United States Patent [19]

Holmes

[11] **3,921,035**

[45] **Nov. 18, 1975**

[54] **SOLID STATE SWITCHING CIRCUIT**

[75] Inventor: **Kenneth P. Holmes,** Houston, Tex.

[73] Assignee: **Esquire, Inc.,** New York, N.Y.

[22] Filed: **July 18, 1974**

[21] Appl. No.: **489,527**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 433,834, Jan. 15, 1974, abandoned.

[52] **U.S. Cl.** **315/307;** 315/205; 315/208; 315/287; 315/291; 315/DIG. 7; 323/4; 323/18

[51] **Int. Cl.**[2] **H05B 41/231;** G05F 1/08

[58] **Field of Search** ..... 307/297, 315; 315/200 R, 315/205, 208, 291, 307, 311, DIG. 5, 315/DIG. 7, 194, 287; 323/1, 4, 323/17, 18, DIG. 1

[56] **References Cited**

UNITED STATES PATENTS

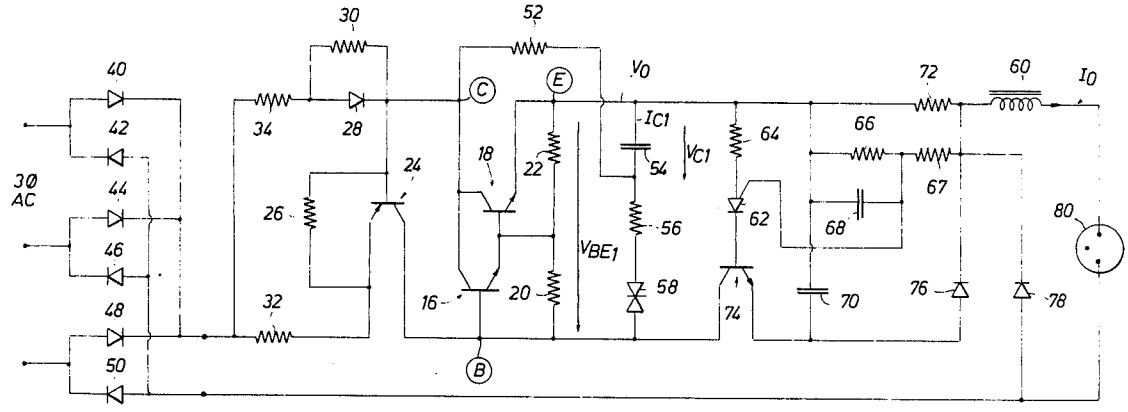
3,626,277 12/1971 Munson ..... 315/194 X

Primary Examiner—James W. Lawrence
Assistant Examiner—E. R. LaRoche
Attorney, Agent, or Firm—Arnold, White & Durkee

[57] **ABSTRACT**

A switching circuit employed in one aspect of the invention a high intensity discharge lamp ballast, the switching circuit having high efficiency switching characteristics over a wide range of applied current conditions, temperatures and voltage variations and providing good regulation to the lamp. A Darlington pair operating in conjunction with a current source is used in a preferred embodiment for the switching device, the current supplied by such current source being dependent on the ratio of load resistors rather than on the product of the betas of the transistors. The switching device may also be employed in circuits other than lamp ballasts, such as in circuit breaker applications and in operating light emitting diodes. Furthermore, the heart of the switching device may be packaged in a convenient capsule for diverse applications as selected by the device user.

109 Claims, 51 Drawing Figures



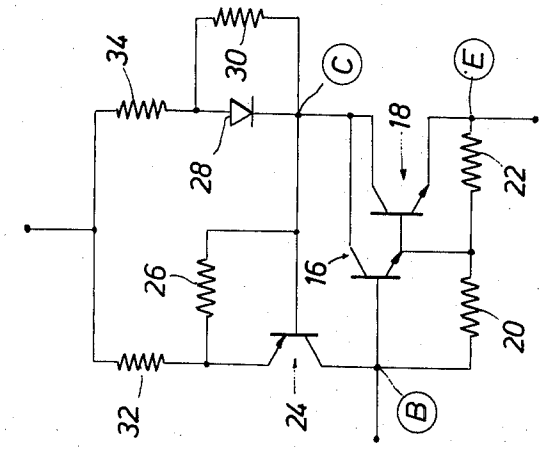


FIG. 4

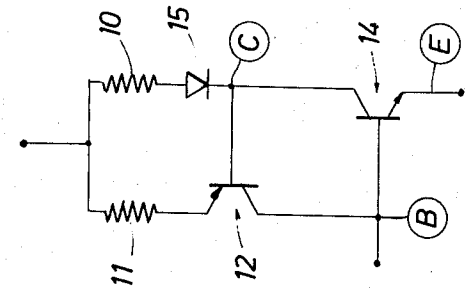


FIG. 3

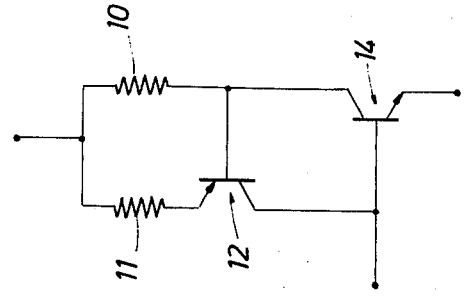


FIG. 2
PRIOR ART

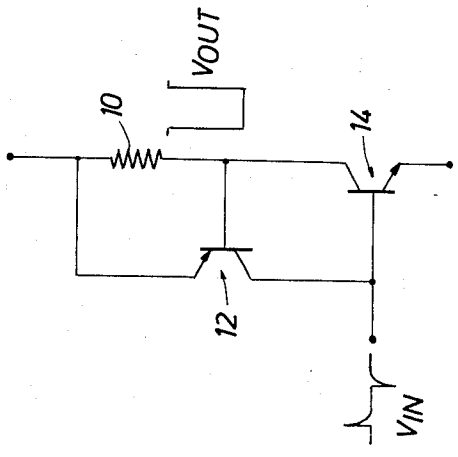


FIG. 1
PRIOR ART

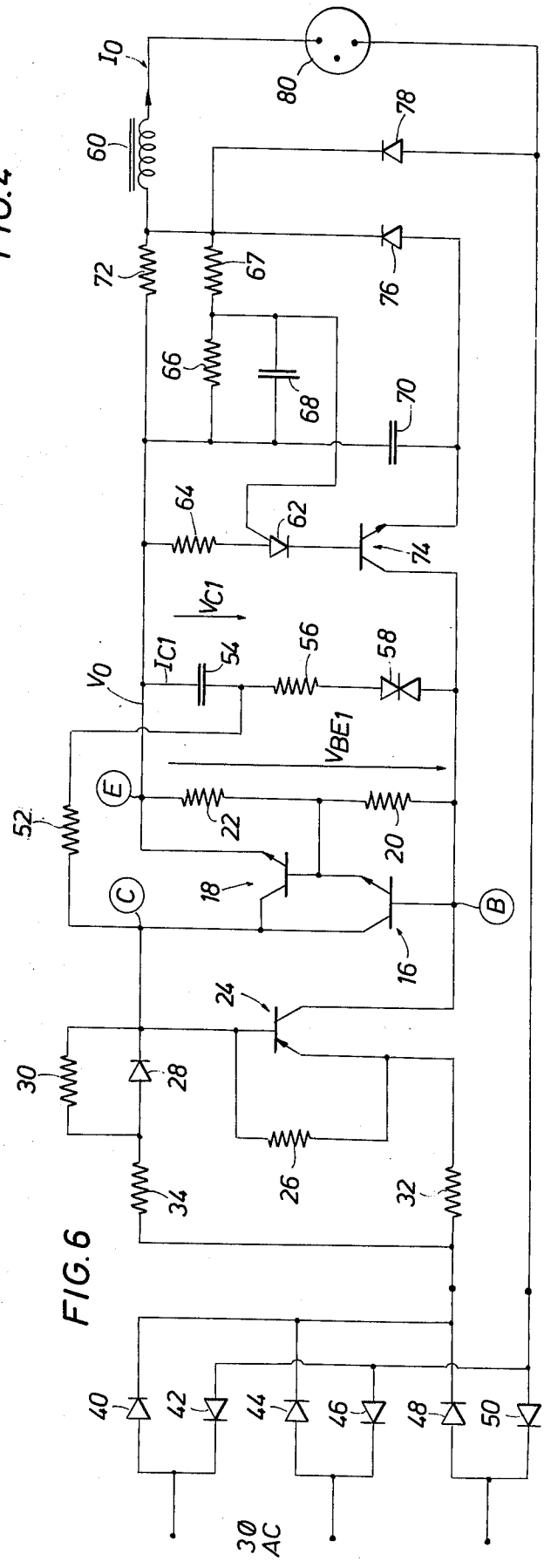


FIG. 6

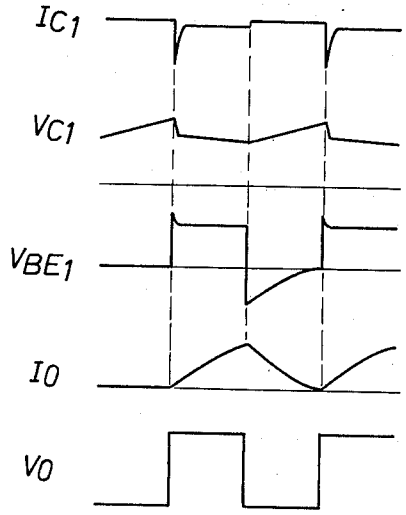


FIG. 7

FIG. 8



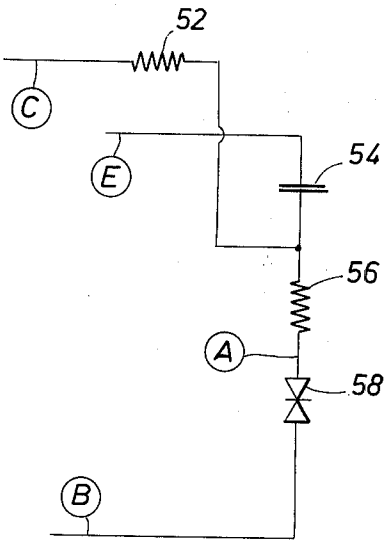


FIG. 9

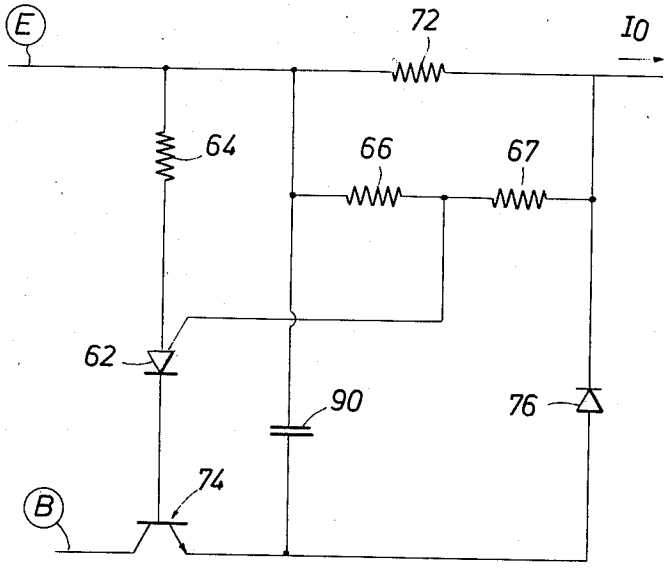


FIG. 10

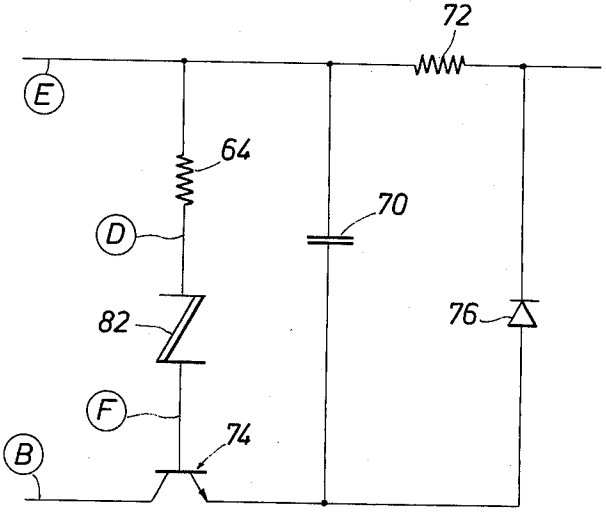
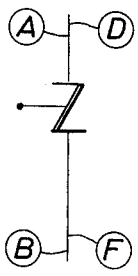
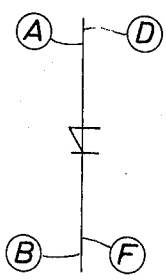


