CURRENT LIMITED TRANSISTOR SWITCH

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FIG. 1.

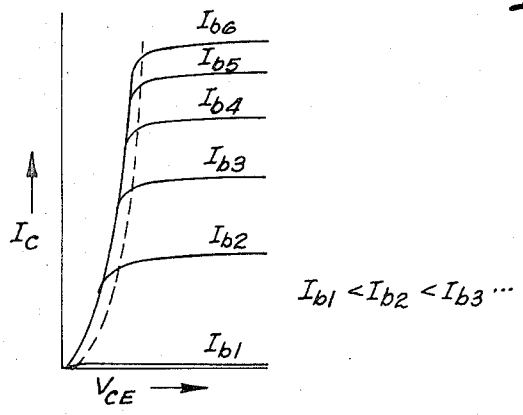


FIG. 15.

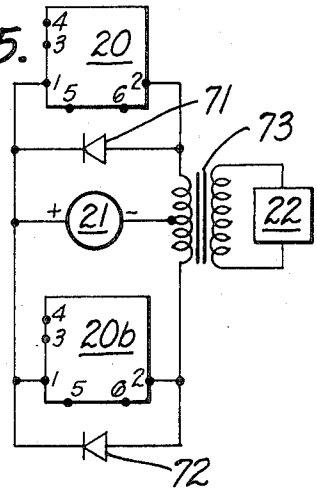


FIG. 2.

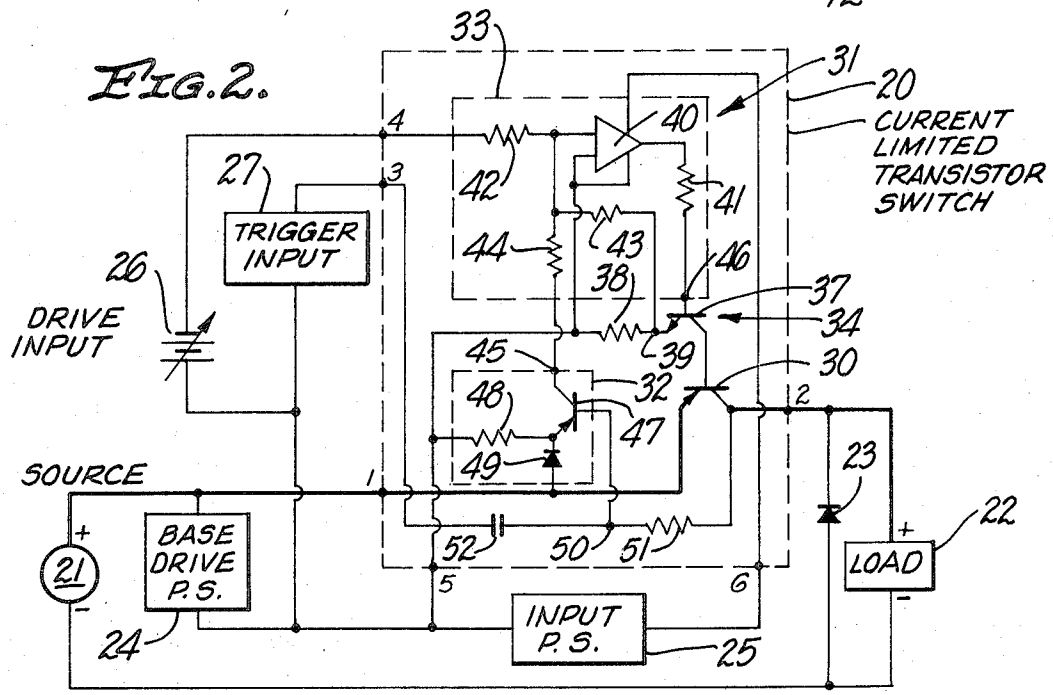


FIG. 16.

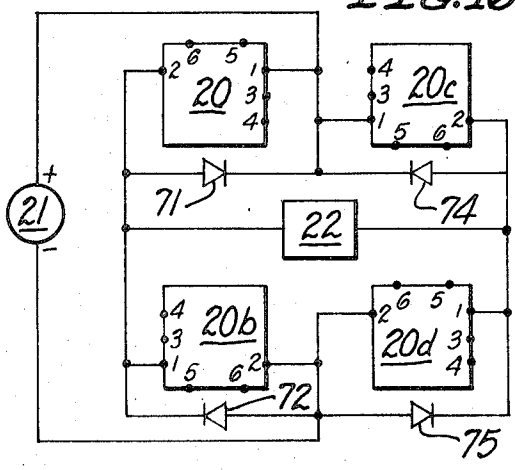
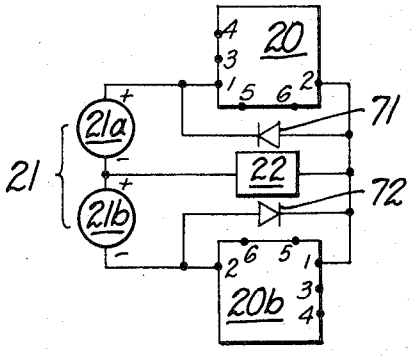


FIG. 17.



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FIG. 3.

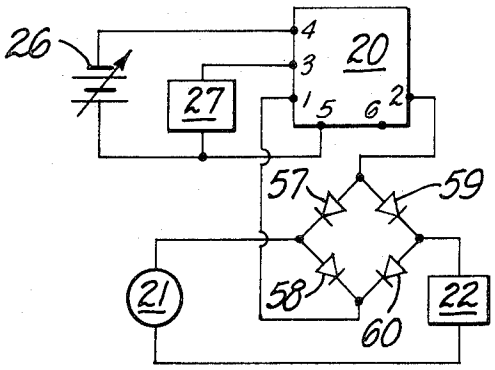


FIG. 4.

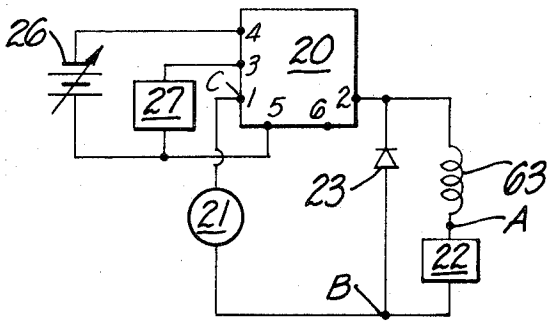


FIG. 5a.

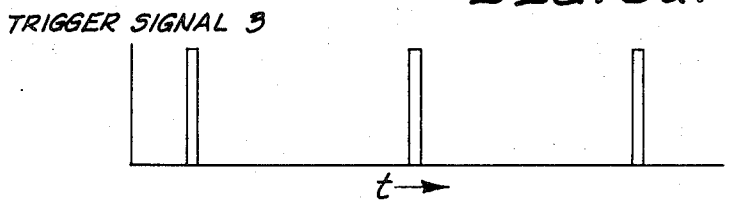


FIG. 5b.

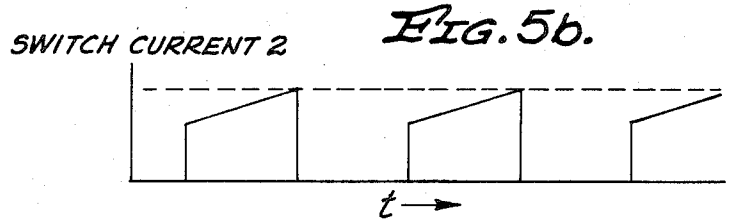


FIG. 5c.

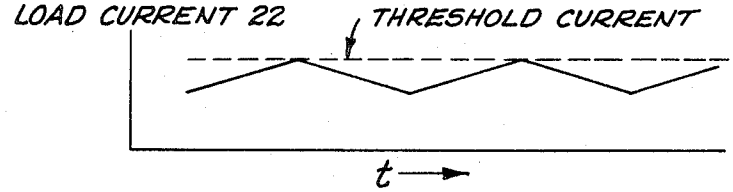


FIG. 6.

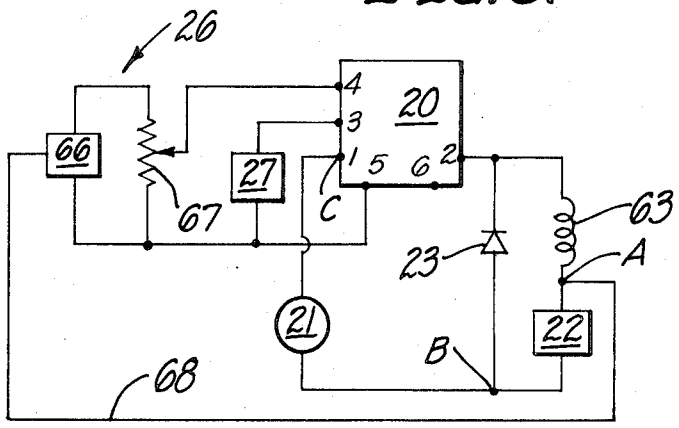


FIG. 7a.

