April 16, 1968 T. C. GOODENOW 3,378,758

SWITCHING VOLTAGE REGULATOR

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FIG. 1

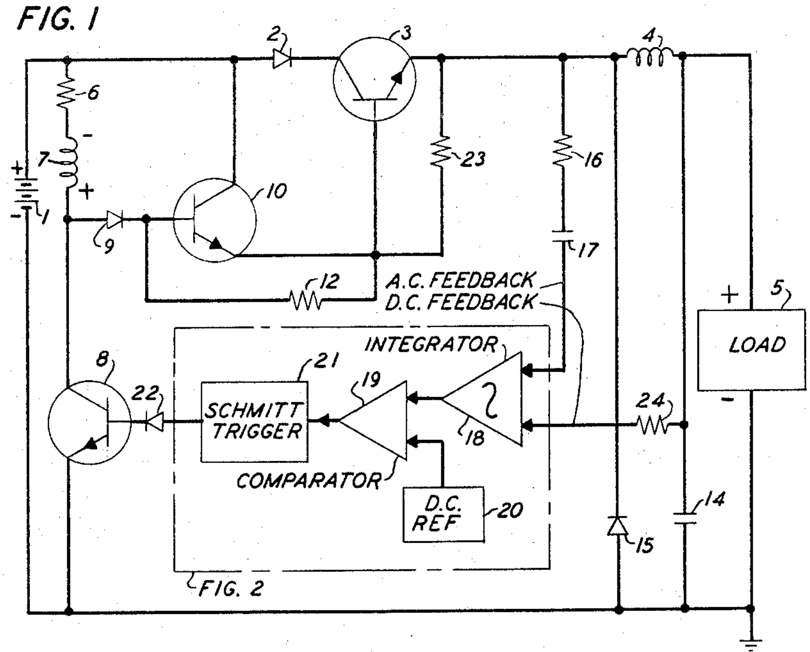
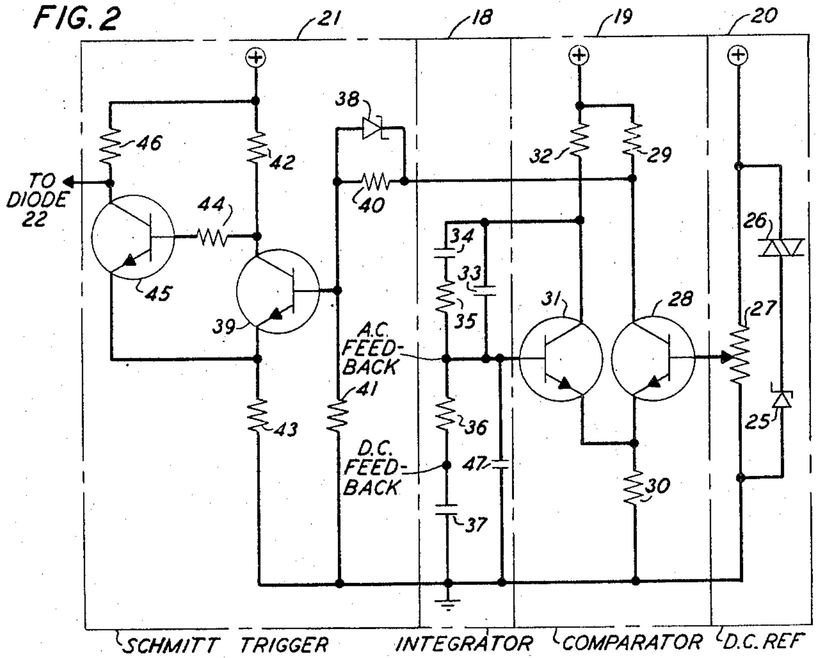


FIG. 2



INVENTOR
T. C. GOODENOW
BY John P. McDonnell
ATTORNEY

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SWITCHING VOLTAGE REGULATOR

Theodore C. Goodenow, Oceanport, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

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ABSTRACT OF THE DISCLOSURE

A switching voltage regulator wherein an inductor is alternately connected between the input source and the base electrode of the regulating transistor in accordance with load voltage variations to switch the regulating transistor in a substantially power lossless manner without the need for resistors in the regulating path.

This invention relates to switching regulators and more particularly to voltage regulators capable of high switching speeds.