FIG. 11



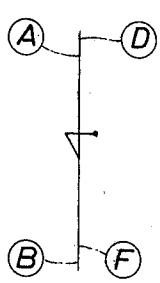
SBS

FIG. 12



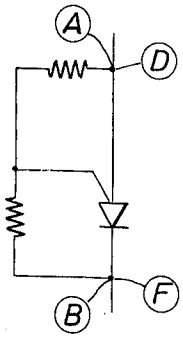
4-LAYER DIODE

FIG. 13



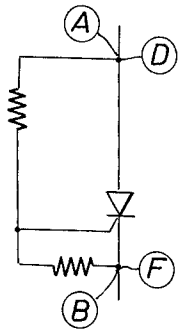
SUS

FIG. 14



PUT

FIG. 15



SCR

FIG. 16

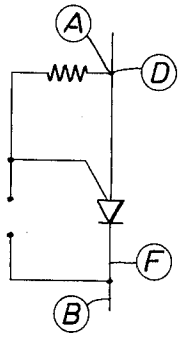


FIG. 17

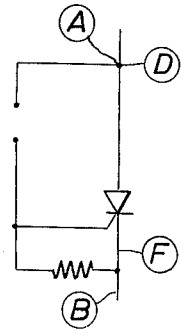


FIG. 18

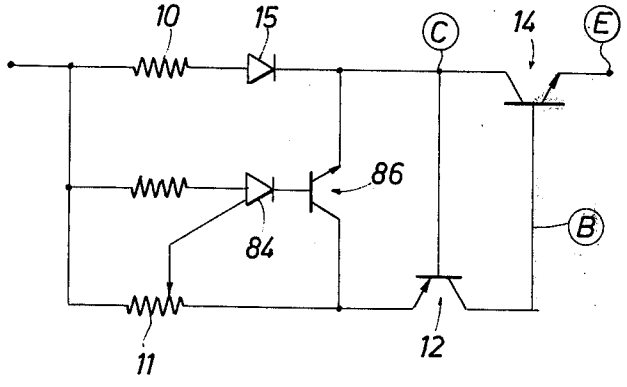


FIG. 19

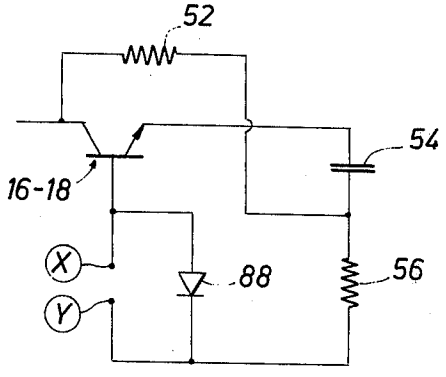


FIG. 20

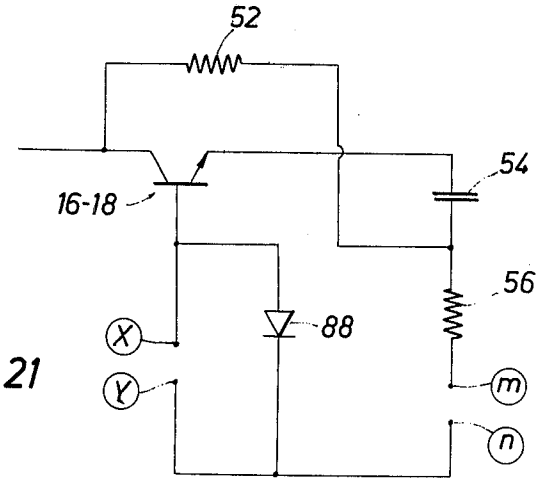


FIG. 21

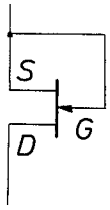


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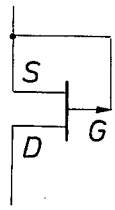


FIG. 23

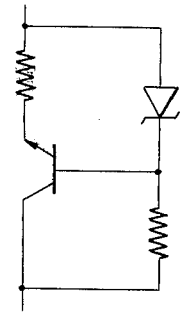


FIG. 24

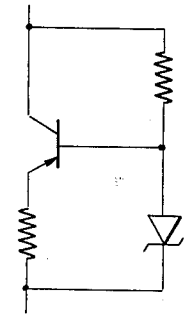


FIG. 25

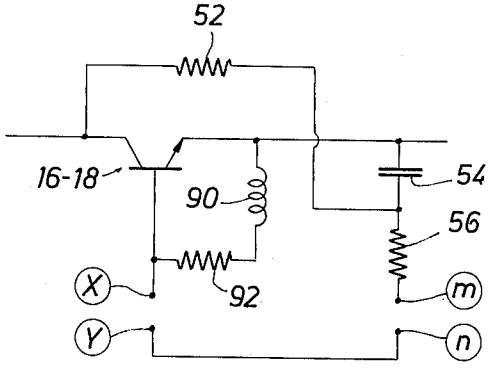


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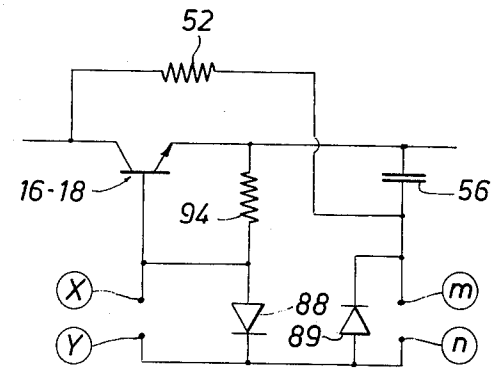


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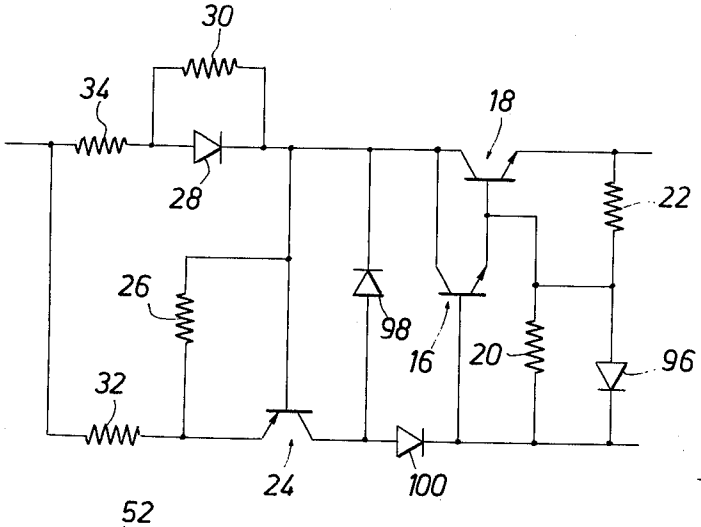


