, the minimum supply voltage must exceed the regulated voltage by a matter of a few volts. Furthermore, if the unregulated supply voltage varies over any substantial range, the power dissipation capability of the series transistor must be even higher. For instance, if the voltage output of the unregulated supply ranges from 80 to 100 volts (approximately plus or minus 10 percent) and the regulated output is at 75 volts, it is apparent that the power dissipation capability of the series transistor must be at least one-third the output power capability of the regulator.

In addition to the above, it is also apparent that if the regulated output voltage is to be controllable by separate control signal, then the power dissipation in the series transistor as compared to the output power of the regulator must be even a higher percentage. For instance, if the output voltage is to be regulated at 50 volts, the power dissipation in the series transistor will equal the output power of the regulator, at least when the unregulated power supply is putting out 100 volts. This also illustrates the fact that the voltage output of the unregulated power supply must be matched reasonably well to the voltage output desired from the regulator, since extremely high power dissipation in the series transistor will result if the regulated voltage is to be only a fraction of the unregulated voltage.

The switching voltage regulator also uses a series transistor and generally uses an L-C filter on the output. The series transistor is switched on and off at a relatively high frequency, the relative ontime being varied to maintain the output voltage across the capacitor at the desired voltage. If the series transistor is always switched between the off condition and saturation, it is apparent that the power dissipation in the series transistor will be quite low, since the off state is characterized by a substantial voltage across, but negligable current through, the transistor, and the saturation state is characterized by substantial current through, but very low voltage across, the transistor. This, of course, remains true even if the regulated output voltage is to be a relatively small fraction of the unregulated supply voltage.

In regulators using an NPN-series transistor and having a negative common, the major source of power dissipation is power dissipation in the series transistor when driven into saturation. If this transistor is driven into true saturation, a base voltage exceeding the unregulated supply voltage must be used. This means that if the full advantage of this type of regulator is to be achieved, a voltage must be created which exceeds the unregulated supply voltage, and this voltage used to supply base current to the series transistor when switched to the saturation condition. Such voltages are commonly generated in the prior art regulators by rectifying and filtering an AC voltage referenced to the high side of the unregulated supply, and using this voltage to force the series transistor into saturation during the on portion of the duty cycle. Such circuits require a source of AC power referenced to one side of the unregulated supply, a rectifier and a filter for creating a DC voltage exceeding the voltage of the unregulated supply. In general this requires additional capacitors, inductors and other circuitry for this purpose.

In regulators using an NPN-series transistor and having a positive common, the major source of power dissipation is the resistor and transistor switch supplying the base current to the series transistor. This base current must be supplied at a potential of only a few volts. Consequently, since the gain of power-switching transistor is characteristically rather low and such current is normally supplied from the positive common, a large power dissipation occurs in the dropping resistor in series with the base of the series transistor.

BRIEF SUMMARY OF THE INVENTION

The present invention is a regenerative power switch for use in semiconductor circuits such as in voltage regulators controlled by high-frequency pulses and having very low power dissipation. The circuits of the present invention utilize an L-C output filter and are characterized by the use of a feedback voltage from a secondary winding on the filter inductor to drive a series transistor into saturation during the conducting portion of the duty cycle. When the series transistor is initially turned on by high-frequency pulse, the feedback voltage exceeds the unregulated supply voltage and drives the series transistor deep into saturation, thereby minimizing the voltage drop across the transistor. A second transistor is in series with the feedback voltage, and the series transistor is turned off by turning off the second transistor and further biasing the series transistor to the off condition. Thus, the only inductor required in the circuits of the present invention such as in regulators, is the output filter inductor and thus the basic regulator circuit may be readily packaged in hybrid form in a package of minimum size.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is one embodiment of the regulator of the present invention having negative common.

FIG. **2** is a second embodiment of the present invention regulator having a positive common.

FIG. **3*a*** is the waveform of the filter output voltage **V32** at point **32** of FIG. **1** throughout a typical cycle operation of the regulator of FIG. **1**.

FIG. **3*b*** is a typical waveform of the control voltage **V30** applied to point **30** of FIG. **1** throughout the same time period as the waveform of FIG. **3*a***.

FIG. **3*c*** is the waveform of the voltage **V54** on line **54** of FIG. **1** throughout the same time period as the waveform of FIG. **3*a***.

FIG. **3*d*** is a waveform of the current **I26** through the inductor **26** of FIG. **1** throughout the same time period as the waveform of FIG. **3*a***.