The concept of serially connecting a semiconductor device as a load voltage variation controlled switch between an input source and a load to provide voltage regulation is known to the regulating art. If there are no power consuming elements in the regulating path and the semiconductor regulating element, which may be a transistor, is switched rapidly between the minimal power loss states of saturation and cutoff, high efficiency regulation will be obtained. Either the presence of power consuming elements, such as transistor biasing resistors, in the regulating path or relatively long regulating transistor switching times (i.e., the time required to switch the transistor between the states of saturation and cutoff during which the transistor acts as a power consuming impedance) will, however, appreciably lower the efficiency of regulation. Lengthy switching times also imply lower switching frequencies and physically large filtering components, the latter of which considerably increase the size of the overall circuit.

The relatively lengthy switching times of the switching devices of the prior art have both limited the efficiency and increased the physical size of switching regulators. In regulators employing only transistors of a single conductivity type, the efficiency of regulation has been reduced even further by the need for resistors in the regulating path to adjust the potentials appearing at the electrodes of the regulating transistor so that the regulating transistor may be biased into saturation.

The need for these potential adjusting resistors is easily seen once it is remembered that in the usual voltage regulator configuration the regulating transistor is serially connected between the input source and the load and, at a point close to transistor saturation, the collector and emitter electrodes of the regulating transistor will be at a potential essentially that of the input source. The input source potential is, however, normally the highest potential available to the regulator, and since the potential at the base electrode of the regulating transistor must exceed the potential at the emitter electrode before the transistor can be biased fully into saturation, the insertion of a resistor in the series regulating path is necessary to lower the potential at the collector and emitter electrodes to a value less than the source potential. The resistors in the regulating path thus permit the application of a potential higher than the collector-emitter potential, such as the potential of the source, to the base electrode of the regulating transistor so that this transistor may be driven into saturation. As noted, however, a resistor in the regulating path consumes power and lowers the efficiency of the circuit. Although it has been possible to use opposite conductivity type transistors for the regulating and driving transistors to eliminate this need for resistors in the regulating path, this is not always desirable in applications where the use of a single conductivity type of transistor is desired.

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It is, therefore, an object of the invention to provide a switching voltage regulator employing only transistors of a single conductivity type which does not require resistors in the regulating path.

It is another object of the invention to increase the switching frequency and efficiency, while decreasing the physical size, of switching voltage regulators.

The present invention employs an energy storage inductor that is alternately connected, under the control of load voltage variations, with the input source and the base electrode of the regulating transistor to step-up the voltage at the base electrode of the regulating transistor to a magnitude greater than the potential of the input source. The increased base voltage quickly biases the regulating transistor fully into saturation to reduce the regulating transistor switching time and eliminate the need for resistors in the regulating path. To accomplish this voltage step-up, energy is supplied to the inductor through a charging path transistor from the input source at intervals controlled by the difference between the sum of an A.C. and D.C. feedback signal and a reference signal. Once the charging path is opened, a driving network transistor is switched into conduction by the energy stored in the inductor and the regulating transistor is quickly, and hence efficiently, biased into saturation. In the succeeding interval, the charging path is again completed, the driving transistor is switched out of conduction, and the regulating transistor, which no longer has any base drive supplied thereto, is cut-off. The elimination of the need for resistors in the regulating path permits the design of a highly efficient voltage switching regulator wherein all of the transistors are of a single conductivity type. As discussed heretofore, the reduction in the switching time of the regulating transistor increases the efficiency of regulation and, additionally, permits higher switching frequencies and the circuit miniaturization advantages associated therewith.

Other objects and features of the present invention will become apparent upon consideration of the following detailed description when taken in connection with the accompanying drawing, in which:

FIG. 1 is a schematic diagram of an embodiment of the invention; and

FIG. 2 illustrates the circuitry of the feedback loop blocks shown in FIG. 1.