FIG. 28

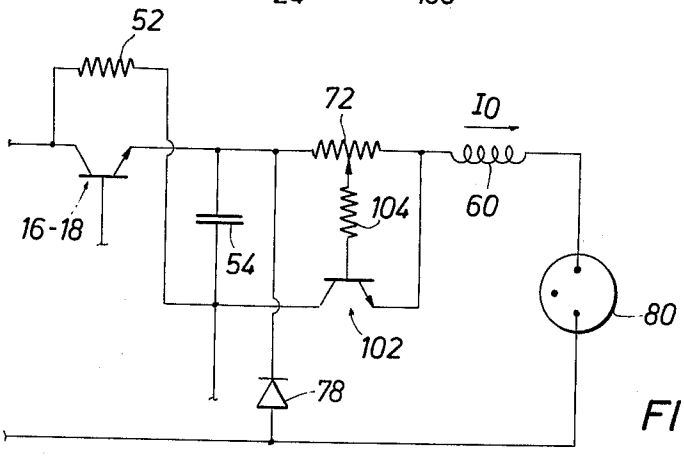


FIG. 29

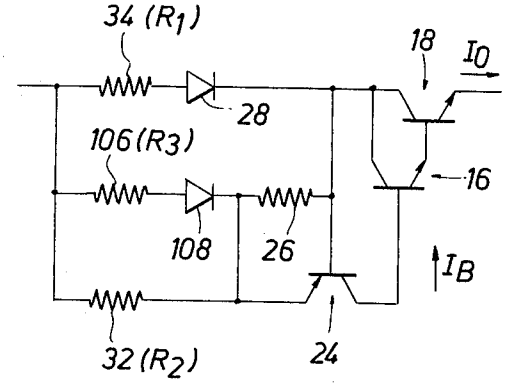


FIG. 30

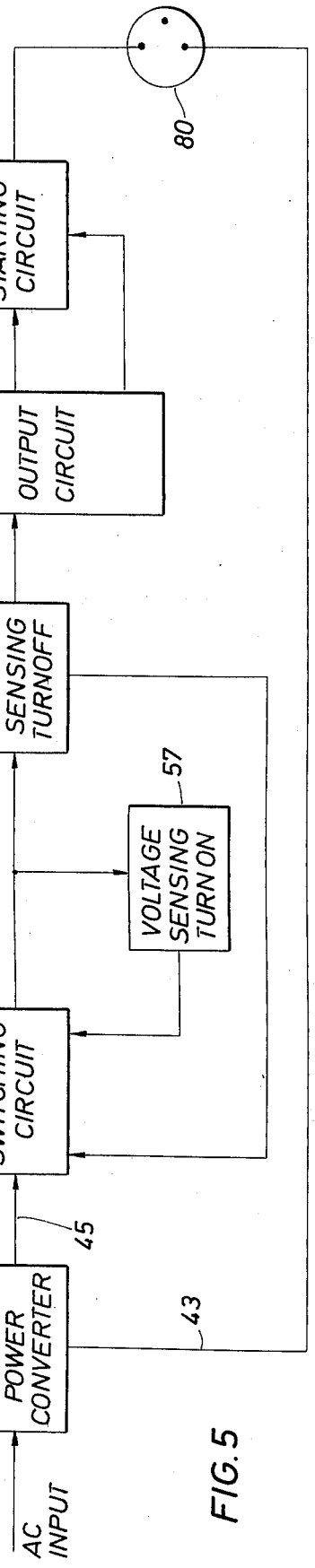


FIG. 5

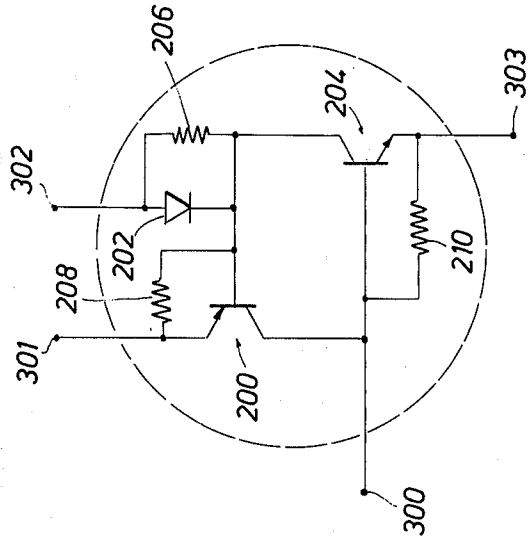


FIG. 33

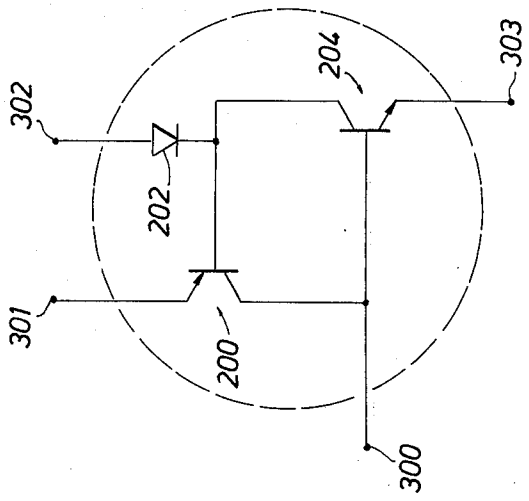


FIG. 32

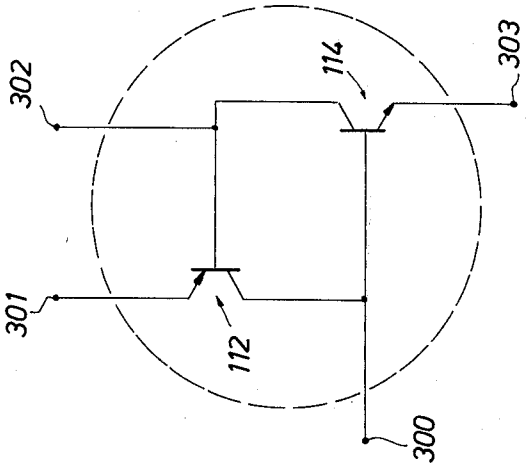


FIG. 31
PRIOR ART

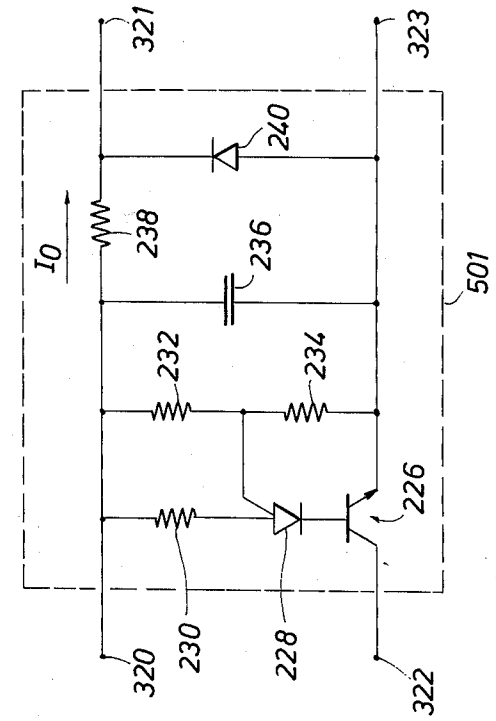


FIG. 35

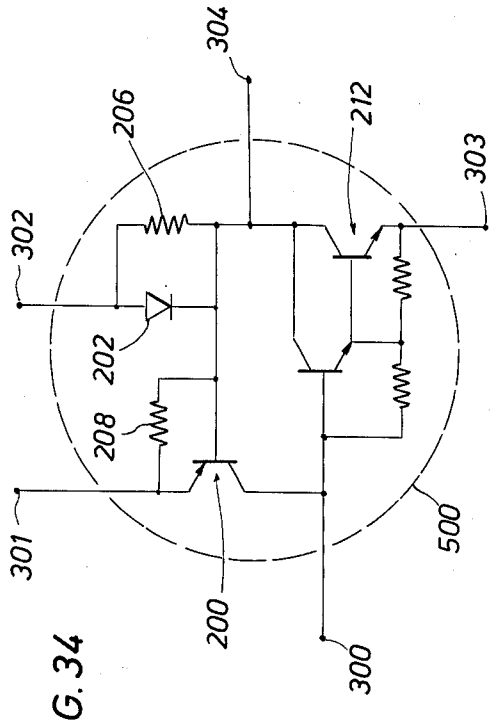


FIG. 34

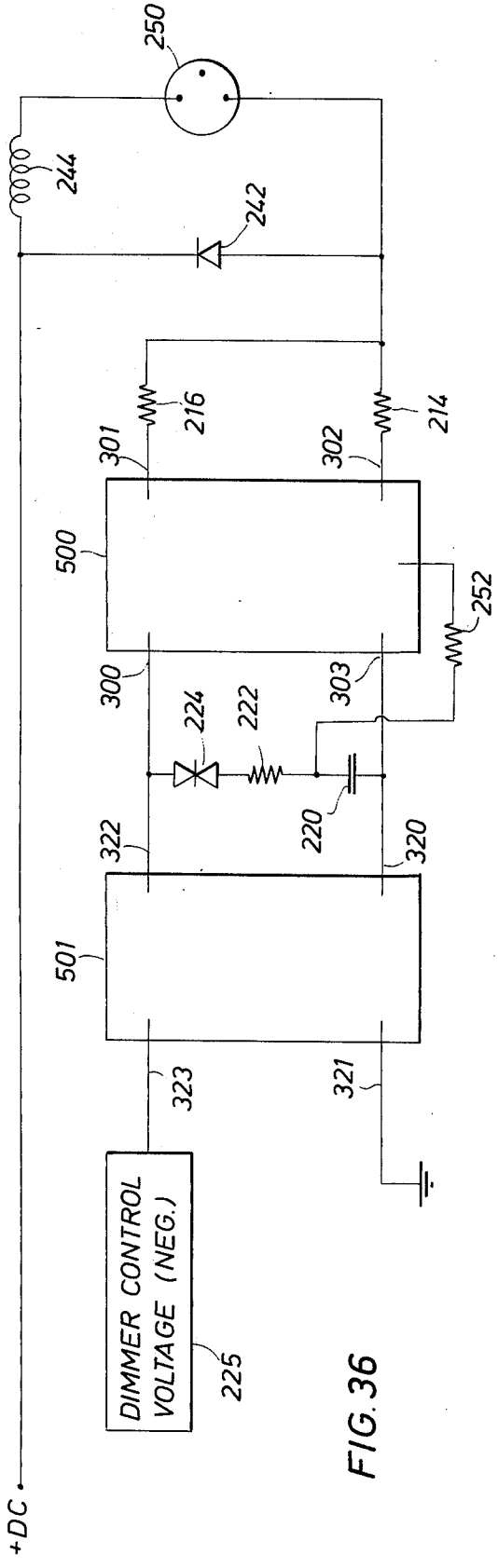


FIG. 36

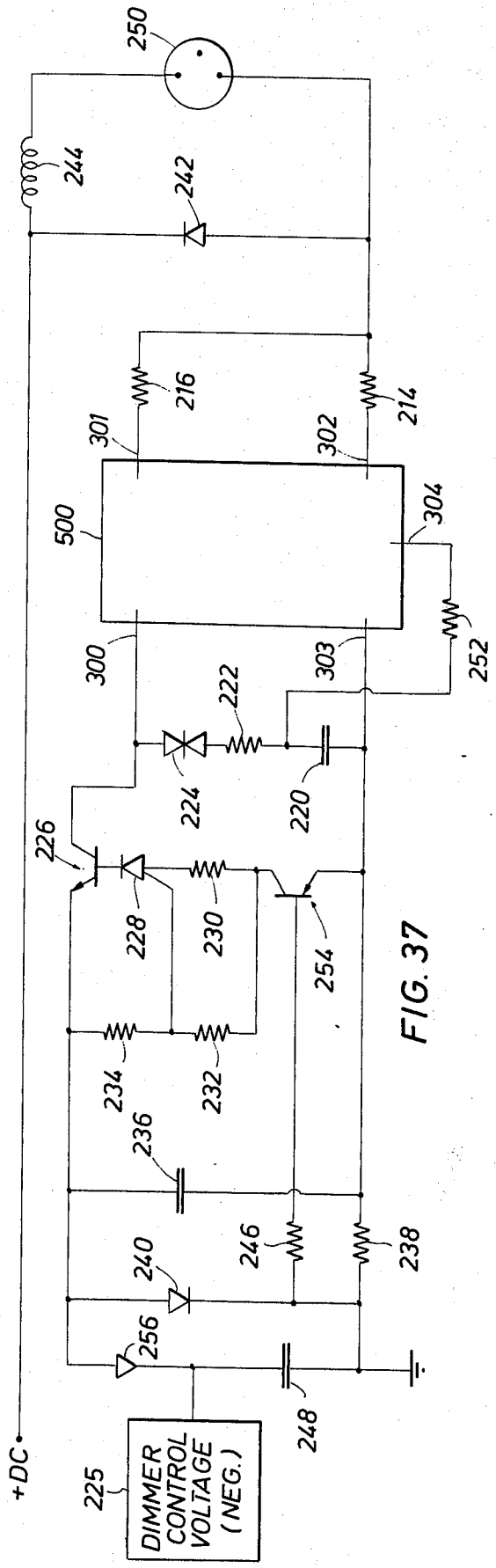

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DIMMER CONTROL VOLTAGE (NEG.)

FIG. 37

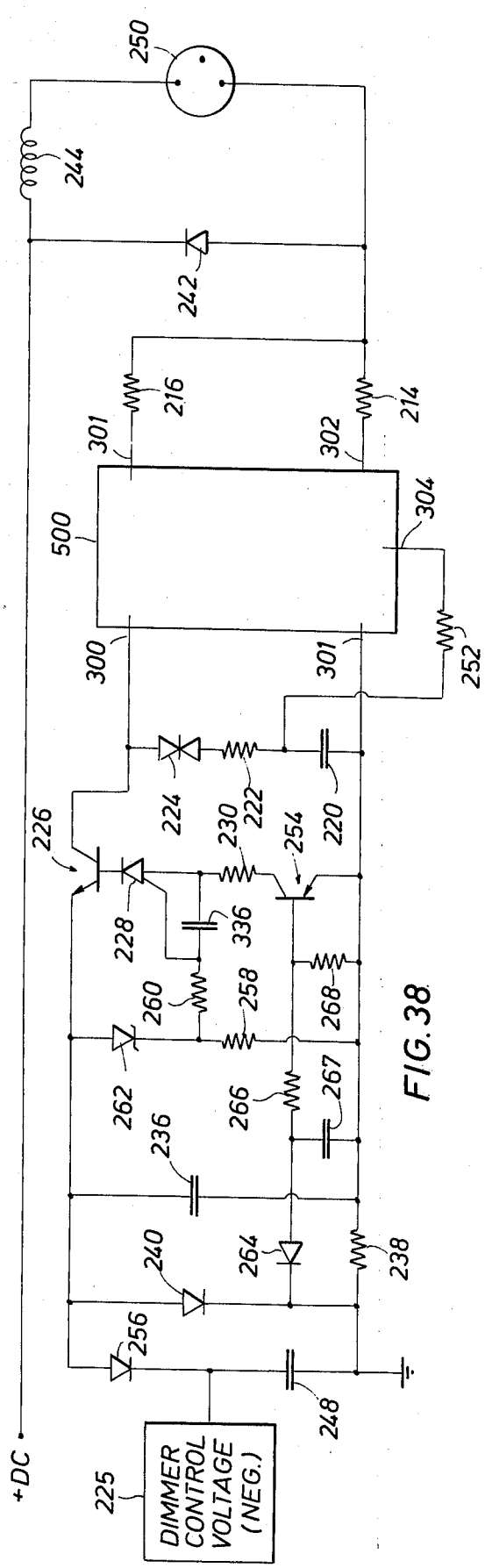

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+DC
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DIMMER CONTROL VOLTAGE (NEG.)