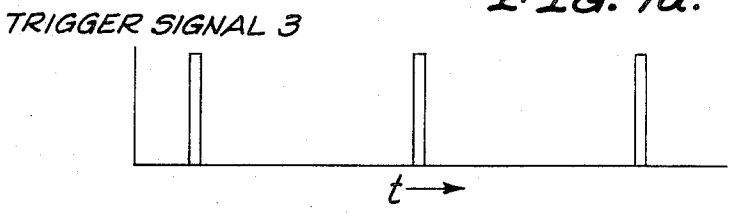


FIG. 7b.

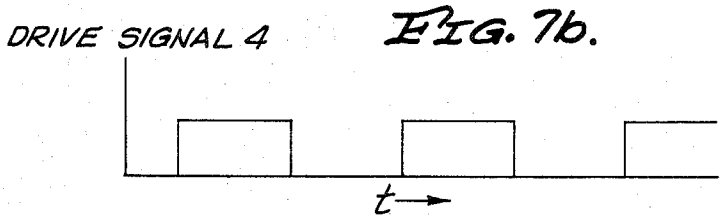


FIG. 7c.

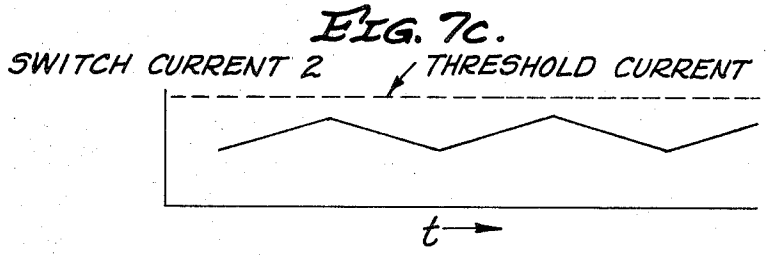


FIG. 8.

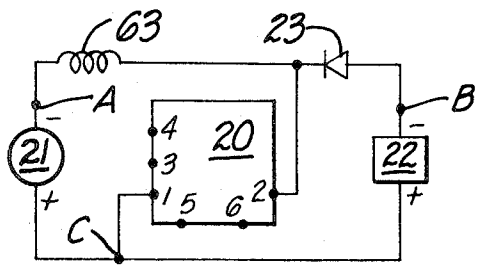


FIG. 9.

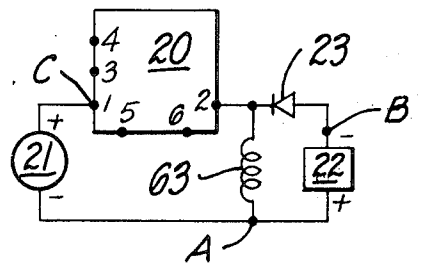
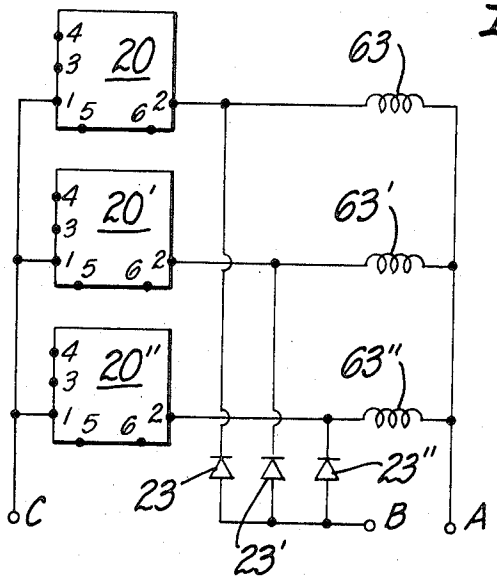


FIG. 10.



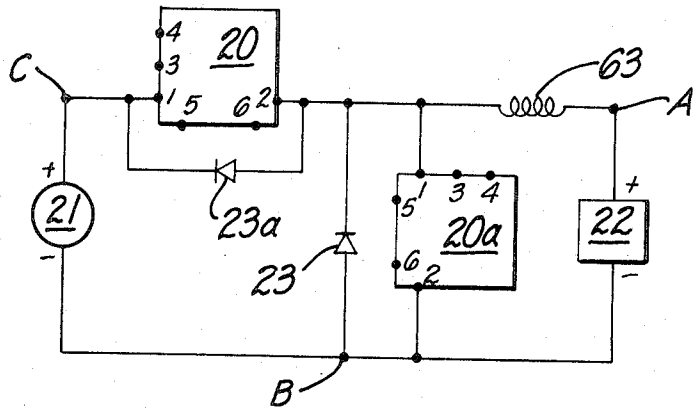
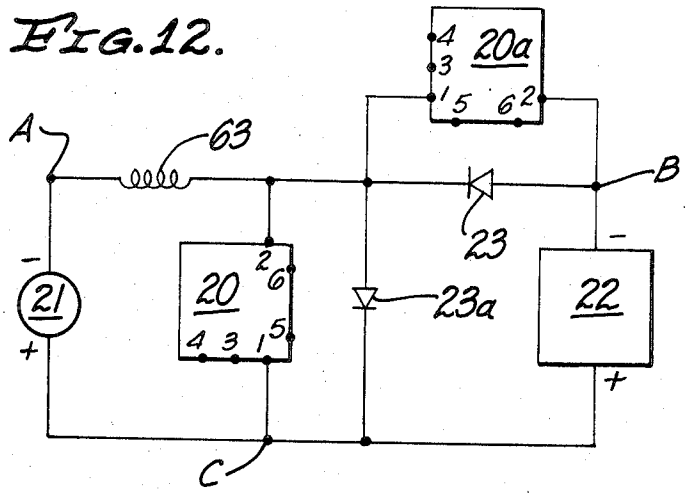


FIG. 11.

FIG. 12.



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FIG. 13.

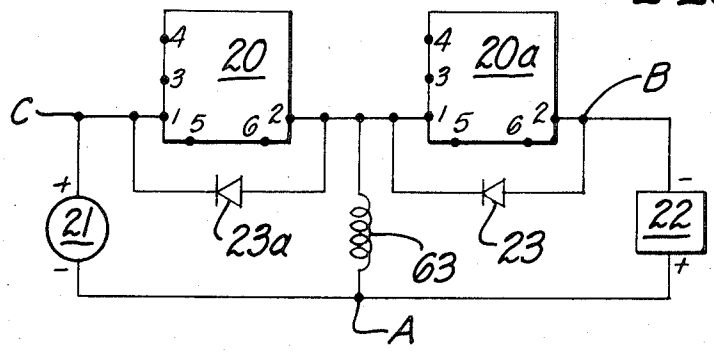
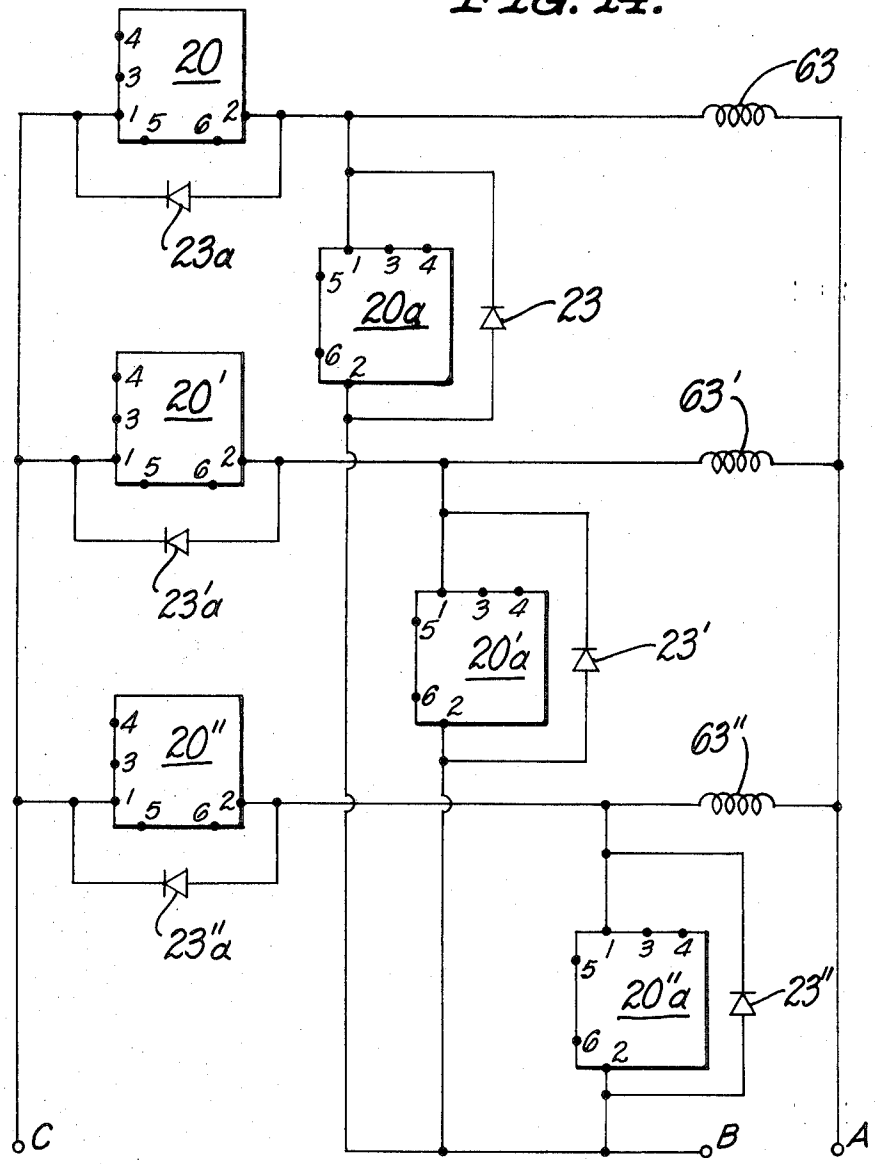