As can be seen from FIG. 1 of the drawing, an input d.c. source **1** is serially connected with the anode-cathode path of a diode **2**, the collector-emitter path of regulating transistor **3**, filter inductor **4**, and the load **5**. Current limiting and time constant control resistor **6** is serially connected with energy storage inductor **7** and the collector-emitter path of control transistor **8**. The anode-cathode path of diode **9** is connected from the collector electrode of transistor **8** to the base electrode of transistor **10**. The collector-emitter path of transistor **10** is serially connected from the positive terminal of the input source **1** to the base electrode of regulating transistor **3**. Resistor **12** connects the base electrode of transistor **10** to the base electrode of transistor **3** to improve the turn-off action of transistor **10**. Resistor **23** is connected across the base and emitter electrodes of regulating transistor **3** to improve the turn-off action of transistor **3**. Filter capacitor **14** is connected across the load **5**, and the anode-cathode path fly-back diode **15** is connected from the common ground terminal to the juncture of the emitter electrode of transistor **3** and filter inductor **4**. Resistor **16** and capacitor **17** are serially connected from the emitter electrode of transistor **3** to the first input of integrator 18 to provide an A.C. feedback path, while resistor 19 is connected between the positive load terminal and the second input of integrator 18 to provide a D.C. feedback path. The output of integrator 18 is fed to a comparator or differential amplifier 19. The comparator 19 compares the composite output of integrator 18 with the potential of the D.C. reference source 20 connected thereto. The output of comparator 19 in turn is fed to a Schmitt trigger 21 which, as discussed hereinafter, is designed to have predetermined lower and upper switching (hysteresis) limits. The anode-cathode path of bias level change diode 22 is connected from the output of the Schmitt trigger 21 to the base electrode of transistor 8.

The principles of switching regulation are, of course, well known to the art, as exemplified by the early thyratron switching regulators. Switching regulation may be obtained either by varying the switching frequency of the regulating element under the control of a load voltage variation responsive feedback loop or by varying the duty cycle of a constant frequency switching element, again under the control of a feedback loop. In a manner similar to both the foregoing methods, regulation may also be obtained by varying the ratio of the conducting to nonconducting interval of the switching element, with either the conducting or nonconducting interval remaining constant. This latter method of regulation thus varies both the "duty cycle" and the switching frequency, both of which again would be under the control of a feedback loop. As will be apparent from the following discussion, in circuits such as the present circuit, the parameters of the feedback loops may be chosen so as to provide one or the other of the noted methods of regulation.

The manner in which both A.C. and D.C. feedback loops are employed to provide switching regulation with a feedback loop comprising an integrator, a comparator, a reference voltage source, and a Schmitt trigger, is discussed in detail in the copending application of L. E. Gallaher and R. J. Redner, Serial No. 383,038, filed July 16, 1964. For present purposes, therefore, it appears sufficient to discuss the manner in which closed loop regulation is thus obtained only briefly.

Switching regulator transistor 3 is switched between saturation and cutoff under the control of the closed feedback loop to intermittently connect the source 1, through forward biased diode 2 and filter inductor 4, to the load 5. Capacitor 14 is a filter capacitor, while diode 15 performs the well known fly-back function by providing a path for the energy stored in filter inductor 4 to discharge through the load 5 when regulating transistor 3 is cut-off and thereby, in combination with filter capacitor 14, keeps the load voltage relatively constant. A variation in load voltage, due to either a load transient or change in load condition, will be transmitted as a d.c. feedback voltage through resistor 19 to the input of integrator 18. An A.C. signal, which is determined by the potential at the emitter electrode, and hence the relative state of conduction, of regulating transistor 3, will be transmitted via resistor 16 and blocking capacitor 17 as an A.C. feedback voltage, also to the input of integrator 18. Integrator 18, which is discussed in detail hereinafter in connection with FIG. 2, integrates or adds the A.C. and D.C. feedback signals and transmits a composite output signal to the comparator or differential amplifier 19, the latter of which is also discussed in detail hereinafter in connection with FIG. 2. The comparator 19 compares the signal from the integrator with a D.C. reference voltage 20. The difference between the composite feedback signal from the integrator 18 and the D.C. reference voltage 20 is then transmitted to the Schmitt trigger 21.

As is well known to the art, Schmitt triggers may be designed with a "window" or hysteresis, i.e., two distinctive switching potentials. In the case of a Schmitt trigger with n-p-n transistors, when the input signal falls to a magnitude less than the lower switching potential or limit of the trigger, the normally conductive input transistor

is biased into cutoff and the normally nonconductive output transistor is regeneratively biased into conduction. The output transistor will remain conductive until the normally conductive input transistor is again conductive. The input transistor, however, remains nonconductive until the input potential rises to the upper switching potential or limit, the magnitude of which is higher than the lower potential that initially caused the normally conductive input transistor to become nonconductive and start the regenerative cycle. The output wave form of Schmitt trigger 21, which controls the conduction through bias level changing diode 22, is taken from the normally nonconductive output transistor of the Schmitt trigger, as discussed in detail hereinafter in connection with FIG. 2, and is a square wave, the intervals of which are proportional to the time required for the input signal to the Schmitt trigger to rise to the upper switching potential after the input signal has fallen below the lower switching potential. Since the input signal to the Schmitt trigger is the difference between the sum of the A.C. and D.C. feedback signals and a reference potential, the output wave form of the Schmitt trigger is thus controlled by the feedback loop.