FIG. 38

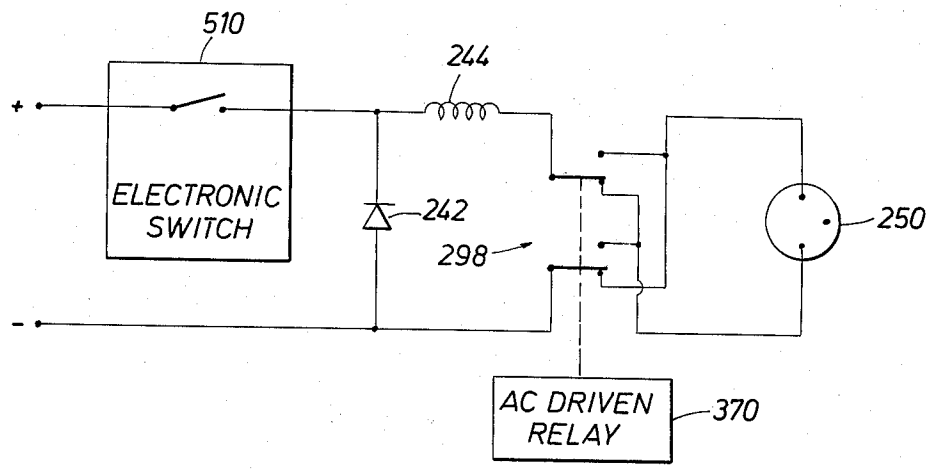


FIG. 39

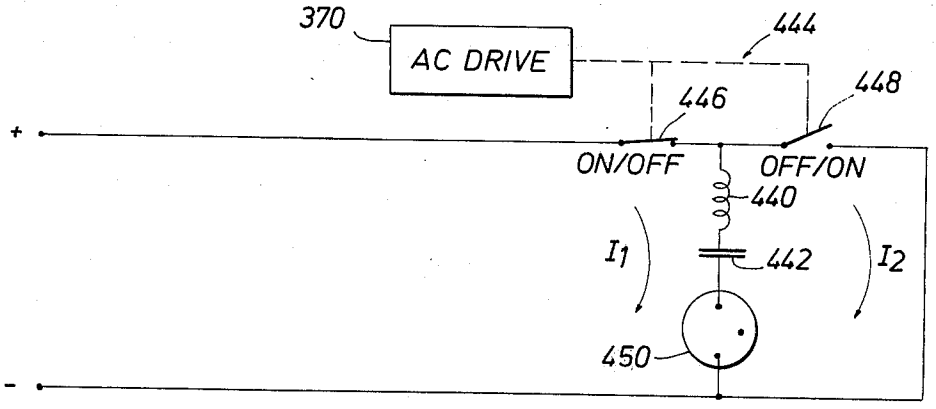


FIG. 40

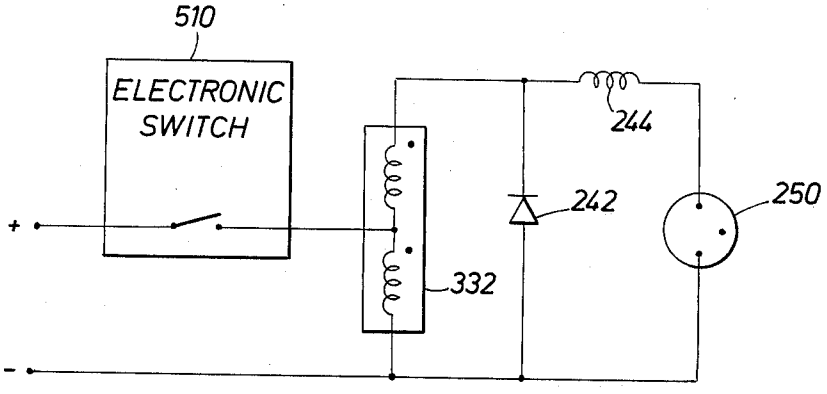


FIG. 41

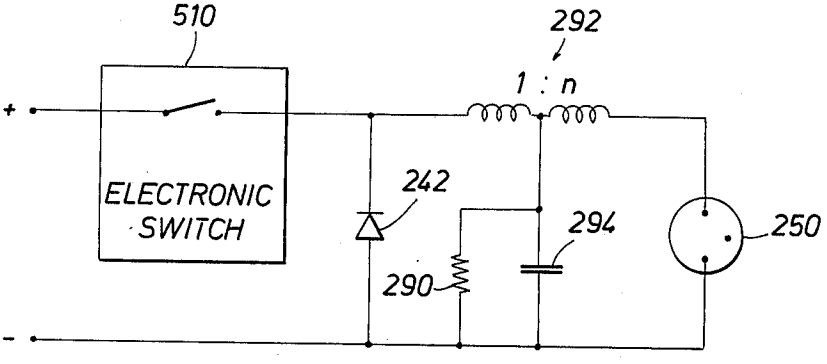


FIG. 42

FIG. 43

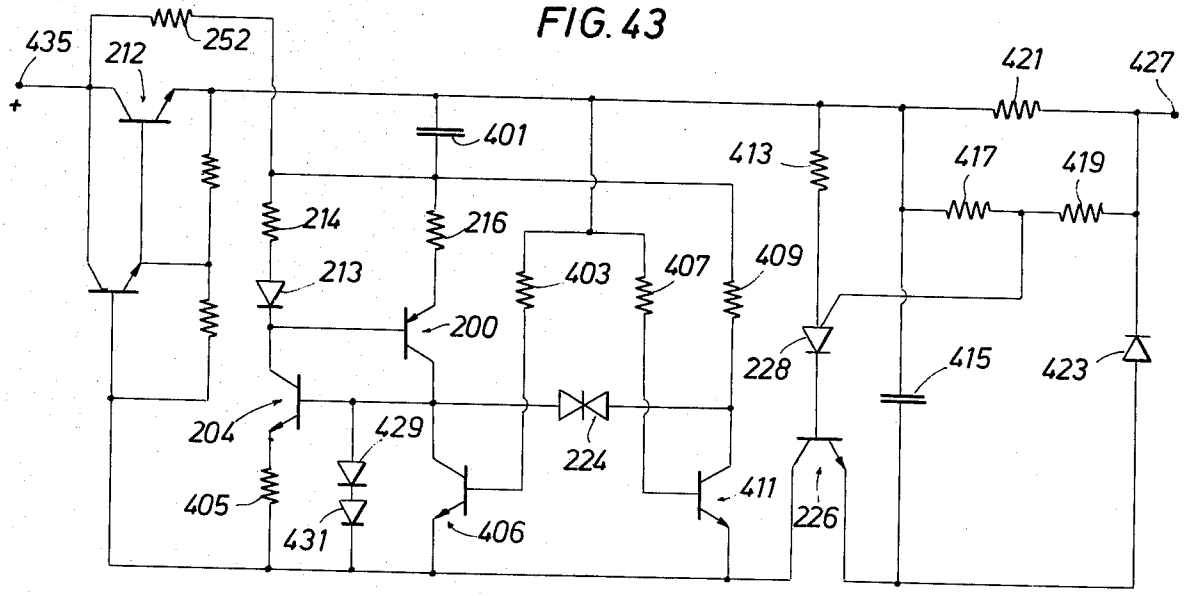
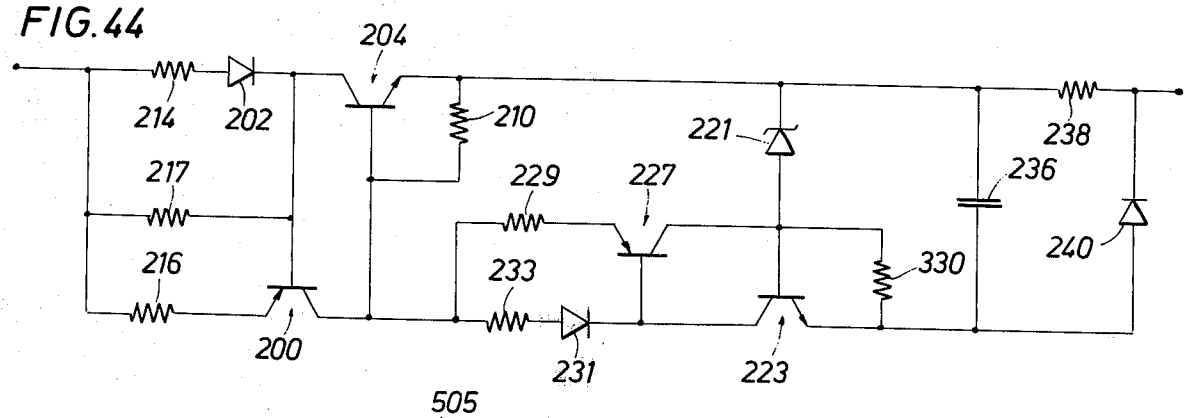