FIG. 14.



United States Patent Office 3,721,836 Patented Mar. 20, 1973

3,721,836

CURRENT LIMITED TRANSISTOR SWITCH

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Filed Nov. 24, 1971, Ser. No. 201,671
Int. Cl. H03k 17/60
U.S. Cl. 307—253 22 Claims

ABSTRACT OF THE DISCLOSURE

A current limited transistor switch providing switching action between a source and a load in response to turn-on and turn-off signals, and providing current threshold sensing for automatic switching to the off condition when desaturation occurs. Choppers, inverters and circuit breakers incorporating a current limited transistor switch.

BACKGROUND OF THE INVENTION

This invention relates to a new and improved transistor switching circuit and to choppers, regulators, inverters, circuit breakers and the like incorporating transistor switching circuits. The invention is particularly directed to a new and improved current limited transistor switch which can be turned on and off as desired and which always conducts in the saturation condition and which will automatically turn off if a desaturation condition develops.

A transistor is a three terminal solid-state device, the collector terminal current (I_c) of which is a joint function of the base terminal current (I_b) and the voltage between the collector and emitter terminals (V_{ce}) (see FIG. 1).

A line V' divides the base current characteristic curves into two operating regions. The area to the right of this line is referred to as the active region, while area enclosed between the line and the I_c axis is referred to as the saturated region. The distance between V' and the I_c axis is called the collector to emitter saturation voltage ($V_{ce\ sat}$), and is a function of I_c. Typical values of V_{ce} range between .05 volt and 1.5 volts.

In cases where the transistor is to be used as a linear or semi-linear amplifier, the active region characteristics are of importance. Conversely, in digital and power control applications, where the transistor is to perform an on-off or switching action, the saturated region characteristics are of prime importance, since they correspond to the on-state of the transistor. The off-state, it will be noted, is attained by simply making $I_b=0$. The transistor may be used as a current-controlled switch, where switching action takes place between the emitter and collector terminals, and is controlled by action of the base terminal current.

When operating the transistor in the on-state, a sufficiently large value of I_b must be present to insure saturation ($V_{ce}<V_{ce\ sat}$). Accordingly, for a given value of base current, collector current must not exceed a certain critical limit, lest the transistor desaturate.

There exist a large spectrum of applications where transistors are used in the switching modes. Switching applications may further be divided into two sub-classes, namely digital signal processing and power control applications. With signal processing, transistor current and power levels are generally small compared to maximum ratings and accordingly, there is little concern about energy factors such as second breakdown, thermal runaway, excessive junction heating and the like.

Conversely, in power control applications, the story is quite different and the above factors become most vital. For example, in many chopper and inverter applications, should the collector current become larger than a certain level, desaturation will occur and within a few milliseconds, the transistor will be thermally destroyed.

In recent years, due mainly to advances in transistor fabrication techniques, a tremendous number of power control applications have come into practice where power transistors are used as switches. For example, in the data processing industry, power transistors are used in the switching mode to turn on and off display lights and to activate solenoid drivers used in printers and key punches. In the instrumentation area, power transistors, operated in the switching mode, are used for all sorts of voltage and current regulated power supplies. In areas where portable A.C. power is required, switching mode transistor circuits convert D.C. from batteries to A.C. at a desired frequency. And, in a wide variety of applications, ranging from portable electric hand tools to electrically driven vehicles, transistors, used in the switching mode, chop the battery power for efficient control of energy flow from the battery to the electric motor. Other applications where transistors are operated in the switching mode to effect power control include bidirectional choppers, controlled rectifier arrays, cyclo-inverters, cyclo-choppers, crowbars, and electronic circuit breakers.

In virtually all of the above power applications, three problems arise. On one hand, should the switching currents, even momentarily, exceed a certain critical limit, full turn-on of the switching transistor will not be achieved which in turn will result in both a loss of energy conversion efficiency and increased transistor dissipation, the latter of which is generally destructive to the switching transistor.

The second problem is a result of the remedy to the first problem. In an attempt to insure full saturation under worse case conditions, base drive currents considerably in excess of those actually required are supplied. Since all of the energy delivered to the base-emitter junction ends up as heat on the junction, it follows that the above practice represents a lower than optimal efficiency state, especially since in most cases, this same high base drive current is used even when the switching currents may be relatively small.

Problem three is that when a fault condition occurs, a combination of desaturation and high current conditions will prevail which will inevitably cause rapid thermal destruction of the switching transistor.

In various applications, such as inverters and chopper regulators, protection schemes have been devised which either directly or indirectly remove base drive in the event that load current exceeds a predetermined value. Most of these schemes, however, employ complicated feedback circuits which increase size, weight and cost of the system. Furthermore, in all but the most complex schemes, base drive is set at a fixed level which results in higher than needed base-emitter power losses, especially during other than full load operation.

SUMMARY OF THE INVENTION

The current limited transistor switch includes a switching transistor connected between source and load terminals and a drive control circuit for the base current. A current threshold level is maintained by the drive control circuit which maintains conduction in the switching transistor in the saturation condition. If the transistor starts to desaturate, feedback through an on-off control circuit gates the base current off. Base current is gated on by a turn-on trigger pulse and the switching transistor remains on if conducting in the saturation condition.

The switch performs a function similar to conventional circuits where a transistor is used as a unidirectional switch, but with several features of improvement. Turn-on action is initiated by a trigger input. A high speed turn-off action automatically results when current through the switching transistor becomes larger than a

threshold level, which in turn is proportionate to a voltage supplied by a drive input.

As a result of the above features, the switch of the invention offers both fail-safe protection to the power switching transistor, while also providing current-controlled behavior when used in applications such as chopper regulators. The switch is universal in nature, and may be used in a variety of equipments, including chopper regulators, D.C. to A.C. inverters, controlled rectifier arrays, cyclo-inverters, cyclo-choppers, electronic circuit breakers, and the like.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a set of typical transistor characteristic curves;

FIG. 2 is a diagram of a switching apparatus incorporating a presently preferred embodiment of the invention;

FIG. 3 is a diagram of an A.C. switch or circuit breaker incorporating the switch of FIG. 2.