The feedback loop of the present switching voltage regulator differs from the feedback loop of the switching current regulator of the noted copending application in that it has been found preferable, for voltage regulation, to choose the parameters of the feedback loop so that the A.C. feedback is of magnitude sufficient to exert dominant control of the switching frequency, while the D.C. feedback varies the duration of the saturation and cutoff intervals of the regulating transistor. This mode of oepration differs from the frequency and "duty cycle" control method of regulation described in the noted copending application in that the D.C. feedback has a lesser effect on the switching frequency which in the present voltage regulator has been found to vary only slightly when supplying normal loads. Aside from this difference, the feedback loops of both regulating circuits function in substantially the same manner.

As noted heretofore, the output signals of Schmitt trigger 21 forward bias diode 22 and hence the base-emitter path of transistor 8 into conduction and saturation at intervals controlled by the feedback signals. When transistor 8 is switched into saturation, current flows from the positive terminal of the source 1 through resistor 6, inductor 7, the collector-emitter path of transistor 8, and back to the negative terminal of source 1. When the output signal from the Schmitt trigger 21 is such that diode 22 and transistor 8 are biased out of conduction, the inherent effect of the energy stored in inductor 7 is such as to attempt to sustain a current flow in the inductor of the same magnitude and direction as when transistor 8 was conducting. The potential induced by the collapsing flux in the inductor 7 to maintain this current flow is of the polarity shown on FIG. 1 of the drawing. As can be seen from the drawing, the polarity of this induced potential will forward bias diode 9 and the base-emitter paths of transistors 10 and 3 into conduction. In a preferred embodiment, the inductance of inductor 7 will be chosen so that a potential greater than the potential of the source 1 will be induced therein. Transistors 10 and 3 are thus normally biased quickly into saturation. Current will now flow in the bias network path from the positive terminal of the source 1, through the collector-emitter path of transistor 10, the base-emitter path of transistor 3, filter inductor 4, load 5, and back to the negative terminal of the source 1. This extra bias insures that the regulating transistor 3 is biased quickly into saturation. Resistor 23 improves the turn-off action of regulating transistor 3.

Diode 2 and filter inductor 4 absorb the difference between the source and load potentials during the intervals that transistor 3 is saturated and therefore permit transistor 3 to operate in the saturated condition. If the diode 2 and inductor 4 were not provided, the potentials in the loop would be such that the potential across the collector and emitter electrodes of transistor **3**, which is the difference between the source **1** and load **5** potentials, would be greater than the negligible potential across these electrodes at transistor saturation and hence restrict transistor **3** to operation in the variable impedance power wasting condition discussed heretofore.

Once regulating transistor **3** is biased into saturation, current will flow through the main power or regulating path from the positive terminal of source **1**, through forward biased diode **2**, the collector-emitter path of saturated transistor **3**, filter inductor **4**, the load **5**, and back to the negative terminal of the source **1**. Current will continue to flow in the regulating path through saturated transistor **3** until transistor **8** is again biased into saturation by Schmitt trigger **21** which, it will be remembered, is under control of the difference between the sum of the A.C. and D.C. feedback signals and a D.C. reference potential. Closed loop feedback regulation is thus obtained. Conduction through the collector-emitter path of transistor **8** causes a potential, of a polarity opposite to the polarity of the potential shown on the drawing, to appear across inductor **7**, thus removing all the forward conduction bias from transistors **3** and **10** and diode **9**. Transistors **3** and **10** will thus be cut off.

The function of the network comprising resistors **6** and **12**, inductor **7**, diode **9**, and transistor **10** should now be apparent. If the potential supplied by inductor **7** were not provided, then the highest possible potential available in the circuit for application to the base electrode of regulating transistor **3** would be that of the source **1**. To bias transistor **3** into saturation, however, the potential at the base electrode must be higher than the potential at the emitter electrode. At a point close to saturation, the emitter potential in the present circuit is essentially the potential of the collector or the source potential. A potential higher than the source or collector potential must therefore be applied to the base electrode of transistor **3** if this latter transistor is to be biased into saturation. The network noted, which comprises transistor **10** and inductor **7**, supplies a saturation bias potential higher than the source potential to the base electrode of regulating transistor **3** and thus makes the design of a switching voltage regulator using only transistors of a single conductivity type possible.