FIG. 44



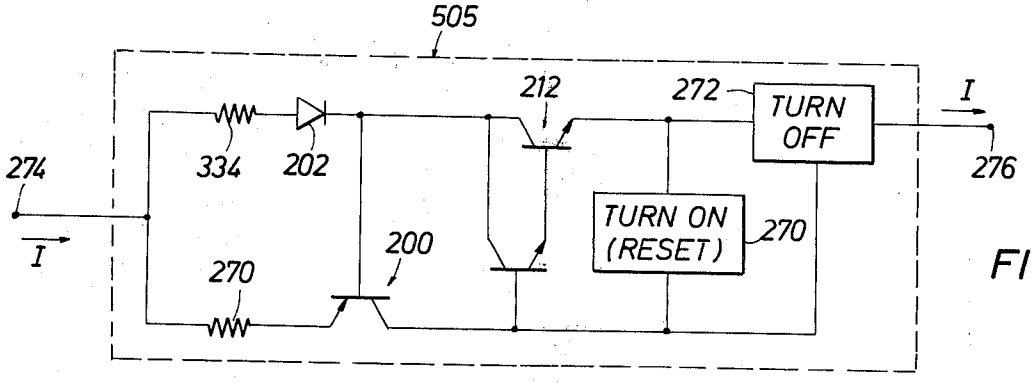


FIG. 45

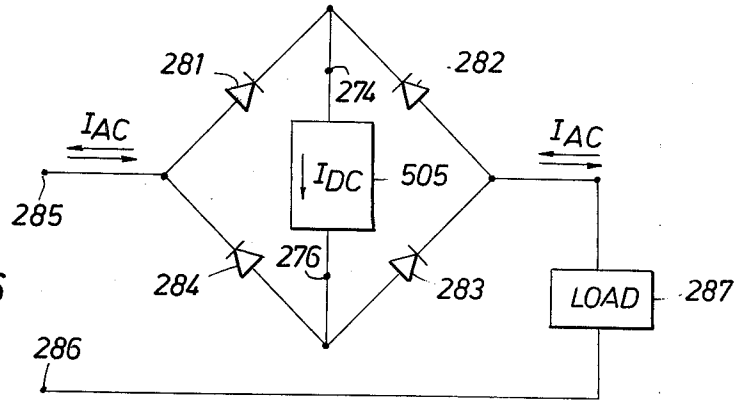


FIG. 46

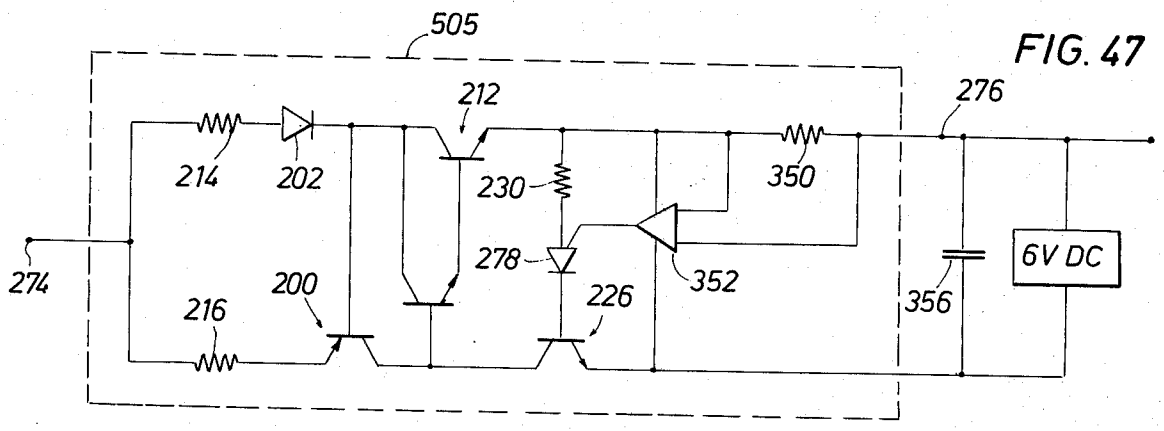


FIG. 47

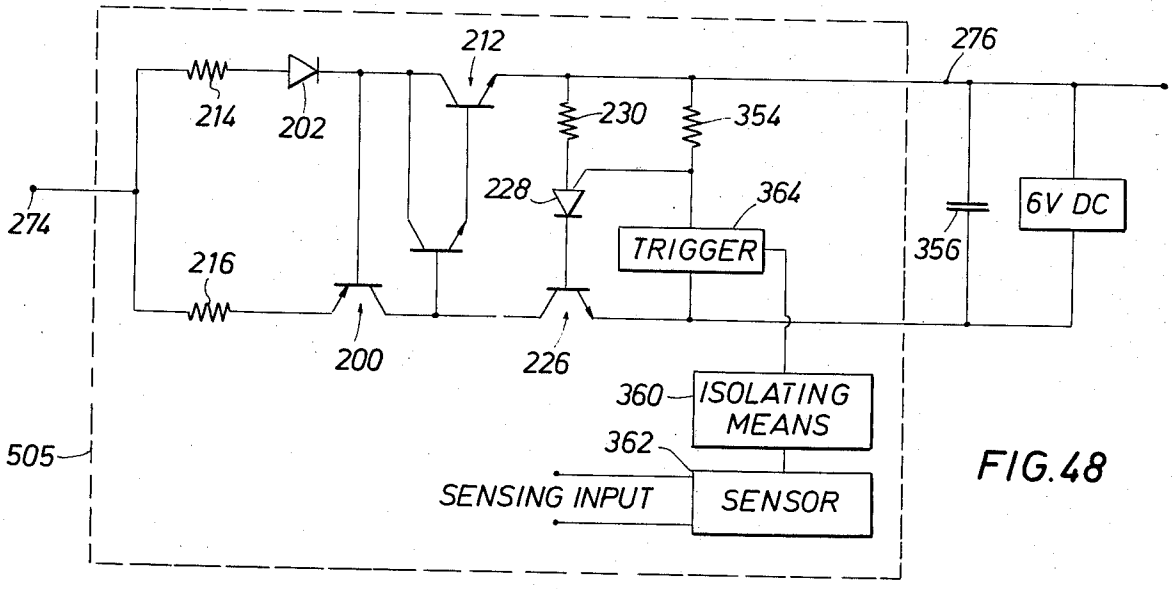


FIG. 48

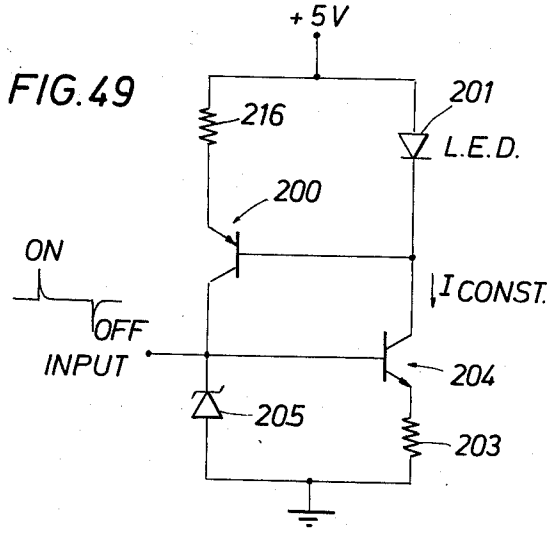


FIG. 49

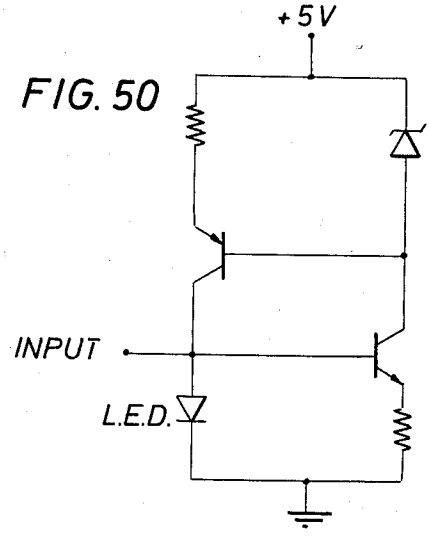


FIG. 50

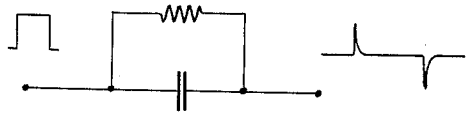


FIG. 51

SOLID STATE SWITCHING CIRCUIT

This application is a continuation-in-part of copending application Ser. No. 433,834, filed Jan. 15, 1974, now abandoned, of the same inventor.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to switching circuits, such as switching circuits used in ballast circuits for high intensity gaseous discharge lamps utilizing mostly solid state devices.

2. Description of the Prior Art

Conventional ballasting of high intensity discharge lamps, such as metal-additive arc lamps, employ transformers, capacitors, or inductor coils in various combinations to provide proper voltage for starting and for limiting the current during operation. Such ballasts are large, relatively expensive, and not efficient at low cost. Furthermore, the simple inductor ballast provides poor regulation for line voltage variations.

Regulated solid state ballasts have been developed, but heretofore no commercial ballast has been developed which is suitable for coping with the starting and operating conditions of high pressure mercury, sodium and metal halide lamps to give proper control of lamp wattage for wide ranges of lamp voltages, line voltage fluctuations and temperatures.

High frequency switching regulators in combination with an inductor have been employed under ideal conditions, but without success on a commercial scale. Such prior art attempts have included a low rectification efficiency bridge and capacitor circuit for converting applied ac to nearly pure dc for operation. In addition, such attempts have included complex sensing networks for sensing current and voltage at the load and providing feedback to control the duty cycle of the switching circuit. Moreover, such circuits have been three-terminal devices, rather than the preferred two-terminal devices. In addition to the expensive complexities and use of high precision components, high losses in the drive circuit has also resulted in low overall circuit efficiency.

Therefore, it is a feature of this invention to provide an improved ballasting circuit for a high intensity discharge lamp that includes a switching circuit which operates at high energy levels with low energy losses, and which provides satisfactory switching over a wide range of voltage fluctuations and temperature conditions, such operation achieving relatively low energy consumption.

It is another feature of this invention to provide an improved ballasting circuit for high intensity discharge lamps that is self-regulating to provide uniform average current to the lamp with fluctuations in applied line voltage.

It is yet another feature of the present invention to provide improved positive, high-speed, on-off switching of a silicon controlled switching circuit.

It is still another feature of this invention to provide an improved positive, high-speed, on-off switching device for application in either an ac or a dc circuit breaker application.

It is yet another feature of this invention to provide a means for encapsulating the basic components of an improved positive, high-speed, on-off switching device.

It is still another feature of this invention to provide an improved bi-stable light emitting diode circuit employing a positive, high-speed circuit.

SUMMARY OF THE INVENTION

A preferred embodiment of the present invention includes a regulating ballast circuit for a high intensity discharge lamp, comprising a solid-state switching circuit, turn-on means, turn-off means, and a small inductor element in series with the lamp. The switching circuit utilize high-gain, high-beta means in the form of a Darlington pair. Also employed is a transistor connected as a current source for the Darlington pair. Hence, the turn-off gain of the switching circuit is not dependent on the product of the betas of the transistors, but is related to the resistance values in the load circuits for the current source transistor and the Darlington pair.

The time required to turn on the switch is determined by the line voltage charging an RC network and a diac. The time required to turn off the circuit is determined by a current sensing programmable unijunction circuit.

Switching rate of the switching circuit is determined by the level of the applied line voltage and of the lamp voltage. Variations effect the frequency of the switching and hence the current through the lamp is not maintained constant, but the cyclical switching does provide uniform average current values, thereby achieving regulation. Also, the rectification circuit to convert the applied ac to dc may be simple. There is no need for a large filter capacitor even though the applied line voltage may be high in ripple content. Such ripple does not degrade operation of the circuit.

Several alternate circuit variations for the switching circuit, the turn-on means and the turn-off means are also disclosed for achieving comparable switching performance.

In addition, the switching circuit is disclosed in applications other than in a regulating ballast circuit for a high intensity discharge lamp. for example, it is shown as a high speed fuse, as a driving circuit for light emitting diodes and in encapsulated form for general application.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above-recited features, advantages and objects of the invention, as well as others which will become apparent, are attained and can be understood in detail, more particular description of the invention briefly summarized above may be had by reference to the embodiments thereof which are illustrated in the appended drawings, which drawings form a part of this specification. It is to be noted, however, that the appended drawings illustrate only typical embodiments of the invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

In the Drawings:

FIG. 1 is a simplified schematic diagram of a prior art switching circuit.

FIG. 2 is a simplified schematic of another prior art switching circuit.

FIG. 3 is a schematic diagram of the basic switching circuit employed in the present invention.

FIG. 4 is a schematic diagram of a preferred embodiment of the switching circuit employed in the present invention.

FIG. 5 is a block diagram of a preferred embodiment of the present invention.

FIG. 6 is a schematic diagram of a preferred embodiment of the present invention.

FIG. 7 is a waveform diagram of some representative voltage and current values of the circuit illustrated in FIG. 6.

FIG. 8 is a waveform diagram showing the current being regulated through the lamp by the embodiment of the invention illustrated in FIG. 6.

FIG. 9 is a simplified schematic diagram of the basic turn-on circuit employed in the present invention.

FIG. 10 is a simplified schematic diagram of the basic turn-off circuit employed in the present invention.

FIG. 11 is a simplified schematic diagram of another embodiment of a turn-off circuit employed in the present invention.

FIGS. 12–18 are simplified schematic diagrams of device variations employable in the basic turn-on and turn-off circuits employed in the present invention.

FIG. 19 is a simplified schematic diagram of yet another turn-off circuit employed in the present invention.

FIG. 20 is a simplified schematic diagram of another turn-on circuit having a turn-off element employed in the present invention.

FIG. 21 is a simplified schematic diagram of yet another turn-on circuit employed in the present invention.

FIGS. 22–25 are simplified schematic diagrams of illustrative constant current sources that may be employed in the turn-on circuit employed in the present invention.

FIG. 26 is a simplified schematic diagram of still another turn-on circuit employed in the present invention, employing a turn-off aid.

FIG. 27 is a simplified schematic diagram of yet another turn-on circuit that may be employed in the present invention, including a turn-off aid.

FIG. 28 is a schematic diagram of a turn-off circuit in accordance with the present invention including diodes connected for high speed operation.

FIG. 29 is a partial schematic diagram of a ballast circuit in accordance with the present invention including components for reducing frequency of operation during warm-up of the associated high intensity discharge lamp.

FIG. 30 is a schematic diagram of a gain reduction network which may be employed with a turn-off circuit in accordance with the present invention.

FIG. 31 is a schematic diagram of an encapsulated prior art switching circuit.

FIG. 32 is a schematic diagram of an encapsulated switching circuit in accordance with the present invention.

FIG. 33 is a schematic diagram of another encapsulated switching circuit in accordance with the present invention.

FIG. 34 is a schematic diagram of a preferred encapsulated switching circuit in accordance with the present invention.

FIG. 35 is a schematic diagram of an encapsulated turn-off circuit in accordance with the present invention.

FIG. 36 is a partial schematic, partial block diagram of the switching circuit of the present invention employed to connect a dimmer circuit into a gas discharge ballast circuit.

FIG. 37 is a partial schematic, partial block diagram of another switching circuit of the present invention employed to connect a dimmer circuit into a gas discharge ballast circuit.

FIG. 38 is a partial schematic, partial block diagram of a preferred embodiment of the switching circuit of the present invention employed to connect a dimmer circuit into a gas discharge lamp circuit.

FIG. 39 is a simplified schematic diagram of an application of an electronic switch to a ballast lamp through a phase reversing DPDT relay in accordance with the present invention.

FIG. 40 is a simplified schematic diagram of an application of an electronic switch to a ballast lamp through an LC switching circuit, thereby providing ac current to the lamp.

FIG. 41 is a simplified schematic diagram of an application of an electronic switch in accordance with the present invention, the connection being made to a ballast lamp through an autotransformer.

FIG. 42 is a simplified schematic diagram of an application of an electronic switch in a starter circuit for a ballast lamp in accordance with the present invention.

FIG. 43 is a schematic diagram of the electronic switch as a low power switching circuit to control a high powered transistor.

FIG. 44 is a schematic diagram of an alternate connection for a switching and a turn-off circuit in accordance with the present invention.

FIG. 45 is a simplified schematic and block diagram of an electronic switch in accordance with the present invention in an application as an electronic fuse in a dc circuit.

FIG. 46 is a block diagram of the electronic fuse shown in FIG. 45 connected in an ac circuit.

FIG. 47 is a simplilied schematic diagram of an electronic fuse as shown in FIG. 45 including a preferred embodiment of a turn-off circuit in accordance with the present invention.

FIG. 48 is a simplified schematic diagram of an electronic fuse as shown in FIG. 45 including an alternate embodiment of a turn-off circuit in accordance with the present invention.

FIG. 49 is a simplified schematic diagram of a switching circuit in accordance with the present invention in an application with a bi-stable light emitting diode.

FIG. 50 is a simplified schematic diagram of a switching circuit in accordance with the present invention in another application with a bi-stable light emitting diode.

FIG. 51 is a simplified schematic diagram of a circuit useful as the interface between digital logic and a bi-stable light emitting diode for turning on and off the device shown in FIGS. 49 and 50.