FIG. 4 is a diagram of a current regulating D.C. chopper incorporating the switch of FIG. 2;

FIGS. *5a*, *5b* and *5c* are timing diagrams illustrating the operation of the chopper of FIG. 4;

FIG. 6 is a diagram of a voltage and current regulating D.C. chopper incorporating the switch of FIG. 2;

FIGS. *7a*, *7b*, and *7c* are timing diagrams illustrating the operation of the chopper of FIG. 6;

FIG. 8 is a diagram of a voltage boosting chopper similar to that of FIG. 4;

FIG. 9 is a diagram of a voltage changing chopper similar to those of FIGS. 4 and 8;

FIG. 10 is a diagram of a current regulating poly D.C. chopper incorporating the switch of FIG. 2;

FIGS. 11, 12 and 13 are diagrams of three variations of bidirectional choppers incorporating the switch of FIG. 2;

FIG. 14 is a diagram of a bidirectional poly chopper similar to those of FIGS. 10, 11, 12 and 13; and

FIGS. 15, 16 and 17 are diagrams of three variations of inverters incorporating the switch of FIG. 2.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The circuit of FIG. 2 includes a current limited transistor switch **20** connected between a source **21** and a load **22**, with a diode **23** connected across the load. The circuit also includes a base drive power supply **24**, an input power supply **25**, a drive input voltage source **26**, and a trigger input or turn-on pulse source **27**.

The base drive power supply **24** is connected between a source terminal **1** and a base drive terminal **5** of the switch **20**. The input power supply **26** is connected between a terminal **6** and the base drive terminal **5**. The drive input voltage source **26** is connected between a drive input terminal **4** and the terminal **5**, and the trigger input is connected between a turn-on pulse terminal **3** and the terminal **5**. The source **21** is connected to the source terminal **1** and the load **22** is connected to a load terminal **2**.

The transistor switch **20** includes a switching transistor **30** with emitter and collector connected between the source terminal **1** and load terminal **2**. The transistor switch also includes a drive control circuit **31** and an on-off control circuit **32**. The drive control circuit **31** includes a threshold level unit **33** and a current control unit **34**.

In the preferred embodiment illustrated, the current control unit **34** includes a transistor **37** connected in series with a resistor **38** between the base of the switching transistor **30** and the base drive terminal **5**.

The preferred threshold level unit **33** as illustrated in FIG. 2 includes an operational amplifier **40** with its output connected through a resistor **41** to the base of the current control unit transistor **37**. The drive input terminal **4** is connected as an input to the amplifier **40** through resistor **42**. A resistor **43** is connected between the input of the amplifier **40** and the junction between the transistor **37** and resistor **38** to provide another input to the amplifier. The on-off control circuit **32** is connected as an input to the amplifier **40** through a resistor **44**.

The preferred form of the on-off control circuit **32** includes a transistor **47** with emitter connected to the base drive terminal **5** through a resistor **48** and with the emitter connected to the source terminal **1** through a diode **49**. The collector of the transistor **47** is connected to the resistor **44** and the base is connected to a junction point **50**.

A resistor **51** is connected between the switching transistor **30** and a junction point **50**, to provide a turn-off signal as will be described below. A capacitor **52** is connected between the turn-on pulse terminal **3** and the junction point **50** for transmitting a turn-on pulse, as will be described below.

While specific polarities for voltages, transistors and diodes have been indicated in the circuit of FIG. 2, it will be readily understood that those skilled in the art may change polarities as desired.

The base drive supply **24** supplies base drive requirements for the switching transistor **30**. For typical operation, power supply **24** runs as a constant voltage source on the order of 2 to 4 volts. The input power supply **25** supplies operating power to the operational amplifier **40**. In the case of a monopolar operational amplifier, as shown in FIG. 2, a monopolar power supply is used. If desired, a bipolar operational amplifier may be used, in which case a suitable bipolar power supply is used. In either case, the power supply **25** supplies constant voltage(s), the actual value(s) of which depend on the operational amplifier. With supplies **24** and **25** energized, terminals **1** and **2** will be nonconductive, until the proper voltages have been applied between terminal pairs **3**, **5** and **4**, **5**.

In order to cause turn-on action between terminals **1** and **2**, two conditions must prevail. First, a non-zero, unidirectional voltage of the correct polarity, which may be constant or time varying, must be applied between drive input terminal **4** and common or base drive terminal **5**. Next, a trigger pulse of the correct polarity, duration and magnitude must be supplied between turn-on pulse terminal **3** and terminal **5**.

During the time of the trigger pulse, current will flow between terminals **1** and **2**, the magnitude of which is either limited by the load, or is limited by action of the switching transistor, in which case, the current is approximately proportionate to the instantaneous value of the drive voltage between terminals **4** and **5**.

Upon completion of the trigger pulse, terminals **1** and **2** will remain in a mutually conductive state if and only if saturation of the switching transistor was achieved during the time of the trigger pulse. If the switching transistor failed to saturate during the time of the trigger pulse, the circuit will automatically revert to the off-state and erminals **1** and **2** will be mutually non-conductive, following the trigger pulse.

Should the case prevail where the switching transistor attains saturation during the trigger pulse, terminals **1** and **2** will remain mutually conductive until the current through terminals **1** and **2** exceeds a certain threshold which, in turn, is approximately proportionate to the instantaneous voltage between terminals **4** and **5**—at which time, the switching transistor will be rapidly turned off. The drive input voltage at terminal **4** may be reduced to effect turn-off.

A second mode of turn-off is also possible. If a voltage pulse of sufficient magnitude and of the correct polarity (reverse polarity of turn-on pulse) is applied between terminals **3** and **5**, turn-off will subsequently follow and terminals **1** and **2** will revert to the non-conductive state.

The switching transistor **30** receives base drive current which is supplied by base drive supply **24** and is

controlled by action of driver transistor 37. Transistor 37 is in turn driven by the output of operational amplifier 40. Accordingly, when the output of amplifier 40 swings sufficiently positive, transistor 30 will be driven into saturation.

For the moment, assume that transistor 30 is in saturation (i.e., its collector to emitter voltage is less than 1 volt). Assuming that no current is caused to flow in terminal 3, it then follows that the base of silicon transistor 47 will be less than 1 volt negative with respect to the emitter of transistor 30. Next, we note that resistor 48 biases silicon diode 49 into forward conduction, making the emitter of transistor 47 about .7 volt with respect to the emitter of transistor 30. From these relations, it follows that the base-emitter junction of transistor 47 will be forward biased by no more than .3 volt. Hence transistor 47 will be non-conductive and no current will flow through resistor 44. Accordingly, the only currents that will effect the inverting input of amplifier 40 will be those through resistors 42 and 43.

Resistor 38 serves as a current sensing resistor by producing a voltage drop which is proportionate to the current through transistor 37. By action of resistors 42 and 43, amplifier 40 drives transistor 37 such that the current through resistor 38 (and hence the base current to transistor 30) is proportionate to the drive voltage applied between terminals 4 and 5.

If for any reason, transistor 30 desaturates and its collector to emitter voltage exceeds a certain amount (in this case about 1.3 to 1.4 volts), the base-emitter voltage of transistor 47 rises to the turn-on point thus causing collector current to flow through resistor 44. This collector current is of such direction that it opposes current flowing through resistor 42. In particular, if resistor 44 is sufficiently small compared with resistor 42, the resulting current through resistor 44 will completely turn off amplifier 40 thus causing transistors 37 and 30 to also turn off. It is therefore seen that base drive to the main switching transistor 30 is turned off by regenerative action when its collector to emitter voltage exceeds a certain threshold.

Once regenerative action has caused turn-off, transistor 30 will remain in the off state until a voltage pulse of the correct polarity is supplied between terminals 3 and 5. The application of such a pulse, causes momentary diversion of the base drive of transistor 47. As a result, transistor 47 switches off and remains off for the duration of the trigger pulse, during which time amplifier 40, in conjunction with transistor 37, causes a base drive to transistor 30 which is proportionate to the drive input voltage. If this base drive to transistor 30 is sufficiently large, transistor 30 will saturate during the time of the trigger pulse whereupon transistor 30 will continue to receive base drive upon termination of the trigger input pulse. If however, the base drive to transistor 30 is not sufficient to enable saturation, base drive to transistor 30 will be removed upon termination of the input trigger pulse.

It should be noted that for the duration of the trigger pulse, transistor 30, if unsaturated, will possibly dissipate a high level of power—perhaps many times its continuous rating capability. It is important therefore that the duration of the trigger pulse be kept sufficiently short so that the thermal capacity of the junction of transistor 30 can absorb the resulting thermal energy without excessive heating. It should also be noted that the duration of the trigger signal must be somewhat longer than the turn-on time of transistor 30. These two considerations give respective upper and lower bounds for the duration of the trigger signal. For most present day silicon switching transistors, having turn-on times of only a few microseconds, it turns out that trigger pulse durations of around 10 microseconds provide both reliable turn-on and at the same time are sufficiently short to guarantee low values of junction heating, even under conditions of fault currents and maximum base drive levels.