The efficiency, small size, and high switching speeds of the circuit of FIG. 1 should not be overlooked. The lack of large impedance elements in the regulating path, and the fact that the regulating transistor **3** when conductive is operated only in the saturated mode, eliminates power losses in the regulating path and significantly increases the efficiency of regulation. Another important advantage of the present regulator is found in the high switching speed capability provided by the network comprising transistor **10** and inductor **7** which drives the transistor sharply from cutoff into saturation and vice versa at precise feedback controlled intervals. Higher switching speed capability in turn implies a reduction in the physical size of the filtering components, and hence of the over-all circuit, as discussed heretofore. The minimal transistor switching times obtained with the present regulator reduces the time heretofore thought to be required to switch the transistor between the states of saturation and cutoff, during which the transistor acts as a power consuming impedance, and increases the efficiency of regulation still further.

The circuit "blocks" in the dotted rectangle of FIG. 1 are shown in detail in FIG. 2. In FIG. 2, a Zener diode **25** is serially connected with a varistor **26** in the inverse direction from a source of positive potential to the common ground terminal. A potentiometer **27** is connected across the Zener diode **23** and the varistor **26**. The base electrode of the first transistor **28** of the comparator or differential amplifier **19** is connected to the wiper arm of potentiometer **27**. The collector-emitter path of transistor **28** is serially connected with collector load resistor **29** and common emitter resistor **30** between a source of positive potential and the common ground terminal. The collector-emitter path of the second transistor **31** of the comparator **19** is serially connected with collector load resistor **32** and common emitter resistor **30** between the source of positive potential and the common ground terminal. Capacitor **33** of integrator **18** is connected across the base and collector electrodes of transistor **31** of the comparator **19**. Capacitor **34** and resistor **35**, also of integrator **18**, are serially connected across capacitor **33**. Resistor **36** and capacitor **37** are serially connected from the base electrode of transistor **31** to the common ground terminal. Capacitor **47** of integrator **18** is also connected from the base electrode of transistor **31** to the common ground terminal. The A.C. feedback is applied directly to the base electrode of transistor **31**, while the D.C. feedback is applied through resistor **36** to the base electrode of transistor **31**.

Zener diode **38** is serially connected in the inverse direction from the output of the comparator **19**, appearing at the collector electrode of transistor **28**, to the base electrode of the input transistor **39** of the Schmitt trigger **21**, as a voltage level shift. Resistor **40** is connected across Zener diode **38**. Bias control resistor **41** is connected from the base electrode of the input transistor of the Schmitt trigger **21** to the common ground terminal. The collector-emitter path of transistor **39** is serially connected with collector resistor **42** and common emitter resistor **43** from a source of positive potential to the common ground terminal. Coupling resistor **44** connects the collector electrode of the first transistor **39** of the Schmitt trigger **21** to the base electrode of the output transistor **45** of the Schmitt trigger **21**. The collector-emitter path of the second or output transistor of the Schmitt trigger is serially connected with collector resistor **46** and common emitter resistor **43** between a source of positive potential and the common ground terminal. The output of the Schmitt trigger **21** is taken from the collector electrode of transistor **45** to intermittently forward bias diode **22**, as discussed heretofore.

As discussed in a general manner heretofore, a predetermined portion of the constant potential appearing across Zener diode **25** and varistor **26** is sampled by potentiometer **27** and fed, via the wiper arm of potentiometer **27**, to the base electrode of comparator transistor **28**. A D.C. reference potential is thus established at the base electrode of transistor **28**. Varistor **26** insures that the voltage appearing across the end terminals of potentiometer **27** is constant, regardless of changes in environment temperature. As also noted in connection with FIG. 1, the A.C. and D.C. feedbacks are fed into the RC integrating network **19**, which comprises resistors **35** and **36** and capacitors **33**, **34**, **37**, and **47**. The integral or sum of these feedback signals is then fed into the base of transistor **31** to increase or decrease the conductivity of this transistor depending upon the magnitude of the composite feedback signal. Altering the conductivity of transistor **31** in turn varies the current flow through common emitter resistor **30** and produces a change in the potential at the emitter electrode of transistor **28**. Since the reference potential at the base electrode of transistor **28** is constant and provides a forward bias to transistor **28**, whereas the potential across the resistor **30** tends to back-bias the transistor **28** (to varying degrees, depending upon the magnitude of the composite feedback signals), a potential difference representative of the difference betwen a constant reference potential and the composite feedback signal appears at the collector electrode of transistor **28**. The level of this signal is shifted by the shunt network of Zener diode **38** and resistor **40** to a more desirable operating level for application to the base electrode of input transistor **39** of Schmitt trigger **21**.