DESCRIPTION OF PREFERRED EMBODIMENTS

Now referring to the drawings and first to FIG. 1, a prior art switching circuit is shown comprising two transistors and a resistor. The input to the circuit is applied to the base of npn transistor 14. A resistor 10 is connected to the collector of transistor 14 and to the applied dc supply voltage. A pnp transistor 12 is connected so that the base thereof is connected to the collector of transistor 14, the collector is connected to the base of transistor 14 and the emitter is connected to the applied dc voltage source.

In operation of the FIG. 1 circuit a trigger voltage (and current) pulse is applied to the base of transistor

14. The turn-on voltage is illustrated as a positive-going spike and the turn-off voltage is illustrated as a negative-going spike. Although illustrated as a spike, the triggering pulse may be any shape of low energy pulse that attains the required minimum amplitude. Other than this limitation, neither the amplitude nor the pulse width is critical. The pulse input applied to the base of transistor **14** turns on the transistor and establishes a current flow through the base-emitter junction thereof and a following current flow through the collector and emitter. The current flow through the collector results in current through resistor **10,** and hence a voltage drop there across. This voltage drop causes an emitter-base forward biasing of transistor **12,** which causes it to turn on. Transistor **12** is a low gain transistor and once turned on draws a small amount of the current through its emitter and collector passing from the power connection. The current flow is sufficient to cause the circuit to be regenerative until the negative input or triggering spike is applied. A total gain of one for transistors **12** and **14** is required for sustaining operation. This gain value is determined by the products of the betas of the two transistors.

Turn off is achieved by the application of a negative pulse. In this instance, the base current is removed from transistor **14** (actually the current from transistor **12** is drawn off at the input terminal) and the negative nature of the input reverse biases the base-emitter junction of transistor **14,** further ensuring turn off. When transistor **14** turns off, transistor **12** turns off, thereby completing the switching action until receipt of another positive input pulse.

It is apparent that the gain of transistor **12** has to be within narrow and well-defined limits to achieve proper switching and the high turn-off gain that is desired. If the gain of transistor **12** is too low, then transistor **12** would not conduct enough in order to cause regenerative current flow with transistor **14** to cause the circuit to latch on. On the other hand, if the gain of transistor **12** is too high, then the turn off gain (i.e., I_{load}/I_{in}) of the circuit would be low, resulting in a low ratio of the load current to required input turn-off current.

Hence, it may be seen that the criticality of the selection of a transistor **12** having proper but low beta properties is important. Not only is such selection expensive from a commercial view point, high and low temperature and load current conditions changing the beta operation points have extremely adverse effects on operation of a practical circuit.

An important variation of the switch circuit shown in FIG. **1** is illustrated in FIG. **2,** wherein a resistor **11** is added connected to the emitter of transistor **12.** This circuit is illustrated as a variable gain transistor (resistor **11** being a variable component) in General Electric Transistor Manual, 1964, at page 401. The circuit is identical in operation to the circuit of FIG. **1,** except that the amount of regeneration can be varied by changing the value of resistor **11.** Hence, this gives control over the beta of the circuit.

Now referring to FIG. **3,** the basic switching mechanism of the present invention is illustrated. The only difference between this circuit and the one illustrated in FIG. **2** is the addition of diode **15,** connected between the collector of transistor **14** (and the base of transistor **12**) and resistor **10.** As will be more completely explained in connection with the FIG. **4** circuit, diode **15** provides a voltage drop which closely matches the voltage drop across the base-to-emitter junction of transistor **12.** This has the effect of making the effective turn-off gain of the circuit substantially independent of the betas of the transistors and, hence, determinable by the resistance ratio of resistors **10** and **11.**

Now referring to FIG. **4,** the switching mechanism of the preferred embodiment of the present invention is illustrated. In this embodiment, high beta transistor means in the form of transistors **16** and **18** connected as a Darlington pair is used as the high gain portion of the switching circuit. Typically, a Darlington pair exhibits high betas of 50–100 or more over a wide range of currents. Conventionally base-to-emitter resistors **20** and **22,** respectively, form shunts for base to emitter. Pnp transistor **24** is connected to the Darlington pair so that the base thereof is connected to their collectors and the collector of transistor **24** is connected to the base of transistor **16.** A resistor **26** shunts the base and the emitter of transistor **24.** Diode **28** shunted by resistor **30** is connected to the collectors of the Darlington pair. Finally, resistors **32** and **34** are connected to the power connection and then, respectively, to the emitter of transistor **24** and to diode **28.**

In operation, the circuit of FIG. **4** may be compared with the operation of the prior art circuits shown in FIGS. **1** and **2,** with some important differences to be hereafter explained. For example, an input spike applied to the base of transistor **16** will cause the Darlington pair to turn on, resulting in a current flow in the collector circuit thereof, and, hence, through resistor **34** and diode **28.** The voltage drop across the base-to-emitter junction of transistor **24** turns this transistor on, thereby providing the base current to transistor **16** to sustain regenerate circuit operation.

It should be noted that a Darlington pair has an extremely high beta over a wide range of collector currents and over a wide range of temperatures. Therefore, the beta of transistor **24** can be either high or low and not effect the turn-on operation of the circuit. That is, the beta of transistor **24** is not critical to operation. It may be recalled that the betas of transistor **12** and **14** are critical in the prior art circuits shown in FIGS. **1** and **2.** More importantly as will be explained below, the beta of transistor **24** is not critical in the operation of the circuit at turn off, either.

At turn off, the negative applied pulse again draws the current through transistor **24** away from the base of transistor **16** and also reverse biases this transistor, thereby turning it off. However, the operation of transistor **24** is like a current source, rather than the prior art voltage source (e.g., transistor **12** of FIG. **1**), and the application of a small negative pulse is sufficient to cause turn off without first increasing the amount of current drawn through transistor **24.**

The components connected to transistor **24** ensure that for a wide range of operation (i.e., temperature, voltage, collector currents) only the ratio of resistors **32** and **34** are important, not the betas of the respective transistors. Diode **28** provides a forward voltage drop comparable to the base-to-emitter voltage drop of transistor **24.** To ensure low charge storage time, resistor **30** is shunted across diode **28,** although it may be omitted when a sufficiently fast-acting diode is employed. Resistance **26** increases the collector-to-emitter voltage capability of transistor **24** by reducing the leakage current therethrough.

If with the various operating currents, the voltage drop across diode **28** and across the base-to-emitter junction of transistor **24** are nearly equal to each other,

then the voltage drop across resistors **32** and **34** remains nearly equal. Hence, the ratio of these resistance values determines the ratio of currents through transistor **24** and transistor **18,** not the betas of the transistors, and hence, current turn-off gain is constant.

At turn off, transistor **24** cannot furnish more current than the resistor ratio permits. Hence, the current through transistor **24** is kept low and the effective turn-off current gain is high. The expression "turn-off current gain" as used herein is defined as the ratio of the load current to the input or control current at turn off. In FIG. **4,** the load current is the current flowing out of terminal E and the control current is the current flowing to and from input terminal B. By making the switching circuit portion of the regulating ballast circuit independent of the betas of the transistors and the input pulses of low energy and duty cycle, it is possible to use such circuit in an overall improved ballast circuit for regulated, low-loss operation of a high intensity discharge lamp.

Althought pulsing on and off was discussed above with respect to pulses applied to the base of the npn transistor (or Darlington pair), if desired pulsing may be with respect to the base of pnp transistor **24.**

Now referring to FIG. **5,** a block diagram of a high intensity discharge lamp ballast employing solid state switching regulation in accordance with the present invention is shown. An ac input is applied to dc power converter **41,** which, in turn, is connected to lamp **80** via connector **43** and to switching circuit **17** via connector **45.** Switching circuit **17** may be the circuit illustrated in FIG. **4** or may be one of the alternatives hereinafter disclosed.

Switching circuit **17** is connected both to voltage sensing turn-on circuit **57** and to current sensing turn-off circuit **73,** as hereinafter disclosed. The output of these circuits are connected to output circuit **61** and starting circuit **63,** which deliver power to lamp **80.** In many embodiments hereinafter described, the output circuit is adequate to handle the power requirements encountered during starting conditions and therefore there is no separate starting circuit **63** in these embodiments.

Now referring to FIGS. **5** and **6,** a preferred embodiment of an overall ballast circuit is shown utilizing the switching circuit of FIG. **4.** In this circuit, three pairs of rectifying diodes **40** and **42, 44** and **46,** and **48** and **50** are shown connected to a three phase ac input. The rectification is sufficient for operation, since it will be observed that the quality of the dc is reasonably good, there being only about **4** percent ripple. However, no further filtering is required for satisfactory performance since the high frequency operation of the circuit provides adequate regulation in spite of ripples occurring at low line frequencies.

The dc applied to the circuit will be applied through resistor **34,** diode **28,** resistor **52** connected thereto and capacitor **54** connected between resistor **52** and the output from the switching regulator. Alternatively, the end of resistor **52** connected to the collector of transistor **18** may be connected to the circuit input, or in other words, to the junction connection of resistors **32** and **34.** Connected also to capacitor **54** is the series connection of resistor **56** and diac **58,** which, in turn, is connected to the base of transistor **16.** Voltage builds up on capacitor **54** as shown at V_{cl} on FIG. **7** until it reaches the threshold level necessary to fire diac **58.** When this occurs, a current I_{cl} discharges therethrough to be applied to the base of transistor **16.** This causes turn on of the switching circuit, as explained above, and an output V_o. The illustration of I_c, through capacitor **54** is drawn negative-going for convenience, but to correspond to the waveform related to FIG. **7,** may be thought of as a negative build up with a positive spike to initiate turn on.

After turn on, there is a current flow I_o through inductor **60** connected in series with lamp **80.** The build up of I_o is exponential as shown in FIG. **8.**

The turn-off circuit includes programmable unijunction transistor **62** connected to the output of the switching circuit through resistor **64.** The output for the unijunction is connected to the base of npn transistor **74** and the gate of the unijunction is connected to a parallel combination of resistor **66** and capacitor **68.** Capacitor **68** is a small capacitor and provides a small delay to prevent premature firing of the unijunction. A capacitor **70** connected at the output of the regulator is charged by the voltage resulting from the current flow through resistor **72,** connected to supply current to inductor **60.** Resistor **67** is connected in series with resistor **66** and, together with resistor **66,** is connected in parallel with resistor **72.** When the gate voltage threshold for unijunction **62** is reached, a discharge path is provided through resistor **64,** unijunction **62** the emitter-base junction of transistor **74,** and capacitor **70.** Diode **76** prevents discharge of capacitor **70** through the resistor **72** charging path. Turn on of transistor **74** provides a path for the drawing of the current from the base of the Darlington pair or the current of transistor **24** and of reverse biasing the baseemitter junction of the Darlington, as explained above.

Diode **78** is connected across inductor **60** and lamp **80** and acts as a flyback or free-wheeling diode for providing a conducting path for the current in inductor **60.**

FIG. **8** illustrates the good regulation properties of the circuit. For purposes hereof, "effective current" is defined as either being the average current or the rms current. The term does not mean either instantaneous current or peak current. A duty cycle regulation of substantially constant effective current is achieved by the circuits herein used in a lamp ballast application. The dotted line assumes the build up of I_o through the lamp at nominal line voltage. The current build up and decay times are as previously explained. Charge up time of I_o through the switch is determined by the value of

$$\frac{V_o - V_L}{L},$$

wherein V_o is the output voltage from the switching regulator, V_L is the voltage across lamp **80** and L is the value of the inductance of inductor **60.** V_o is nearly equal to the input voltage (only less the small voltage drops across resistor **34,** resistor **72,** diode **28** and the collector-to-emitter junctions of the Darlington when fully saturated). A higher V_o causes a more rapid build up of I_o and a lower V_o causes a slower build up of I_o. The decay is always the same slope, viz., the slope caused by the time constants of the inductance of inductor **60** and the resistances of lamp **62** and diode **78.** (Lamp **80** is nearly pure resistance at high frequencies.) However, the minimum value of I_o is not always the same. Therefore, the curve in solid line of FIG. **7** corresponding to a lower applied voltage, terminates at a lower value than for the dotted curve. (That is, the build-up of the turn-on charge on capacitor **54** is longer

than for the nominal input voltage and therefore I_o has time to reach a lower value.) The area under the curves, however, are essentially equal and therefore the regulation is kept relatively constant.

In like manner, a higher-than-nominal line voltage would cause I_o to build up faster and would also cause it to have a shorter down side. But, the area would remain relatively constant to provide good regulation.