One of the key features of the disclosure that should be noted is that switching transistor 30 is used in both a conventional as well as unconventional way. The switching action it effects is conventional. The current sensing function it provides, however, is unconventional. In essence, transistor 30 is used as a current sensor or more accurately as a current-threshold sensor. For a given level of base current, the collector to emitter voltage remains small and nearly constant until a certain magnitude of collector current is reached (threshold current) at which time the collector to emitter voltage increases rapidly with increasing collector current. For a wide range of base currents, the above mentioned collector threshold current is nearly proportionate to the base drive current.

In a more generalized consideration, the threshold unit 33 may be a nonlinear, active circuit having a time dependent response. Input supply voltage is applied between terminals 6 and 5. The drive input is applied between terminals 4 and 5. The shunt voltage signal, which is proportionate to the base drive current of transistor 30, is applied between terminals 39 and 5. A gating signal, which when present, causes the output to be zero, regardless of other input signals, is applied between terminals 45 and 5. Finally, output of the unit 33 is between terminals 46 and 5. The above can be summarized mathematically as

$$i_{46}=f_1\ (V_4,\ V_{39},\ t) \text{ if } i_{45}\simeq 0$$

$$i_{46}=0 \text{ if } i_{45}>0$$

where i_j is the current through the j^{th} terminal and V_j is the voltage between terminal j and terminal 5.

The function f_1 is restricted to those cases where i_{46} is increasing with respect to V_4 and decreasing with respect to V_{39}. f_1 is also constrained such that the resulting circuit response will be stable.

In a more generalized consideration, the on-off control circuit 32 may be a circuit wherein the output current of which at terminal 45 is a nonlinear time dependent function of the collector to emitter voltage of the switching transistor 30. In summary,

$$i_{45}=f_2(V_{ce},\ t)$$

f_2 must be an increasing function with respect to V_{ce}.

By using various functions f_1 and f_2, various modified circuit responses may be achieved. For example, by adjusting the time dependence part of f_1, various base drive responses (stable and unstable) can be obtained from a given signal applied to the drive input. And, with respect to f_2, it is noted that by introducing nonlinearities (e.g. Schmitt trigger action) and time dependence where dV_{ce}/dt is taken into account, turn-off of transistor 30 may be initiated by more general features of the characteristic curves of transistor 30.

By way of summary of operation, the voltage signal at the drive input terminal 4 sets the current threshold level for the switching transistor 30 through the threshold level unit 33 and current control unit 34 of the drive control circuit 31. A feedback to the input is provided from terminal 39 through resistor 43.

The switching transistor 30 is turned on or switched into conduction by a turn-on pulse at terminal 3 which is coupled to the threshold level unit 33 by the on-off control circuit 32.

The switching transistor 30 may be turned off or switched to nonconduction in two ways. One is by means of a turn-off pulse at terminal 3. The other is by means of feedback from the transistor 30 to the on-off control circuit 32 through resistor 51. Turn-off occurs automatically when the switching transistor 30 desaturates. This may occur at any time during operation of the circuit and serves a safety function preventing damage to the transistor. This may be caused to occur by varying the drive input voltage at terminal 4.

Various apparatus incorporating the current limited transistor switch are possible and several embodiments are described hereinbelow.

ON-OFF D.C. SWITCH

In the circuit of FIG. 2, the current limited transistor switch **20** may be used as a voltage controlled switch whereby the load **22** may be connected or disconnected from the D.C. power source **21**, the voltage of which may be either constant or time varying. The trigger input **27** is a time dependent voltage source which is used to trigger on and may be used to trigger off the current limited transistor switch by application of voltage pulses of correct wave shapes to the terminal **3**. The drive input **26** may be a battery which provides a constant D.C. voltage of the correct polarity and of sufficient magnitude to the drive input, so that after trigger source **27** has initiated the turn-on of the transistor switch, it will not revert to the off state, until an appropriate off pulse has been generated by voltage source **27**. The diode **23** need be included in only those cases where the load **22** is inductive, in which case the diode serves as a bypass path for inductively driven currents which persist after switching transistor **30** has been turned off.

The behavior of the on-off D.C. switch circuit of FIG. 2 is such that:

(1) The transistor switch will connect the load **22** across the voltage source **21** upon an appropriate command from trigger source **27**. Assuming that the load current remains sufficiently small, for a given value of battery **26** voltage, continuity will remain indefinitely.

(2) The transistor switch will revert to the off-state upon an appropriate command from trigger source **27**.

(3) The transistor switch will revert to the off-state if battery **26** voltage is reduced below a certain threshold which is roughly proportionate to the load current.

D.C. CIRCUIT BREAKER

The circuit of FIG. 2 also may serve as a D.C. circuit breaker which has an adjustable trip point and is reset by the application of a voltage signal.

In particular, it will be noted that the magnitude of battery **26** voltage regulates the threshold value of current at which the current limited transistor switch **20** will revert to the off-state. Accordingly, by making voltage source **26** an adjustable voltage source, it is possible to regulate the threshold point at which reversion to the off-state will occur. In all cases, trigger source **27** provides turn-on or reset. As with the on-off switch application, trigger source **27** may also be used to turn off the transistor switch.

In the case where the trigger input **27** is able to provide recurrent turn-on pulses, an automatic reset action of the previously described circuit is possible. For example, if the trigger input **27** provides 10 pulses per second, of the correct wave shape, automatic reset will occur within .1 second after the time of fault removal.

It should be noted that the speed of circuit breaking action is limited only by switching speed limitations of the semiconductor devices used in the current limited transistor switch. Accordingly, durations of less than one microsecond between the occurrence of a fault load and the time of turn-off are possible. This extremely fast response time makes the above mentioned electronic circuit breaker especially valuable where protection of solid-state equipment is involved.

ON-OFF A.C. SWITCH

In the circuit of FIG. 3, the current limited transistor switch **20** is used in a voltage-controlled switch, whereby a load **22** may be connected or disconnected from an A.C. power source **21**. Throughout the figures of the drawings corresponding elements are identified by the same reference numerals. In FIG. 3 and succeeding figures, the power supplies **24** and **25** are omitted in order to simplify the figures, but of course they would be utilized in each embodiment, connected to terminals **1** and **5**, and **6** and **5**, respectively. Diodes **57–60** are connected as a full wave rectifier.

In explaining the theory of operation of the A.C. switch of FIG. 3, it is noted that there are four instantaneous conditions of state. In case **1**, the upper terminal of source **21** is positive with respect to the lower terminal and switch **20** is in the non-conductive state. Case **2** is the same as case **1** but source **21** has reversed polarity. Case **3** is the same as case **1**, except that switch **20** is in the conductive state. In case **4**, the upper terminal of source **21** is negative with respect to its lower terminal and switch **20** is in the on-state.

Assuming no load E.M.F., as with a resistive load, it is noted that no load current flows in either case **1** or **2**, and that in both these cases, terminal **1** of the switch is positive with respect to switch terminal **2**. Hence, when switch **20** is in the off-state, the load is effectively disconnected from the A.C. power source.

In case **3**, current will flow from the upper terminal of source **21**, through diode **58**, through transistor switch **20**, through diode **59**, and through load **22** to the lower terminal of the source **21**. Neglecting the voltage drops of diodes **58** and **19** and neglecting the voltage drop of transistor switch **20**, it is seen that load **22** is effectively connected across source **21** in this case. In like manner, it will be noted that load **22** is also connected across source **21** in case **4**.

As a result of the analyses of cases **1** through **4**, it is seen that the transistor switch in FIG. 3 can serve to effectively connect and disconnect load **22** from an A.C. source **21**.

As in the previous cases, switch **20** is turned on by action of a voltage pulse from trigger source **27** and turn-off is initiated by either decreasing the voltage between terminals **4** and **5**, or by providing a reverse voltage pulse between terminals **3** and **5**.

A.C. CIRCUIT BREAKER

The circuit of FIG. 3 may also serve as an A.C. circuit breaker which has adjustable peak current trip point and is reset by application of a voltage signal.

It will be noted that load current, whether positive or negative, must flow through switch **20**. Accordingly, whenever either the positive or the negative peak of the load current exceeds a certain threshold, which is approximately proportionate to the voltage of drive input voltage source **26**, the current limited transistor switch **20** reverts to the off-state, thus carrying out the action of an A.C. circuit breaker.

Reset action is provided by the application of a pulse voltage of the correct shape between terminals **3** and **5**. As with the D.C. circuit breaker application, a source of repetitive voltage pulse may be used for the trigger input **27** thus enabling automatic reset.