FIG. **3*e*** is a waveform of the current **I50** through transistor **50** of FIG. **1** throughout the same time period as the waveform of FIG. **3*a***.

FIG. **3*f*** is a waveform of the current **I66** through diode **66** of FIG. **1** throughout the same time period as the waveform of FIG. **3*a***.

FIG. 3*g* is a waveform of the feedback voltage V60 on line 60 of FIG. 1 over the same time period as the waveform of FIG. 3*a*.

DETAILED DESCRIPTION OF THE INVENTION

First referring to FIG. 1, one embodiment of the present invention regulator, may be seen. This embodiment is intended for use with an unregulated supply having a negative common. The regulator circuit enclosed within the box 20 of FIG. 1 connects to an unregulated voltage supply at points 22 and 24, and delivers power to the output filter comprised of choke 26 and output capacitor 28 in a manner controlled by a high-frequency pulse signal applied to point 30. The pulse applied to point 30 for purposes of control of the voltage regulator may be of constant frequency but of varying pulse widths, that is, a pulse width modulated signal, or may be a varying frequency signal such as that created by a Schmitt trigger. Such a signal could be generated by comparing the output voltage at point 32 with a reference voltage, such as a zener diode reference voltage, and the error signal used to drive a Schmitt trigger. In the description to follow it will be assumed that a Schmitt trigger is used to generate the feedback signal, though it is to be understood that other feedback signals such as a constant frequency, varying pulse width signal may also be used.

The operation of the circuit of FIG. 1 may be described as follows. When the output voltage at point 32 falls below the control value, the Schmitt trigger initiates a negative pulse at point 30. This negative pulse turns off transistor 34. The turning off of transistor 34 turns on transistor 36 by supplying base current through resistor 38 so that current is supplied to the collector of transistor 40 through transistor 36, resistor 44 and diode 46. Since transistor 40 is turned on, current to the base of the series transistor 50 is supplied through transistor 40 and resistor 52. This partially turns on transistor 50 and suddenly raises the voltage in line 54. Since the voltage across capacitor 28 may not be changed quickly, the increase in voltage on line 54 results in an equivalent increase in voltage across the inductor 26. Also wound on the same core as inductor 26 is a secondary coil 56, one end of which is connected to lead 54 and the other end of which is connected to diode 58. The winding sense of the secondary coil 56, as compared to the inductor 26, is such that the increase in the voltage across the inductor 26 due to the partial turn-on of transistor 50 results in a positive induced voltage on line 60, which is imposed on the base of transistor 50 through diode 58, transistor 40 and resistor 52, thereby driving transistor 50 quickly and completely into saturation. Though transistor 40 is initially turned on by current supplied through transistor 36, resistor 44, diode 46, and resistor 48, transistor 40 is maintained in the on condition by the high collector voltage on transistor 40 as a result of the feedback from the secondary coil 56 and the current supplied to the base of transistor 40 through resistor 48.

When the voltage at line 60 rises beyond that at line 24, the voltage at line 61 also exceeds that at line 24, thus reverse biasing diode 46 and turning off transistor 36. Regeneration of the voltage at line 24 supplies a source of current to maintain transistor 40 in the on state.

When capacitor 28 is charged to the control voltage, the Schmitt trigger changes the polarity of the voltage supplied to point 30 to a positive voltage. This turns on transistor 34, resulting in a substantial drop in the voltage in line 62, thereby turning off transistor 50 through diode 64 and resistor 42, and turning off transistor 40 by depleting the base current to this transistor which was previously supplied by resistor 48.

When transistor 50 is turned off, the voltage on line 54 drops, and since the current in inductor 26 may not be abruptly changed, current temporarily continues to flow in inductor 26 to charge capacitor 28 as a result of the back EMF induced in inductor 26. This back EMF is substantially equal to the voltage across capacitor 28 plus the voltage drop in diode 66 and continues to charge capacitor 28 (or at least supply part of the output current) until the magnetic field in the inductor 26 falls to zero or until the switching cycle is reinitiated. Since the voltage across inductor 26 during this time is of opposite polarity from the voltage occuring across the inductor when transistor 50 is on, the voltage induced in the secondary coil 56 is also of opposite polarity. Therefore, the voltage in line 60 when transistor 50 is off and the magnetic field in the inductor 26 is decreasing, is negative, and this voltage is isolated from transistor 40 by the back biasing of diode 58. (Resistor 51 is a base-emitter return, that is, a leakage current return which enhances the stability of operation of transistor 50).