Illustrated in FIGS. **9–18** are several alternate component variations that may be employed in the circuit of FIG. **6.** For convenience of illustration, FIG. **9** is the basic turn-on circuit comprising resistors **52** and **56,** capacitor **54** and diac **58,** exactly as they are shown in FIG. **6.** Further for convenience, the connection to resistor **52** is marked as reference point C, the point between resistor **56** and diac **58** is marked as reference point A, the connection to capacitor **54** is marked as reference point E, and the connection to diac **58** is marked as reference point B.

First, it is permissible that resistor **56** and diac **58** be reversed without effecting operation. This reversal of position is also permissible with all of the devices of FIGS. **12–18,** as hereafter explained.

The devices illustrated in FIGS. **12–18** may be substituted between reference points A and B of FIG. **9** for diac **58.** FIG. **12** illustrates a silicon bilateral switch (SBS); FIG. **13** illustrates a 4-layer diode; FIG. **14** illustrates a silicon unilateral switch (SUS); FIG. **15** illustrates a programmable unijunction transistor (PUT) with two resistors; and FIG. **16** illustrates a silicon controlled rectifier (SCR) with two resistors.

FIG. **17** and FIG. **18** illustrate additional device arrangements that can be connected between points A and B. FIG. **17** is a PUT device with connecting terminals suitable for connection, to any of the devices illustrated in FIGS. **12–16.** Also a Zener diode may be similarly connected. FIG. **18** is an SCR device with connecting terminals suitable for connection to any of the devices illustrated in FIGS. **12–16.** Also, a Zener diode may be similarly connected.

FIG. **10** illustrates a circuit which is the basic turnoff circuit of FIG. **6,** deleting only small capacitor **68.** In addition, a zener diode may be substituted for resistor **67,** if desired. FIG. **11** shows a suitable turn-off alternative device variation in which SBS **82** is connected between resistor **64** and npn transistor **74.** That is SBS **82** is the active element operating as a latching device in place of unijunction transistor **62.** In addition, the resistors connected to the gate of the unijunction transistor are not present.

For convenience of reference, the connection to resistor **64** has been marked as reference point E, the point between resistor **64** and SBS **82** has been marked as reference point D, the base of transistor **74** has been marked as reference point F, and the collector of transistor **74** has been marked as reference point B. Points B and E coincide with points similarly marked in FIG. **6.**

Again, the devices illustrated in FIGS. **12–18** may be substituted between reference points D and F, as illustrated. Moreover, in the case of FIGS. **16** and **17,** the open terminal connections are suitable for accepting any of the devices shown in FIGS. **12–16.**

FIG. **19** illustrates yet another alternate variation of turning off the basic switching circuit. In this case, PUT device **84** is connected so that its cathode is connected to the base of transistor **86** and the collector of transistor **86** is connected to the emitter of transistor **12.** As illustrated the gate of PUT **84** is connected to resistor **11** or resistor **10.** Further, the various devices illustrated in FIGS. **12–18** may be substituted for PUT device **84.**

FIG. **20** illustrates a turn-on circuit variation. Note that in this circuit the base of transistor **16–18** is connected to diode **88,** which allows good npn turn-off and permits whatever device is connected across terminals X–Y to be turned off at the same time transistor **16–18** is turned off. Any of the various turn-on devices illustrated in FIGS. **9** and **12–18** may be connected to the terminals X–Y.

FIG. **21** illustrates yet another turn-on circuit variation. This circuit is identical with FIG. **20** except that it includes terminals M–N to which a constant current source may be placed at the same time a turn-on device is placed at terminals X–Y. Alternatively a constant current source may be placed at X–Y if the turn-on device is placed at terminals M–N. FIGS. **22–25** illustrate various conventional constant current sources that may be used in conjunction with FIGS. **21, 26** and **27.** FIGS. **22** and **23** illustrate junction field effect transistors and FIGS. **24** and **25** illustrate conventional transistors, each in combination with a Zener diode, for accomplishing constant current operation.

FIG. **26** illustrates the addition to the previous circuits of an inductor **90** and series resistor **92** connected from the base to the emitter of transistor **16–18.** Note also that no diode **88** is used in this circuit. Turn on operation is the same as before. Turn-off operation is aided by the presence of inductor **90** across the emitter-base junction of transistor **16–18** independent of other turn-off circuits. That is, the LR connection shunting the base-emitter of transistor **16–18** reverse biases transistor **16–18** during turn off independent of the connection across terminals X–Y.

FIG. **27** illustrates the alternative of including an element for aiding turn-off in a turn-on device. In this embodiment, the components are the same as in FIG. **21** with the addition of resistor **94** from diode **88** to the emitter of transistor **16–18** and bypass diode **89** located across terminals M–N. When an inductor is placed across either the X–Y terminals or the M–N terminals, and a turn-on device is placed at the alternate set of terminals, a sinusoidal current pulse would flow into the base and out of the emitter. At the end of the sinusoidal pulse, the charge on capacitor **56** reverse biases the base-emitter junction, the reverse bias current flowing from capacitor **56,** through resistor **94,** through diode **88** and diode **89.** This operation has a tendency to turn-off transistor **16–18** independent of other turn-off circuits.

In order to square up the leading edge of a sinusoidal pulse, a shunting resistor across any of the inductors previously mentioned may be used.

As an additional alternative, resistor **52** in any of the above circuits may be replaced with a constant current source.

Illustrated in FIG. **28** is a method for improving the speed of turn-off of the switching circuit by the addition of diodes. For instance, diode **96** placed in parallel with resistor **20** to enhance the base-emitter reverse biasing of transistor **18.** Diodes **98** and **100** may be employed with or without diode **96** to form a "Baker" clamp (R. H. Baker, "Maximum Efficiency Switching Circuits," MIT Lincoln Laboratory Report, TR-110, 1956), keeping the Darlington pair out of saturation and reducing the amount of base storage charge. It

should be noted that slightly higher losses result during the period that the switch is turned on, but the time and switching on-off losses are much reduced.

Although several alternative circuits have been described, additional method of sensing turn-on and turn-off conditions are available. For example, tunnel diodes may be used, Schmitt triggering may be used, a pulse transformer coupled to the base emitters of the transistors may be used and current transformer terminals may be used.

Now referring to FIG. **29,** a method is shown of reducing switching frequency during lamp warm up. In this event, capacitor **54** is shorted until current I_o through inductor **60** decreases below a set level during the off condition of transistor **16–18.** This switch operation is performed by connecting an npn transistor **102** so that its base is connected to resistor **72** through resistor **104** and its emitter is connected to inductor **60** while its collector is connected to capacitor **54.** An FET may be used in place of the npn transistor **102.**

Turn-off gain can be reduced for very high I_o, and the Darlington pair kept saturated by employing the circuit shown in FIG. **30.** In this circuit, a series resistor **106** and diode **108** are shown connected in parallel around resistor **32.** The Darlington pair is kept saturated by increasing the I_B/I_o ratio with these two additional components. Whenever the voltage drop across resistor **32,** and hence resistor **106** and diode **108,** is equal to or less than 0.7 volts, the current gain is approximately equal to the ratio of the values of resistor **32** and **34.** When the voltage across resistor **32** is much greater than 0.7 volts, the current gain approaches (with higher load currents)

$$\frac{1}{R1} \times \frac{R2 \times R3}{R2 + R3}$$

where the resistance values of resistors **34, 32** and **106** are respectively designated **R1, R2** and **R3.**

Encapsulating components comprising the heart of basic circuits is common. Such encapsulation provides a package that may be presized, preassembled and pretested for inserting in a plurality of circuit applications. This is particularly advantageous for versatile circuits having a wide range of uses or for high volume circuit assembly. An appreciation of the advantages of such encapsulation may be further realized when it is considered that such circuits can be even manufactured to a great extent simultaneously using a common semi-conductor chip or slice as a substrate for some or all of the components in the assembly. Further, through photoengraving or similar techniques, the interconnecting wiring of the components may also be made as a manufacturing step in the making of the solid state assembly.

For example, complementary transistors **112** and **114,** identical to transistors **12** and **14** shown in FIGS. **1** and **2,** may be packaged in a common capsule as shown in FIG. **31.** Four terminals to the capsule provide for external connections. The collector of pnp transistor **112** is connected to terminal **300** and to the base of transistor **114.** The emitter of npn transistor **114** is connected to terminal **303.** The collector of transistor **114** is connected to terminal **302** and the base of transistor **112.** The emitter of transistor **112** is connected to terminal **301.** As is apparent, the transistors may be connected with appropriate resistors into either the circuit shown in FIG. **1** or in the circuit shown in FIG. **2,** or with the addition of a diode, into the circuit shown in FIG. **3.**

FIG. **32** shows an encapsulated, high speed, switching circuit in accordance with the present invention. Again, this embodiment has four terminals **300, 301, 302** and **303** for external connections. Terminal **300** is connected to the collector of pnp transistor **200** and to the base of npn transistor **204.** Terminal **301** is connected to the emitter of pnp transistor **200.** Terminal **302** is connected to the anode of diode **202** and the cathode of the diode is connected to the base of transistor **200** and to the collector of transistor **204.** Terminal **303** is connected to the emitter of npn transistor **204.** Transistor **204** is chosen such that it will exhibit a high gain over a wide range of applied operating currents.

In operation for high speed switching in accordance with the present invention, terminal **301** and **302** may be connected through external resistors to an external positive power source. When a positive voltage with respect to terminal **303** appears on terminal **300,** the base-emitter junction of transistor **204** is forward biased, and current flows from the power source through diode **202,** into the collector of transistor **204,** and out the emitter of transistor **204.** At this time, voltage on the collector of transistor **204** decreases, causing the base-emitter junction of transistor **200** to be forward biased. Therefore current begins to flow into the emitter and out of the collector of transistor **200.**

Since the voltage drop across diode **202** very nearly approximates the base-to-emitter voltage drop of transistor **200,** the ratio of the currents flowing in the collector of transistor **204** and the collector of transistor **200** is very nearly approximated by the ratio of the external resistors to which terminals **301** and **302** are connected.

Essentially all the current flowing in the collector of transistor **200** flows into the base of transistor **204.** Therefore the ratio of collector current in transistor **204** to the base current in transistor **204,** i.e., the forced gain of transistor **204,** is determined by the ratio of the external resistors connected to terminals **301** and **302,** and the ratio is not dependent on the value of the beta of transistor **204,** as was the case in the prior art.

When a negative voltage appears on terminal **300** with respect to terminal **303,** the base-emitter junction of transistor **204** is reversed biased, and the transistor cuts the current off, i.e., collector and emitter currents cease to flow. The voltage on the collector of transistor **204** increases and the voltage across diode **202** and the external resistance connected to terminal **302** goes to zero, during which time transistor **200** is reverse biased by the external voltage across the external resistance connected to terminal **301.** Therefore, transistor **200** also turns off and the switching circuit returns to what might be termed its off condition.

The encapsulated device of FIG. **33** is an improvement in the high speed switching circuit of FIG. **32.** This improvement is accomplished by the inclusion of resistors **206, 208** and **210.** One end of resistor **208** is connected to the base of transistor **200** and the other end of resistor **208** is connected to the emitter of transistor **200.** One end of resistor **210** is connected to the base of transistor **204** and the other end of resistor **210** is connected to the emitter of transistor **204.** Both resistors **208** and **210** therefore shunt the base-emitter junction of transistors **200** and **204,** respectively. A shunt resistor connected in this manner prevents collector-to-base leakage current from being amplified by the beta

of shunted transistor **200**. Resistor **206** is connected in parallel with diode **204** to reduce the forward recovery time of diode **202** so that the base-emitter junction of pnp transistor **200** will not remain forward biased when turn off is desirable.

The switching circuit of FIG. **33** operates in exactly the same manner as the circuit in FIG. **32**, with the exception that the leakage currents are now better controlled, and that the forward recovery time of diode **202** is now reduced.

FIG. **34** shows high speed switching device **500**, which has five terminals **300, 301, 302, 303** and **304**. The device **500** is very similar to the device of FIG. **33** except that Darlington transistor **212** is substituted for transistor **204**. Note that the collector of the Darlington, the base of the Darlington, and the emitter of the Darlington are substituted directly for the collector, base and emitter of transistor **204**, respectively. Darlington transistor **212** is such that it is provided with internal shunt resistors across each base-emitter junction of the two transistors. This switching circuit operates in a manner identical to that described in FIG. **32**. The utilization of Darlington transistor **212** is an improvement over transistor **204** in that a Darlington configuration inherently exhibits a high gain over a wide range of operating currents, which is important in the application in FIG. **34**. Note further that connection terminals **301** and **302** may be internally or externally connected together if the ratio of the emitter current to base-emitter voltage of transistor **200** is matched with the ratio of current through diode **202** to the voltage thereacross.