CURRENT REGULATING D.C. CHOPER

In many applications, especially where D.C. motors are used, a control device is required which provides lossless energy conversion where energy is obtained from a source of constant or nearly constant voltage and supplied to a load, the characteristics of which vary with time. Using the current limited transistor switch **20**, it is possible to obtain a circuit which provides a near lossless transfer of energy from source to load and one where load current remains regulated at a value which is approximately proportionate to an input control voltage. One such circuit is shown in FIG. 4.

The D.C. power source **21** may be constant or time varying. The trigger input **27** is a source of recurrent trigger pulses which are capable of triggering transistor switch **20** into conduction. The diode **23** is the conventional free-wheel diode and inductor **63** is a load current smoothing inductor.

The operation is as follows. Assume that drive input voltage source **26** is held at a constant value and that

trigger source 27 supplies a train of turn-on trigger pulses (FIG. 5*a*). Furthermore, assume that voltage 26 is set at a sufficiently low value such that the transistor switch cannot maintain the resulting steady-state load current without reverting to the off-state.

Initially assume the load current (FIG. 5*c*) is zero. When the first trigger pulse is applied to terminal 3, the transistor switch will switch on and will remain on until the load current reaches the threshold level, (FIG. 5*b*) which in turn is determined by the magnitude of voltage 26 at terminal 4. The time required until this threshold level is reached will of course be determined by the value of the inductor 63 and parameters of the load 35.

Directly after switch 20 reverts to the off-state, load current will flow in a circular path through free-wheel diode 23. The rate of decay of this current will be determined by the ratio of the resistance to inductance of load 22 and inductor 63.

Eventually, after a time interval, which is long compared to the above mentioned time constant of the load, a steady-state condition will be attained. Under this condition, switch 20 will be turned on with each trigger pulse; load current will rise to the threshold point between trigger pulses and hence turn-off will also occur between successive trigger pulses. As a result, source and load current wave-forms as shown in FIGS. 5*b* and 5*c*, respectively, will prevail.

In the case where the load time constant is long compared with the period between successive trigger pulses, the ripple component of the load current will be small compared with the D.C. component of the load current. In this case, the D.C. load current component will be nearly equal to the peak load current. Since the peak current and the turn-off threshold current are the same, it follows that in this case, the D.C. load current will be proportionate to the drive voltage supplied by source 26. In effect then, the circuit of FIG. 4 provides a lossless transfer of energy from voltage source 21 to load 22 such that the D.C. component of load current is maintained nearly proportionate to the drive voltage applied between terminals 4 and 5. Of course, in reality, some small losses will occur which are the sum of switch losses, diode 23 losses, and losses due to resistance associated with inductor 63.

In addition to the features already mentioned, the circuit of FIG. 4 has a number of other very advantageous characteristics. First of all, should the load become shorted, the action of transistor switch 20 is such that the resulting currents will remain at safe values and no damage will occur to any of the circuit components. Similarly, there is no danger to any of the circuit components should load 22 generate transient load changes during the course of operation.

Next, it will be noted that the base drive power drawn from supply 24 to terminals 1 and 5 (see FIG. 2) is proportionate to the magnitude of drive voltage 26. Hence, under low current conditions, where drive voltage 26 is adjusted to a relatively small value, the power drawn from supply 24 is also small and hence the overall circuit efficiency remains high.

Another important point of the circuit of FIG. 4 is its extreme simplicity. With conventional chopper schemes, a current sensing circuit plus a duty cycle generator would be required to effect the same action of current limiting. That the FIG. 4 circuit does not require these components means both an improvement in reliability and a reduction in weight, size and expense.

A number of useful modifications of the FIG. 4 circuit may be made. For example, the recurrent trigger pulse source 27 may be replaced with a similar pulse source, the frequency of which, rather than being constant, is made a function of drive voltage 26. With this modification, it is possible to further optimize energy conversion efficiency over a wider range of operating conditions. A second useful modification is to replace the D.-C. voltage source 26 with a D.-C. time varying voltage source. In the case where the modified voltage source generates a voltage which is periodic and has the same period as the trigger pulses from source 27, various voltage-current relations, in addition to the previously described constant current case, can be attained. *a* third modification would be the inclusion of a more advanced output filter, which could be connected between the output of inductor 63 and the load 22.

VOLTAGE REGULATING-CURRENT REGULATING D.C. CHOPPER

In many applications, a control device is required which provides lossless energy conversion where energy is obtained from a source of constant or nearly constant voltage and supplied to a load in such a way that either the voltage across the load will be held at a determined value or the current through the load will be held at a determined value.

The current limited transistor switch 20 may be utilized in an apparatus whereby the above action can be carried out. One such scheme is shown in FIG. 6 which is identical with the circuit of FIG. 4 with the exception that generator 66 and potentiometer 67 are used for the drive input 26 between terminals 4 and 5, with a feedback connection 68 from the load to the generator 66. The generator 66 is a voltage-controlled duty-cycle generator which functions to produce an output signal as shown in FIG. 7*b*, where the generator output pulses at terminal 4 are synchronized with the trigger pulses at terminal 3, and where the duty cycle is proportionate to the difference between the actual output voltage and a desired voltage level (reference).

In those cases where the output current is sufficiently low, compared to the drive signal applied to terminal 4, the on-period of switch 20 will correspond exactly with the on-period of the drive voltage applied to terminal 4. In this case, a condition of output voltage regulation will exist and the load voltage will be maintained very nearly equal to the reference voltage (see FIG. 7*c*).

However, in those cases where the switch current reaches the threshold value within the period of the duty cycle of generator 66, circuit operation will be identical with the circuit of FIG. 4. Accordingly, a condition of current control will take place and the load voltage will, in general, be significantly below the reference level. This in turn will cause the duty cycle of geneartor 66 to attain its maximum value. Accordingly, turn-off of switch 20 will no longer be initiated by the duty cycle generator, but rather by action of the current threshold effect inherent in the current limited transistor switch itself. In this mode of operation, it will be noted that the drive signal to input terminal 4 is proportionate to the setting of potentiometer 67 which is connected across the output of the generator 66. It therefore follows that the current limit is regulated in proportion to the setting of potentiometer 67.

A modification of the apparatus is to have the duty cycle generator act through the trigger input, rather than through the drive input, since turn-off of switch 20 can be accomplished by applying a pulse of the correct polarity (reverse of the turn-on pulse) to the trigger input. In this case, the drive input would simply be connected to an adjustable D.-C. voltage source, as in FIG. 4. Other modifications, similar to those discussed in connection with the FIG. 4 circuit are possible.

VOLTAGE BOOSTING CURRENT REGULATING D.C. CHOPPER

In the apparatus of FIGS. 4 and 6, transistor switch 20, diode 23 and inductor 63 join together and form a three terminal network A, B, C. In the most frequently used case, the diode 23 is common to both the input 21 and output 22 of the chopper, as in FIGS. 4 and 6. However, the same network of elements 23, 63, and 20 can

be applied usefully where either the inductor **63** or the transistor switch **20** terminals are common to both input and output.

In FIG. 8 and succeeding figures, the turn-on pulse source **27** and the drive input voltage source **26** are omitted in order to simplify the figures, but of course they would be utilized in each embodiment, connected to terminals **3** and **5**, and **4** and **5**, respectively.

In the circuit of FIG. 8, the interconnection between elements **23**, **63** and **20** is indeed the same as with FIGS. 4 and 6. However, in FIG. 8, terminal **1** of the transistor switch is common to both the power source **21** and the load **22**, and a voltage step-up action between the source and the load is possible. In particular, it is noted that as the duty cycle of switch **20** is increased from zero to unity, the effective step-up ratio between the load voltage and the source voltage increases, ranging between unity and an unbounded limit.

In the case where a recurrent source of voltage pulses is applied between terminals **3** and **5**, and where a fixed source of D.-C. voltage is applied between terminals **4** and **5**, energy will be removed from voltage source **21** and delivered to load **22** in such a way that the average current drawn from source **21** will remain proportionate to the D.-C. drive voltage applied between terminals **4** and **5**. Furthermore, the current drawn from source **21** will remain essentially constant, with respect to changes in: source **21** voltage, load **22** impedance, and load **22** E.M.F. The circuit just described may be modified in ways exactly analogous to the modifications discussed in association with FIGS. 4 and 6.

VOLTAGE CHANGING CURRENT REGULATING D.C. CHOPPER

The apparatus of FIG. 9 provides a third way in which the basic circuit consisting of switch **20**, diode **23**, and inductor **63** may be connected to the source and load, to produce a useful effect. The unique feature of the circuit of FIG. 9 is that energy may efficiently be transferred from a D.-C. voltage source **21** to a load **22** regardless of the load E.M.F.. In both the cases where the load E.M.F. is greater or less than the source E.M.F., efficient energy transfer is possible. In the case where load **22** is resistive, the load voltage may be controlled to any value whatsoever, within the limitations of the circuit component ratings. Thus, this circuit may be used to produce either a step-up or a step-down action.