If the pulse to point 30 remains positive for a sufficient length of time, (indicating little or no load connected to the output terminals of the regulator) the magnetic field in inductor 26 will fall to zero, and at that time, the voltage across the inductor 26 will go to zero and the voltage across diode 66 will equal the voltage across capacitor 28. In this condition the voltage induced in the secondary coil 56 will be zero and, therefore, the voltage in line 60 will be equal to the voltage across the output capacitor 28. Since transistor 34 will still be on, diode 58 will be forward biased, and the collector of transistor 40 will be at a voltage just slightly below the output voltage across capacitor 28. However, the voltage at the base of transistor 40 will be substantially lower than that on the collector of transistor 40 because of the voltage drop in resistor 48 due to the current flowing through resistor 48, resistor 42 and transistor 34. Also the base of transistor 50 will be at a voltage substantially equal to the voltage on the base of transistor 40 because it is connected to the base of transistor 40 through diode 64. Since this voltage on the base of transistor 50 is substantially less than the voltage in line 54, which is the voltage in the emitter of transistor 50, transistor 50 will remain in the off condition.

When the output voltage across capacitor 28 drops to the control level, the Schmitt trigger will change the pulse applied to point 30 to a negative pulse and the regenerative sequence previously described is reinitiated. It is, therefore, apparent that the series transistor 50 is always rapidly switched into saturation as a result of the feedback of the induced voltage in the secondary coil 56, and is rapidly switched out of saturation by the drop in the base voltage on transistor 50 as a result of turning on of transistor 34. Consequently, the power dissipation in transistor 50 is minimized since the voltage drop across transistor 50 is minimized when the transistor 50 is conducting. Furthermore, this has been achieved without requiring additional inductive devices, other than a secondary winding on the output filter inductor, and without requiring a filter capacitor in a rectifier circuit for generating a DC voltage exceeding the supply voltage for supplying a base current to the series transistor to force that transistor into saturation.

Having now described the sequential operation of the circuit of FIG. 1, the operation of the circuit may be further illustrated by reference to FIGS. 3*a* through 3*g*, which present typical waveforms for various voltages and currents within the circuit throughout a typical operating cycle. In these figures, a voltage at a particular point or for a particular line of the circuit of FIG. 1 is represented by a V followed by the numeral representing that point in FIG. 1. Similarly, a current in a given line is denoted by an I followed by the appropriate numeral.

In these figures, it has been assumed that the Schmitt trigger has a fixed unique trigger level and is entirely free of hysteresis. However, most Schmitt triggers have a significant hysteresis and it will become apparent in the explanation to follow how hysteresis of the Schmitt trigger affects the operation of the circuit.

In FIG. 3*a*, the voltage V32 of line 32 is shown as it varies with time throughout one cycle of operation of the circuit, that is, throughout the time T1 to time T5. Between time T1 and T3 the voltage V32 is below the voltage labeled VC, which represents the control voltage for the Schmitt trigger, and between T3 and T5 is above the control voltage.

Between time T1 and T3, transistor **50** is turned on. Thus, the voltage *V54* of line **54** in this time interval is substantially equal to the supply voltage *V24* of the unregulated supply as shown in FIG. 3*c*. However, at time T1 the current *I26* through inductor **26** (FIG. 3*d*) is slightly less than the load current *Il*, that is, the current through the load attached to the output terminals of the regulator. When transistor **50** is first switched on at time T1, the current through inductor **26** increases at a rate equal to $V54-V32=L\ dI/dt$; where *L* is the inductance of inductor **26**. Since during this part of the cycle the current *I26* through inductor **26** is also the current *I50* through transistor **50**, (FIG. 3*e*) is the same as *I26*. Also during this time, the voltage across inductor **26**, (*V54*−*V32*) is substantially constant, since the voltage *V32* varies only within a narrow control margin, (the periodic variation in voltage *V32* as shown in FIG. 3*a* is grossly out of scale for purposes of this explanation). Therefore, the rate of increase of the current *I26* in FIG. 3*d* is substantially linear, in the period T1 to T3. In the time period between T1 and T2, the current *I26* is less than the load current *Il* and, consequently, the output voltage *V32* drops to a minimum value at time T2 because of the discharge of capacitor **28** through the load therein. Between time T2 and T3, the current *I26* exceeds the load current, and the capacitor **28** is again recharged, causing the voltage *V32* to increase to the Schmitt trigger control voltage VC at time T3. Between time T1 and T3, the diode **66** is back biased and, therefore, the current *I66* in diode **66**, (FIG. 3*f*), is substantially zero.