As discussed heretofore, difference signals below the predetermined lower switching limit of the Schmitt trigger will cause normally conductive input transistor **39** of the Schmitt trigger to become nonconductive and, due to the regenerative coupling of resistor **44** to the base electrode of transistor **45**, normally nonconductive output transistor **45** of the Schmitt trigger to become conductive. Resistors **41**, **42**, **43**, **44**, and **46** are chosen so that output transistor **45** will thus remain conductive until the difference signal input at the base electrode of input transistor **39** rises above an upper switching limit, a second predetermined potential higher than the first predetermined potential of the lower switching limit. When this latter potential is reached, due to an increase in the difference potential appearing at the base electrode of input transistor **39**, transistor **39** will revert to its normally conductive state and output transistor **45** will also revert to its normally nonconductive condition. As noted heretofore, the signal at the collector electrode of output transistor **45** of the Schmitt trigger **21** is transmitted to diode **22** to control the forward conduction through this diode.

The manner in which load voltage variations in a regulator with A.C. and D.C. feedback control the switching frequency of the regulating transistor is, as noted heretofore, discussed in detail in the copending patent application. As also noted, the parameters of the control circuitry of the present invention are chosen such that the A.C. feedback substantially controls the switching frequency at a constant rate while the D.C. feedback varies the duration of the saturation and cutoff intervals of the regulating transistor. Aside from this difference, the feedback circuitry in the dotted rectangle of FIG. 1 operates in a manner substantially identical to the comparable circuitry of the noted copending application.

Again, it should be noted that all the control and regulating circuitry of the present invention uses only n-p-n transistors and other inexpensive circuit elements to obtain the advantages of higher switching speeds, higher efficiency, and relatively small physical size, at a surprisingly low over-all circuit cost.

The above described arrangement is illustrative of the principles of the invention. Other embodiments may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A switching voltage regulator comprising a source of unregulated potential, a load, a regulating transistor having base, collector, and emitter electrodes, means serially connecting the emitter and collector electrodes of said regulating transistor between said source and said load in a substantially lossless regulating path, a detector connected to a source of reference voltage and said load to be responsive to variations of load voltage from said reference voltage and thereby provide a signal representative of the magnitude of said variations, voltage step-up means, and means connected to said detector, said voltage step-up means, and the base electrode of said regulating transistor for intermittently connecting said voltage step-up means to the base electrode of said regulating transistor under the control of the signal from said detector, whereby the regulating transistor is switched in a substantially lossless manner between cutoff and saturation in accordance with load voltage variations.

2. A switching voltage regulator comprising a source of unregulated potential, a load, a regulating transistor having base, collector, and emitter electrodes, means serially connecting the collector and emitter electrodes of said regulating transistor between said source and said load in a substantially lossless regulating path, a detector connected to a source of reference voltage and said load to be responsive to variations of load voltage from said reference voltage and thereby provide a signal representative of the magnitude of said load voltage variations, energy storage means, and switching means connected to said detector, said energy storage means, and the base electrode of said regulating transistor to alternately connect said energy storage means with said source for one interval and with the base electrode of said regulating transistor for the succeeding interval so that energy stored in said energy storage means during said one interval is applied to said regulating transistor during said succeeding interval to switch said regulating transistor rapidly between cutoff and saturation at intervals proportional to the variations of load voltage from said reference voltage.