As with the FIG. 8 circuit, a source of voltage pulses is connected between terminals **3** and **5** and an adjustable D.-C. voltage is connected between terminals **4** and **5**. The action of these two voltage sources is virtually the same as with the FIG. 8 circuit.

In the circuit of FIG. 9, the average current drawn from source **21** is a joint function of both the magnitude of the voltage applied to the drive input, and the parameters of the load. Both the peak source and peak load currents are limited (and equal to) the threshold current of the current limited transistor switch; this threshold current in turn is proportionate to the drive input voltage.

This circuit may be modified in ways exactly analogous to the modifications discussed in association with FIGS. 4 and 6.

CURRENT REGULATING DUAL D.C. CHOPPER

One of the disadvantages of using choppers as a means of D.-C. power control is that the chopping action introduces undesired A.-C. current harmonics into both the source and load circuits. While filter circuits can be used to reduce the content of these current harmonics, such filters add greatly to the weight and cost of the chopper system and also introduce losses of their own.

Chopper circuits have been developed in recent years which greatly reduces the above mentioned current harmonics without the addition of filter circuits. These are sometimes referred to as dual choppers and poly choppers, where two or a plurality of switches are used. Such chopper circuits are described in:

(1) "Three-Phase Silicon Controlled Rectifier Battery Charger"—by Wally E. Rippel—IEEE Region 6 Conference-Proceedings—IEEE Resources Roundup—April, 1969.

(2) "A High Performance Electric Vehicle Control System"—Master's Thesis by Wally E. Rippel—published with Cornell University's School of Electrical Engineering—1971.

(3) "Dual SCR Chopper as a Motor Controller for an Electric Car"—by Wally E. Rippel—IEEE Transactions on Vehicular Technology, vol. VT—20, No. 2—May, 1971.

A poly chopper circuit is illustrated in FIG. 10 with the three terminal network A, B, C designation of FIGS. 4, 8 and 9. The source **21** and load **22** may be connected as in FIG. 4 or as in FIG. 8 or as in FIG. 9. Consider first the operation as a dual chopper with two current limited transistor switches **20**, **20'**. The duty cycles of switch **20'** may be caused to lag (or lead) the duty cycles of switch **20** by exactly one half switching period by controlling the timing of the turn-on pulses at terminals **3**. Then all of the odd current harmonics induced in both source **21** and load **22** which result from the switching action of switch **20** are completely cancalled by the corresponding odd current harmonics generated by action of switch **20'**. Because of this odd harmonic cancellation, the r.m.s. content of current harmonics delivered to the load is reduced by more than a factor of 10 for typical circuit parameters, while the input r.m.s. harmonic content is approximately cut in half, for typical circuit parameters.

If current limited transistor switches are used in place of conventional electronic switches, a number of improvements result. First of all, the circuit of FIG. 10 has all the advantages of the circuit of FIG. 4 plus the features of reduced harmonic content.

Also of importance is the fact that, in the current regulating mode, an automatic effect of load sharing takes place between the switching transistor of switch **20** and the switching transistor of switch **20'**. Furthermore, because of automatic turn-off of both switches, load sharing continues in the event of a component failure (e.g., diode **23** or inductor **63**).

It will further be noted that dual chopper equivalents of the circuits of FIGS. 4, 6, 8 and 9 are possible (including dual chopper equivalents of their corresponding modifications), and that with each of these dual chopper equivalents, all of the previously described circuit characteristics remain, but with the added features of reduced current harmonics.

CURRENT REGULATING POLY D.C. CHOPPER

The dual chopper technique related may be extended to any number of switches in the poly chopper, and three are shown in FIG. 10, namely **20**, **20'**, **20''**.

By providing the proper phase delays between the various switches of the poly chopper, current harmonic contents at terminals A, B, and C can be further reduced relative to the corresponding terminal currents of the dual chopper circuit. It should be noted that as the number of chopping elements is increased, harmonic contents continue to decrease.

As with the dual chopper circuit, the current limited transistor switch also finds favorable application with the poly chopper circuit and with its various modes of connection and modification.

BIDIRECTIONAL CHOPPER APPLICATIONS

By combining the circuit of FIG. 4 with the circuit of FIG. 8, a bidirectional control element results which is capable of efficiently transferring D.-C. energy from a voltage source **21** to a load **22**, and in the case where the load possesses an E.M.F., energy can also be efficiently

transferred from the load back to the source. Such an apparatus is shown in FIG. 11.

Enregy transfer from source **21** to load **22** is effected by activating switch **20**, while keeping switch **20***a* in the off-state. Conversely, energy transfer from load **22** to the source **21** is effected by activating switch **20***a*, while keeping switch **20** in the off-state.

The current limited transistor switch may be directly applied to the circuit of FIG. 11 and is connected as indicated and all of the previously mentioned advantages of the current limited transistor switch circuit are retained. One particular advantage of the invention relevant to the application of FIG. 11 is that in the event simultaneous trigger pulses are supplied to switches **20** and **20***a*, the resulting fault currents that normally would flow through switches **20** and **20***a*, are prevented by the inherent turn-off action of the current limited transistor switches.

Circuit analysis of FIG. 11 reveals that the E.M.F. of load **22** must be less than the E.M.F. of source **21**, if proper operation is to occur. In cases where the load E.M.F. is always greater than the source E.M.F., and bidirectional energy control is desired, a modification of the FIG. 11 circuit results in the circuit of FIG. 12. Note that in both circuits, switches **20** and **20***a*, diodes **23** and **23***a*, and inductor **63** are identically interconnected forming a three terminal network ABC.

The current limited transistor switch finds application in a third version of the bidirectional chopper, with FIG. 13 being a bidirectional version of the FIG. 9 circuit. The circuit of FIG. 12 is capable of transferring energy, in either direction between voltage source **21** and load **22**, where the load E.M.F. may be either greater than, equal to, or less than the E.M.F. of the source.

The modifications and performance features associated with the circuits depicted in FIGS. 4, 6, 8, and 9 are applicable to the circuits of FIGS. 11, 12 and 13.

By combining the principles of the bidirectional chopper and the poly chopper, a composite three terminal chopper circuit is obtained which may be connected in arrangements analogous to the circuits of FIGS. 10 and FIGS. 11, 12, and 13, and such a circuit is shown in FIG. 14. The operation will be as described in conjunction with FIGS. 10–13.

INVERTER APPLICATIONS

The current limited transistor switch may be utilized in various inverter circuits, wherein D.-C. energy is transformed to A.-C. enregy. The application of the current limited transistor switch to three inverter circuits is shown in FIGS. 15, 16 and 17.

With the inverter of FIG. 15, switches **20** and **20***b* may be current limited transistor switches as described above. The operation of the inverter circuit entails making switches **20** and **20***b* alternately conductive at a frequency equal to the desired frequency of inversion, by means of appropriately timed pulses at terminals **3**. Diodes **71** and **72** provide return paths for reactive currents which result from transformer and load reactance.

In the conventional inverter connected as shown in FIG. 13, the transistors used for the switches **20** and **20***b* receive base drive either from an external circuit (case **1**), or from auxiliary windings included with transformer **73** (case 2).

In the case **1**, where base drive is obtained from an external circuit, precise, frequency control and in some instances, a certain degree of output voltage control is possible. In this case, however, overcurrent protection of the switching transistors and/or control of the load current require complicated and expensive auxiliary circuits.

In case **2**, where base drive is obtained from transformer **73**, extreme circuit simplicity plus a certain degree of overcurrent protection results. There are, however, a large number of disadvantages which result in this second case, among which are lack of accurate frequency control, lack of voltage control, and lack of current control.

If current limited transistor switches are used in place of conventional transistors, a number of advantages result, among which are high energy conversion efficiency, inherent component protection with respect to overcurrent conditions, voltage control capability, and current control capability.

Operational details are as follows: Switches **20** and **20***b* are caused to conduct alternately and at the desired frequency. In the case where voltage control is desired, both switches **20** and **20***b* are allowed to conduct for less than one half cycle. By controlling the precise intervals over which switches **20** and **20***b* conduct, precise control of the A.-C. output voltage is achieved. The actual implementation of this control is exactly analogous with the circuit of FIG. 6. Furthermore, the regenerative turn-off action of the current limited transistor switches can be used to separately control both the positive and the negative peak load currents. This action is caused simply by separate control of the voltages applied between terminal pairs **3** and **5** of each switch.