The winding sense of the secondary coil **56** is chosen so that the voltage V60 in line **60** is positive with respect to the voltage in line **54** when there is a positive rate of increase in the current through inductor **26**. Therefore, when the voltage V30 at point **30** first goes negative and transistor **50** is thereby partially turned on, the voltage V54 in line **54** increases, causing a positive rate of increase of current *I26* in inductor **26** and a voltage in line **60** exceeding that in line **54**. Since transistor **40** is ON at this time, this further turning on transistor **50**, further increasing the voltage in line **54** and the rate of increase of current I26 in inductor **26**, and thereby causing an increased feedback voltage at line **60**. Consequently, when the voltage **V30** first goes negative at time T1, the transistor **50** is rapidly switched into saturation as a result of the regenerative feedback caused by the secondary coil **56** on inductor **26**. This also causes the voltage on line **54** to very quickly increase to a value substantially equal to the input voltage to the regulator and, therefore, the voltage V60 in line **60** to be substantially above the supply voltage VS to the regulator as shown in FIG. 3*g*. Furthermore, the voltage V60 remains substantially above the supply voltage VS throughout the time period T1 to T3, since the current I26 is steadily increasing during this time period, thereby causing a positive feedback from the secondary coil **56**. The voltage **V60** is used as previously described to supply the base current to transistor **50** to force it into saturation and to maintain the transistor **50** in saturation throughout the time period T1 to T3.

At time T3, the output voltage *V32* again achieves the Schmitt trigger control voltage VC as shown in FIG. 3*a* and the voltage *V30* switches to a positive value, causing transistor **50** to be switched off. Thus, the current *I50* immediately goes to zero, but since the current in inductor **26** may not change instantaneously, the voltage across the inductor **26** will reverse polarity so as to instantaneously maintain the same current in the inductor. Thus the current flow through inductor **26** will be temporarily maintained by current supplied through diode **66**. This current will decrease at a rate given by the equation $dI26/dt=V32/L$ where *L*, as before, is the inductance of inductor **26**. Since the rate of change of current through inductor **26** reverses at time T3, the voltage induced in the secondary coil **56** also reverses and thus the voltage *V60* as shown in FIG. 3*g* swings negative with respect to voltage *V54*.

Between time T3 and T4, the current I26 in inductor **26** exceeds the load current IL, and thus the output voltage V32 continues to rise between T3 and T4. Between T4 and T5, the current I26 decreases below the load current IL, and therefore, the output voltage V32 across capacitor **28** decreases between T4 and T5 until reaching a value equal to the Schmitt trigger control value at T5. Thus, at time T5, the voltage V30 again swings negative, thereby reinitiating the cycle hereinabove described.

Prior art voltage regulators have heretofore used an L-C output filter such as that shown in FIG. **1** (inductor **26** and the capacitor **28**). Consequently, the invented voltage regulator circuit is comprised in part by the addition of the secondary winding **56** on the inductor and the circuit within the outline **20** in FIG. **1**. Since the circuit within the outline **20** does not contain any capacitive or inductive elements, this circuit is easily packaged in hybrid form with certain of the elements put in in discrete form, depending on the output power requirements of the particular application. By way of example, generally speaking, transistor **50** will be a relatively high current capability device, as will diode **66** and, consequently, both of these components are generally present in the hybrid circuit in discrete form. Using such packaging methods and the circuits of the present invention, voltage regulators with a 200-watt output capability have been readily packaged in the standard TO–3 package.

Now referring to FIG. **2**, an embodiment of the present invention voltage regulator having a positive common may be seen. This embodiment is similar to the embodiment of FIG. **1** in that the output filter inductor **70** is a three-terminal device, two of which are used as the inductor terminals and a third of which is a feedback voltage suitable for use in driving a series transistor into saturation.