3. A switching voltage regulator comprising an input source of unregulated potential, a load, a regulating transistor having base, collector, and emitter electrodes, means serially connecting the collector and emitter electrodes of said regulating transistor with said input source and said load in a substantially lossless regulating path, a source of reference voltage, a detector connected to said load and source of reference voltage to compare variations of the voltage across said load with said reference voltage and thereby provide a signal representative of the magnitude of said variations, energy storage means, charging path means connected to said detector to switch the conductivity state of said charging path means in response to signals from said detector, means connecting said input source, said charging path means, and said energy storage means to intermittently transmit energy from said source to said energy storage means through said charging path means during the conductive intervals of said charging path means, and a driving network connected between said energy storage means and the base electrode of said regulating transistor to apply the potential stored in said energy storage means to the base electrode of said regulating transistor during the nonconductive intervals of said charging path means, whereby said regulating transistor is switched in a substantially lossless manner between cutoff and saturation.

4. A switching voltage regulator comprising a source of unregulated potential, a load, regulating and charging path transistors, each of said transistors being of a single conductivity type and having base, collector, and emitter electrodes, means connecting the collector electrode of said regulating transistor to one terminal of said input source, means connecting the emitter electrode of said regulating transistor to one terminal of said load, means connecting the remaining terminal of said source to the remaining terminal of said load, a source of reference voltage, a detector connected to said load and said source of reference voltage to compare variations of voltage across said load with said reference voltage and thereby provide a signal representative of the magnitude of said variations, means connecting the base electrode of said charging path transistor to said detector to switch the conductivity state of said charging path transistor in response to the signal from said detector, energy storage means, means serially connecting said input source, said energy storage means, and the collector and emitter electrodes of said charging path transistor to transmit energy from said source to said energy storage means during the conductive intervals of said charging path transistor, and a driving network connected between said energy storage means and the base electrode of the said regulating transistor to drive said regulating transistor with the energy stored in said energy storage means during the nonconductive intervals of said charging path transistor so that the regulating transistor is driven rapidly between cutoff and saturation to increase the efficiency of regulation.

5. A switching voltage regulator comprising an input source of unregulated potential, a load, energy storage means, n-p-n regulating, charging path, and driving transistors, each of said transistors having base, collector, and emitter electrodes, means serially connecting said input source, the collector and emitter electrodes of said regulating transistor, and said load, a source of reference voltage, a detector connected to said load and said source of reference voltage to compare variations of the voltage across said load with said reference voltage to thereby provide a signal representative of the magnitude of said variations, means connecting the base and emitter electrodes of said charging path transistor to said detector to switch conductivity through the collector-emitter path of said charging path transistor in response to the signal from said detector, means serially connecting said input source, said energy storage means, and collector and emitter electrodes of said charging path transistor to transmit energy from said input source to said energy storage means during the conductive interval of said charging path transistor, means connecting the base electrode of said driving transistor to said energy storage means to initiate conductivity through the collector-emitter path of said driving transistor at intervals alternate to the conductive intervals of said charging path transistor, means connecting the collector electrode of said driving transistor to the collector electrode of said regulating transistor, and means connecting the emitter electrode of said driving transistor to the base electrode of said regulating transistor, whereby said regulating transistor is intermittently switched between cutoff and saturation by the potential stored in said energy storage means.

6. A switching voltage regulator comprising an input source of unregulated potential, a load, an inductor, a semiconductor diode, n-p-n regulating, charging path, and driving transistors, each of said transistors having base, collector, and emitter electrodes, means serially connecting said input source, said diode in the forward conductivity direction, the collector and emitter electrodes of said regulating transistor, and said load, a source of reference voltage, a detector connected to said load and said source of reference voltage to compare variations of the voltage across said load with said reference voltage and thereby provide a signal representative of the magni-

tude of said variations, means connecting the base and emitter electrodes of said charging path transistor to said detector to switch the conductivity through the collector-emitter path of said charging path transistor in response to the signal from said detector, means serially connecting said input source, said inductor, and the collector and emitter electrodes of said charging path transistor to transmit energy from said source to said energy storage means during the conductive interval of said charging path transistor, means connecting the base electrode of said driving transistor to the juncture of said inductor and the collector electrode of said charging path transistor to initiate conductivity through the collector-emitter path of said driving transistor at intervals alternate to the conductive intervals of said charging path transistor, means connecting the collector electrode of said driving transistor to the juncture of said diode and the collector electrode of said regulating transistor, and means connecting the emitter electrode of said driving transistor to the base electrode of said regulating transistor, whereby said regulating transistor is intermittently switched between cutoff and saturation by the energy stored in said inductor.

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JOHN F. COUCH, *Primary Examiner.*

M. L. WACHTELL, H. HUBERFELD, *Assistant Examiners.*