In summary then, it will be noted that the inverter using current limiting transistor switches is capable of providing frequency control, voltage control, positive peak current control and negative peak current control.

A second type of inverter frequently used is the bridge inverter circuit shown in FIG. 16. In operation, switch pairs **20** and **20***d* are turned on and turned off simultaneously as are switch pairs **20***b* and **20***c*. Diodes **71**, **72**, **74**, **75** return reactive energy from the load **22** to the D.C. energy source **21**. Frequency, voltage, and current control can be attained in ways exactly analogous with the circuit of FIG. 15. Since switches **20** and **20***d* are required to turn on and turn off simultaneously, the voltage signals applied between terminals **3** and **5** must be equal, and the voltage signals applied between terminals **4** and **5** must be equal for both switches. Similar voltage relations must prevail for switches **20***b* and **20***c*.

A third inverter where the current limited transistor switch may be used is shown in FIG. 17. In this case, source **21** is a center tapped voltage source (i.e., the voltage across **21***a* is equal to the voltage across **21***b*). Switches **20** and **20***b* are operated with exactly the same constraints as with the circuit of FIG. 15. Accordingly, frequency, voltage, and current control are attained in ways exactly analogous with the FIG. 15 inverter.

What is claimed is:

1. A current limited transistor switch for operation with a drive input voltage source, a base current source and a turn-on pulse source, comprising in combination:

a switching transistor having collector and emitter connected as a switch between a source terminal and a load terminal;

a drive control circuit for the base current of said switching transistor for setting a current threshold level for said switching transistor varying as a function of a drive input voltage at a drive input terminal of said drive control circuit,

said drive control circuit including a current control unit connected between said switching transistor base and a base drive terminal for controlling the current of the base current source from said base drive terminal to said switching transistor base, and

a threshold level unit having said drive input voltage as an input and a signal varying as a function of the base current of said switching transistor as an input and providing an output in controlling relation to said current control unit for varying said switching transistor base current as a function of said drive input voltage;

an on-off control circuit providing a gating signal as an input of said threshold level unit for changing said current threshold level as a function of inputs to said on-off control circuit to turn said switching transistor on and off;

first circuit means for connecting a turn-off signal vary-

ing as a function of current through said switching transistor between said source and load terminals, to said on-off control circuit as an input to turn said switching transistor off blocking current between said source and load terminals; and

second circuit means for connecting a turn-on pulse to said on-off control circuit as an input to turn said switching transistor on for current conduction between said source and load terminals.

2. Apparatus as defined in claim 1 including a resistor in series between said current control unit and said base drive terminal, with said signal varying as a function of the base current of said switching transistor being developed across said resistor.

3. Apparatus as defined in claim 1 wherein said current control unit includes a current control transistor with emitter and collector connected between said switching transistor base and said base drive terminal, and with said output of said threshold level unit connected to the base of said current control transistor.

4. Apparatus as defined in claim 1 wherein said threshold level unit includes an operational amplifier having a first resistor connected between said drive input terminal and the amplifier input, a second resistor connected between said current control circuit and said amplifier input, and a third resistor connected between said on-off control circuit and said amplifier input.

5. Apparatus as defined in claim 1 wherein said on-off control circuit includes a gating transistor providing current and no-current signals to said threshold level unit input, with said gating transistor controlled by signals at its base.

6. Apparatus as defined in claim 5 wherein said turn-off signal is developed across said switching transistor collector and emitter, and said first circuit means includes a resistor connected between said load terminal and said gating transistor base.

7. Apparatus as defined in claim 6 wherein said second circuit means includes a capacitor connected between said gating transistor base and a turn-on pulse terminal for coupling to said turn-on pulse source.

8. Apparatus as defined in claim 1 wherein said turn-off signal is developed across said switching transistor collector and emitter, and said first circuit means includes a resistor connected between said load terminal and said on-off control circuit input.

9. Apparatus as defined in claim 1 including:

a drive input voltage source connected at said drive input terminal, and

a turn-on pulse source connected at said second circuit means for providing both positive going and negative going pulses for turning said switch on and off.

10. Apparatus as defined in claim 1 including:

an adjustable drive input voltage source connected at said drive input terminal providing an adjustable switch opening point, and

a turn-on pulse source connected at said second circuit means for providing recurring voltage turn-on pulses for resetting said switch to the closed condition after opening.

11. Apparatus as defined in claim 1 including a full wave rectifier having opposed pairs of terminals, with one of said pairs of terminals connected across said switch source and load terminals and with the other of said pairs of rectifier terminals for connection to an A.C. source and a load.

12. Apparatus as defined in claim 1 including:

an inductor connected between said load terminal and an A terminal;

a diode connected between said load terminal and a B terminal, with said source terminal comprising a C terminal, forming a three-terminal network ABC;

a drive input voltage source connected at said drive input terminal providing a drive input voltage of a value less than that required for maintaining a steady state load current through said switch; and

a turn-on pulse source connected at said second circuit means providing recurring voltage turn-on pulses for repeatedly turning said switch on.

13. Apparatus as defined in claim 12 with a source connected between terminals C and B and with a load connected between terminals A and B.

14. Apparatus as defined in claim 12 with a source connected between terminals A and C and a load connected between terminals B and C.

15. Apparatus as defined in claim 12 with a source connected betwen terminals C and A and with a load connected between terminals B and A.

16. Apparatus as defined in claim 1 including:

an inductor connected between said load terminal and an A terminal;

a diode connected between said load terminal and a B terminal, with said source terminal comprising a C terminal, forming a three-terminal network ABC;

a drive input voltage source connected at said drive input terminal providing a drive input voltage pulse of duration varying as a function of the difference between a reference voltage and the voltage at the load;

a voltage feedback connection between the load and said drive input voltage source; and

a turn-on pulse source connected at said second circuit means providing recurring voltage turn-on pulses in synchronism with said drive input voltage pulses.

17. Apparatus as defined in claim 1 including:

a plurality of said switches;

a corresponding plurality of inductors, with an inductor connected between the load terminal of each switch and an A terminal;

a corresponding plurality of diodes, with a diode connected between the load terminal of each switch and a B terminal;

means connecting the source terminals of each switch to a C terminal, forming a three-terminal network ABC;

a drive input voltage source connected at the drive input terminal of each switch; and

a pulse source connected at the second circuit means of each switch and providing recurring voltage turn-on pulses for each of said switches.

18. Apparatus as defined in claim 1 including:

a second of said switches, with the load terminal of the first of said switches and the source terminal of the second of said switches interconnected at a first point;

a first diode connected between said first point and the source terminal of the first switch comprising terminal C;

a second diode connected between said first point and the load terminal of the second switch comprising terminal B;

an inductor connected between said first point and a terminal A, forming a three-terminal network ABC;

a drive input voltage source connected at the drive input terminal of each of said switches; and

a turn-on pulse source connected at the second circuit means of each of said switches providing recurring voltage turn-on pulses alternately for each of said switches.

19. Apparatus as defined in claim 1 including:

a second of said switches;

a transformer having primary and secondary windings;

a load connected across said secondary winding;

a first diode connected across the source and load terminals of the first of said switches;

a second diode connected across the source and load terminals of the second of said switches, with the source terminals of said switches connected to-

gether and with the load terminals of said switches connected across said primary winding; and

a source connected between said source terminals and the midpoint of said primary winding.

20. Apparatus as defined in claim **1** including:

second, third and fourth switches corresponding to said first switch;

four diodes, with a diode connected across the source and load terminals of each of said switches, respectively;

a source connected between the source terminals of said first and third switches and load terminals of said second and fourth switches; and

a load connected between the load terminal of said first switch and source terminal of said second switch and the load terminal of said third switch and source terminal of said fourth switch.

21. Apparatus as defined in claim **1** including:

a second of said switches;

a first diode connected across the source and load terminals of the first switch;

a second diode connected across the source and load terminals of the second switch, with the load terminal of the first switch and source terminal of the second switch interconnected at a first point;

a source connected between the source terminal of the first switch and the load terminal of the second switch; and

a load connected between the midpoint of said source and said first point.

22. Apparatus as defined in claim **1** including:

an inductor connected between said load terminal and an A terminal;

a diode connected between said load terminal and a B terminal, with said source terminal comprising a C terminal, forming a three-terminal network ABC;

a drive input voltage source connected at said drive input terminal;

a pulse source providing both turn-on and turn-off pulses connected at said second circuit means, and providing a time delay between the turn-off and turn-on pulses which is a function of the difference between a reference voltage and the voltage at the load; and

a voltage feedback connection between the load and said pulse source.

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