Line **72** connects to the positive side of the unregulated supply and is common to both the input and output of the regulator. Line **74** connects to the negative side of the supply so that the main current flow is through line **72**, through a load connected to the terminals **76** and **78**, and back through inductor **70**, series transistor **80**, and line **74**. The high-frequency pulse control signal is applied at point **82** by a suitable control device such as a Schmitt trigger responding to variations in the output voltage between terminal **76** and **78**. When the voltage at point **82** switches to its lower value, characteristically a value approaching the voltage on line **74**, transistor **86** is turned off and transistor **84** is turned on, thereby lowering the voltage at point **88** to a value just above the voltage on line **74**. This depletes the base current in transistor **90** through resistor **94**, and through resistor **92** and transistor **84**. Capacitor **96** is connected across resistor **92** and is used to speed up the turn on and turn off of transistor **90** and thus of transistor **80**. When transistor **90** is turned off, transistor **80** is also turned off since resistor **102**, in cooperation with diode **98** and resistor **94**, hold the base of transistor **80** at a voltage very close to the voltage on line **74**.

When transistor **80** is turned off, as previously described, the voltage on line **100** suddenly increases to a value slightly above that of line **72**, so that current continues to flow through inductor **70** (and through diode **104** to charge capacitor **106**) at a steadily decreasing rate in much the same manner as was heretofore described in detail in regard to FIG. **1** and FIGS. 3*a* through 3*g*. Thus, the voltage on line **108** is substantially higher than the voltage at point **78** and is sufficient to supply base current to transistor **80** through transistor **90** when transistor **90** is again turned on. (If the magnetic field in inductor **70** goes to zero and thus, the current in inductor **70** goes to zero before transistor **80** is again turned on, as would be the case for a very light load on the output of the regulator, the voltage on line **108** will go to the voltage at point **78**, which in general will also be sufficiently high to supply base current to transistor **80** through transistor **90** when transistor **90** is turned on).

When the voltage at point **82** is switched to its upper value, typically approximately equal to the voltage on line **72**, transistor **84** is turned off and transistor **86** is turned on, thereby increasing the voltage on line **88** to a value just below that on line **72**. This turns on transistor **90** by supplying current to the base of transistor **90** through the voltage divider comprised of resistor **92** and resistor **94**. When transistor **90** is turned on, transistor **80** is also on because of current supplied through line **108**, resistor **110**, and transistor **90** to the base **112** of transistor **80**. When transistor **80** is on, the voltage in line **100** is substantially equal to the voltage in line **74**. The coil in inductor **70** acts as a voltage divider, with the voltage in line **108** being at a desired value between the voltage in line **74** and the voltage at point **78**. Thus, by proper proportioning of the turns ratio in inductor **70**, that is, by proper placement of the tap in the winding of inductor **70** to be brought out as lead **108**, the voltage in lead **108** when transistor is on may be selected to be only slightly above the voltage drop from the collector to the emitter in transistor **90** plus the voltage drop from the base to the emitter of transistor **80**, when both transistors are on. Thus, resistor **110** has a very low value of resistance and the power dissipation therein is held to a minimum. This is to be compared to the prior art voltage regulators, wherein the base current to the series transistor, such as transistor **80**, was supplied to a resistor connected to the positive line, that is, by connecting resistor **110** to the line **72** rather than to a tap on the output filter inductor **70**. Thus, in the prior art regulators, the voltage drop in the resistor supplying the base current to the series transistor was very nearly equal to the unregulated input voltage to the regulator, and since the gain of power-switching transistors characteristically is low, the power dissipation through a resistor supplying the base current from the positive common line is generally a sizable percentage of the total output power capability of the regulator.

When the voltage at point **82** is again switched to its low value, the sequence previously described is reinitiated. It is thus seen that by using a feedback voltage from the output filter inductor and applying that voltage through a transistor switch to the base of a series transistor in either a positive common or a negative common regulator circuit, the series transistor may be driven into and held in saturation in the desired manner without substantial power dissipation within the regulator itself and without requiring additional inductors to generate appropriate sources of base current for the series transistor. In this manner, voltage regulators of high power output capability may be packaged within a minimum package size and operated at a maximum efficiency.

The high efficiency of the circuits of the present invention is achieved even when the regulated output voltage is substantially below the unregulated input voltage. Thus, in the example described in detail with respect to figures 3*a* through 3*g*, it was assumed that the control voltage VC (and thus the regulator output voltage V32, neglecting output ripple) was approximately two-thirds of the unregulated input voltage V32 applied to point **24** (see FIG. 3*a*). However, the output current I26 (FIG. 3*d*) is the sum of the current I50 from the unregulated supply through transistor **50** and the current I66 through diode **66** after transistor **50** is switched off. As may be seen in FIGS. 3*e* and 3*f*, approximately two-thirds the load current is from the unregulated supply (I50) and one-third (I66) is through diode **66** after transistor **50** is switched off. Thus, neglecting power losses within the circuit, the output voltage is two-thirds the input voltage, but the output current is 1½ times the input current, therefore making the output power equal to the input power.

Regulators have been fabricated with the circuits of the present invention and operated with efficiencies as high as 90 to 95 percent. As a result of these high efficiencies, voltage regulators with a power output capability as high as 200 watts have been built, using the circuits of the present invention, and packaged in a standard T–03 package. Furthermore, such circuits are ideal for fabrication as hybrid circuits because of the absence of inductors in the circuit and the low power dissipation characteristic of the circuit.

I claim:

1. In a voltage regulator, the combination having a positive input terminal, a positive output terminal, a control terminal, and a negative common input-output terminal, comprised of an inductor, having first and second end connections and an intermediate connection, a capacitor, first and second transistor switches, at least one diode and a coupling means;

said capacitor being coupled between said positive output terminal and said common input-output terminal;

said first end connection of said inductor winding being coupled to said positive output terminal;

said first transistor switch being coupled between said first input terminal and said intermediate connection and being responsive to its base current;

said second transistor switch being coupled between said second end connection of said inductor and said base of said first transistor switch and being responsive to its base current;

said coupling means coupling said base of said second transistor switch and the lead of said second transistor switch coupled to said inductor to said control terminal, and being responsive to a pulse control signal applied thereto, to initially supply current through said second transistor switch to said base of said first transistor switch; and,

said intermediate connection and said negative common input-output terminal being coupled through said diode, said diode being conductive when the voltage of said negative common input-output terminal exceeds the voltage on said intermediate connection.

2. The voltage regulator of claim **1** wherein:

said first transistor switch is an NPN-transistor having an emitter, a base, and a collector;

said emitter being coupled to said intermediate connection; and,

said collector being coupled to said first input terminal.

3. A circuit for a voltage regulator, said circuit having a positive input terminal, a positive output terminal, a common negative input-output terminal, a control terminal and a feedback terminal, for use with an output filter of a capacitor and an inductor having a first lead coupled to said capacitor, a second lead coupled to said feedback terminal and a third lead coupled to said positive output terminal, the combination comprised of first and second NPN-transistors, each having an emitter, a base and a collector, a first diode a resistor and a coupling means, said emitter of said first transistor being coupled to said positive output terminal, said collector of said first transistor being coupled to said positive input terminal, said emitter of said second transistor being coupled to said base of said first transistor, said collector of said second transistor being coupled to said feedback terminal through said first diode and to said base of said second transistor through said resistor, said first diode being conductive when the voltage on said feedback terminal exceeds the voltage on said collector of said second transistor, and said coupling means being coupled to said control terminal, to said base and to said collector of said second transistor and being responsive to a pulse control signal applied thereto, to initially supply base current and collector current to said second transistor upon the application of a suitable control pulse to said control terminal.

4. The circuit of claim **3** wherein:

said coupling means is coupled to said collector of said second transistor through a second diode; and,

said second diode being conductive when the voltage on said last-named collector is less than the voltage directed thereto from said coupling means.

5. In a voltage regulator, the combination, having a positive input terminal, a positive output terminal, a control terminal and a negative common input-output terminal comprised of an inductor having first and second end connections and an intermediate connection, a capacitor, first and second NPN-transistors, each having an emitter, a base and a collector, first and second diodes and a coupling means, said capacitor being coupled between said positive output terminal and said common input-output terminal, said first end connection of said inductor being coupled to said positive output terminal, said emitter of said first transistor being coupled to said intermediate connection, said collector of said first transistor being coupled to said positive input terminal, said emitter of said second transistor being coupled to said base of said first transistor, said collector of said second transistor being coupled to said second end connection through a first diode and to said base of said second transistor through a resistor, said first diode being conductive when the voltage on said second end connection exceeds the voltage on said collector of said second transistor switch, said intermediate connection and said negative common input-output terminal being coupled through said second diode, said second diode being conductive when the voltage of said negative common input-output terminal exceeds the voltage on said intermediate connection, said coupling means being coupled to said control terminal, to said base and to said collector of said second transistor and being adapted to initially supply base current and collector current to said second transistor upon the application of a suitable control pulse to said control terminal.

6. The circuit of claim **5** wherein:

said coupling means is coupled to said collector of said second transistor switch through a second diode; and,

said second diode being conductive when the voltage on said last-named collector is less than the voltage directed thereto from said coupling means.

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