FIG. **35** shows an encapsulated turn-off circuit in accordance with the present invention and is identified as device **501**, having terminals **320, 321, 322** and **323**. Device **501** is connected thusly: terminal **320** is connected to a first end of resistor **230**, to a first end of resistor **232**, to a first end of capacitor **236**, and to a first end of resistor **238**; terminal **321** is connected to the second end of resistor **238** and to the cathode of diode **240**; terminal **322** is connected to the collector of transistor **226**; terminal **323** is connected to the anode of diode **240** to the second end of capacitor **236**, to a first end of resistor **234**, and to the emitter of transistor **226**; the second end of resistor **234** is connected to the second end of resistor **232** and to the gate of programmable unijunction transistor (PUT) **228**; the cathode of PUT **228** is connected to the base of npn transistor **226**; and the anode of PUT **228** is connected to the second end of resistor **230**. Alternatively, resistor **234** may be replaced by a zener diode or any of the devices shown in FIGS. **12–18** discussed above.

In operation, terminal **321** is preferably connected to ground, a negative voltage source may be applied to terminal **323**, and a dc current flows into terminal **320**. The dc current flowing into terminal **320** flows into the first end of resistor **238** to ground creating a voltage drop across resistor **238**. This voltage drop plus the negative voltage of the source connected to terminal **323** equals the voltage across capacitor **236**. When the voltage across capacitor **236** is such that the anode-to-gate voltage of PUT **228** exceeds 0.5 volts (determined by resistors **230, 232** and **234**), current flows from the anode to the cathode of PUT **228**. This provides a forward bias for the base-emitter junction of npn transistor **226**. This forward bias turns on transistor **226**, thereby allowing the current from capacitor **236** to flow through resistor **230** and through the emitter of transistor **226**. At this time, current is also flowing in the collector of transistor **226** in a direction inward from terminal **322** into device **501**. When the charge on the capacitor is reduced to such a level that the voltage between the anode of PUT **228** and the gate of PUT **228** is less than 0.5 volts, PUT **228** turns off. Therefore, the forward bias to the base of transistor **226** is removed, and transistor **226** turns off.

It is noted that the expression from the voltage across capacitor **236** is given by the formulas:

$$Vc_{236} = \text{negative source voltage} + I_o R_{238},$$

when a negative voltage applied to terminal **323** is present, and

$$Vc_{236} = I_o R_{238} - V_{240}$$

when no negative voltage is present.

If the negative source voltage is increased (i.e., made more negative), the amount of current I_o that flows before PUT **228** starts to conduct decreases.

It should be noted that any of the encapsulated switching circuits shown in FIGS. **32–34** may be encapsulated together with the turn-off circuit of FIG. **35** in the same capsule or package.

FIG. **36** illustrates a utilization of encapsulated devices **500** and **501** plus additional circuitry to achieve an effective ballast lamp dimmer circuit. FIG. **36** is connected as follows: a first end of inductor **244** is connected to the cathode of diode **242**; the second end of inductor **244** is connected to a first terminal of ballast lamp **250**; the second terminal of ballast lamp **250** is connected to the anode of diode **242**, to a first end of resistor **216**, and to a first end of resistor **214**; the second end of resistor **214** is connected to terminal **302** of a device **500**; the second end of resistor **216** is connected to terminal **301** of device **500**; terminal **300** of device **500** is connected to terminal **322** of a device **501** and to a first end of diac **224**; terminal **303** of device **500** is connected to terminal **320** of device **501** and to a first end of capacitor **220**; the second end of capacitor **220** is connected to a first end of resistor **222**; second end of resistor **222** is, in turn, connected to the second end of diac **224**; terminal **321** of device **501** is connected to ground; terminal **323** is connected to a negative dimmer control voltage source **225**; and the ends of resistor **252** are connected respectively to terminal **304** of device **500** and the junction of the second end of capacitor **220** and the first end of resistor **222**.

When an external dc power is applied to the junction of the cathode of diode **242** and the first end of inductor **244**, current flows through lamp **250**, through resistor **214**, and through resistor **252**, thereby increasing the voltage on capacitor **220**. When the voltage on capacitor **200** is such that the forward breakover voltage of diac **224** is exceeded, current flows through diac **228** into terminal **300** of device **500**. This current flowing into terminal **300** forward biases the Darlington transistor **212** included in device **500** (i.e., the switch of device **500** is turned on). Current from the lamp then flows through resistor **214**, through the "on" switch of device **500**, out terminal **300** of device **500**, into terminal **320** of device **501**, through resistor **238** included in device **501**, and out terminal **321** of device **501** to ground.

Recalling the description of encapsulated device **501** from FIG. **35**, when the voltage of capacitor **236** of device **501** is such that the anode-to-gate voltage of PUT **228** exceeds 0.5 volts, the PUT is turned on, thereby providing a forward bias to the base-emitter junction of transistor **226**. This forward bias causes current to flow in the collector of transistor **226** in a direction from ter-

minal 300 to terminal 322. This current flow reverse biases the base-emitter junction of Darlington transistor 212 included in device 500, thereby attempting to turn off Darlington 212.

The circuit of FIG. 36 has some control disadvantages, however, when the external dimmer control voltage connected to terminal 323 of device 501 exceeds approximately 1.5 volts. It is conceivable that in that instance, once PUT 228 and transistor 226 are turned on, they will have sufficient voltage across them to maintain an "on" condition. Therefore, a constant turn-off current is provided to Darlington transistor 212.

If a greater control range of dimmer voltage is desired, the circuit of FIG. 37 may be utilized. The circuit of FIG. 37 is connected as follows: a first end of inductor 244 is connected to the cathode of diode 242; the second end of inductor 244 is connected to the first terminal of ballast lamp 250; the second terminal of ballast lamp 250 is connected to the anode of diode 242 and to first ends of resistor 214 and 216; the second end of resistor 216 is connected to terminal 301 of device 500; the second end of resistor 214 is connected to terminal 302 of device 500; terminal 300 of device 500 is connected to a first end of diac 224 and to the collector of transistor 226; terminal 303 of device 500 is connected to a first end of capacitor 220 and the emitter of pnp transistor 254, a first end of capacitor 276 and a first end of resistor 238; terminal 304 of device 500 is connected to a first end of resistor 252; the second end of resistor 252 is connected to the second end of capacitor 220 and the first end of resistor 222; the second end of resistor 222 is connected to the second end of diac 224; the base of transistor 226 is connected to the cathode of PUT 228; the collector of transistor 254 is connected to first ends of resistors 232 and 230; the second end of resistor 230 is connected to the anode of PUT 228; the second end of resistor 232 is connected to the first end of resistor 234 and to the gate of PUT 228; the emitter of transistor 226 is connected to the second end of resistor 234, the second end of capacitor 236, and the anodes of diodes 240 and 256; the cathode of diode 240 is connected to the first end of resistor 246 and the second end of resistor 238, the first end of capacitor 248 and to ground; the second end of resistor 246 is connected to the base of transistor 254; and the cathode of diode 256 is connected to the second end of capacitor 248 into the external dimmer control voltage source 225.

Alternative to the above, a zener diode, such as zener diode 262 in FIG. 38, may be substituted for resistor 234.

The switch of device 500 is turned on in the same manner as for FIG. 36 by capacitor 220, resistor 222 and diac 224, as described above. The difference in the operation of the circuits of FIG. 36 and FIG. 37 is in the turn-off means employed. For purposes of description of FIG. 37, it is assumed that the switch of device 500 has been turned on, i.e., current is flowing from terminal 302 and 303 through the switch of device 500.

This current causes a voltage to appear at the first end of resistor 238, and the voltage on capacitor 236 increases. The base-emitter junction of transistor 254 is forward biased when the voltage on resistor 238 exceeds its base-to-emitter voltage, and capacitor 236 continues to charge until the anodeto-gate voltage of PUT 228 is greater than 0.5 volts. At this time, PUT 228 is "turned on," and current flows into PUT 228 from anode to cathode. At this time, the base-to-emitter junction of transistor 226 is forward biased, thereby causing current to flow in the collector of transistor 226 in a direction outward from terminal 300 of device 500. The current flow in the collector of transistor 226 causes a reverse bias to be placed on the base-to-emitter junction of Darlington transistor 212 of device 500, thereby attempting to turn it off.

The flow of current through Darlington transistor 212 decreases as the transistor is turning off. Therefore, the current flowing through resistor 238 begins to decrease. An analysis of the voltage loop formed by capacitor 236, resistor 238 and diode 240 shows that diode 240 is reversed biased shortly after the turn-off pulse current is applied to the Darlington. Therefore, the voltage stored in capacitor 236 must necessarily discharge through transistor 254, through resistor 230, through PUT 228 and through transistor 226. When the voltage across resistor 238 has decreased to such a voltage level that the base-to-emitter of transistor 254 is no longer forward biased, transistor 254 turns off, thereby preventing any further current flow through it. PUT 228 then turns off since the anode-cathode current goes to zero. Lastly, transistor 226 turns off, causing the collector current of transistor 226 to cease to flow. Hence, the length of time that the turn-off current is applied to Darlington transistor 212 of device 500 by the collector of transistor 226 is determined by the length of time it takes $I_{238} \times R_{238}$ to decrease below approximately 0.7 volt, approximately a base-emitter voltage drop of transistor 254. If very high speed switching elements are utilized in device 500, the length of time that the turn-off pulse is applied might be sufficient to insure a complete turn off. However if lower speed switching devices are utilized (which naturally decreases the cost of the devices), it is desirable to have a turn-off current supplied to device 500 for a longer period of time. Hence, the RC time constant or delay circuit provides good noise immunity of the turn-off circuit by providing some delay, and hence helps prevent false triggering because of a spurious change of voltage with respect to time.

An increase in the length of time the current flows in the collector of transistor 226 can be achieved by utilizing the circuit of FIG. 38 in place of the circuit connected to terminal 300 and 303 of device 500. FIG. 38 is connected as follows: terminal 301 of device 500 is connected to the emitter of transistor 254, a first end of resistor 258, a first end of capacitor 267, a first end of capacitor 236 and a first end of resistor 238; terminal 300 of device 500 is connected to the collector of transistor 226; the collector of transistor 254 is connected to a first end of resistor 230; the second end of resisistor 230 is connected to a first end of capacitor 336; the second end of capacitor 336 is connected to the gate of PUT 228 and to the first end of resistor 260; the cathode of PUT 228 is connected to the base of transistor 226 and to the first end of resistor 280; the second end of resistor 260 is connected to the cathode of Zener diode 262 and to the second end of resistor 260; the emitter of transistor 226 is connected to the anode of Zener diode 262, to the second end of resistor 280, to the second end of capacitor 236, to the anode of diode 240 and to the anode of diode 256; the cathode of diode 240 is connected to the second end of resistor 238, to the cathode of diode 264, to the first end of capacitor 248, and to ground; the anode of diode 264 is connected to the second end of capacitor 267 and to

the first end of resistor **266**; the second end of resistor **266** is connected to the second end of resistor **268** and to the base of transistor **254**; and the cathode of diode **256** is connected to the second end of capacitor **248** into the external dimmer control voltage source **225**.

For purposes of discussion of this turn-off circuit, it will once again be assumed that the transistor switch of device **500** has been turned on by the combination of capacitor **220**, resistor **222** and diac **224**. Therefore, current is flowing through the switch and out of terminal **301** of device **500** to the first end of resistor **238**. A voltage appears at the first end of resistor **238**, and the voltages on capacitor **236** and **267** begin to increase. When the voltage appearing across capacitor **267** exceeds the base-to-emitter junction voltage of transistor **254**, transistor **254** turns on.

As in the description of FIG. **37**, the voltage on capacitor **236** increases until the anode-to-gate PUT **226** exceeds 0.5 volts.

Zener diode **262** is used to maintain a very precise voltage on the gate of PUT **228**. This voltage appears when the voltage on capacitor **236** is such that it exceeds the reverse breakdown voltage of Zener diode **262** by the voltage drop across resistor **258**. Capacitor **336** begins to discharge when the voltage between the anode and the gate of PUT **228** exceeds 0.5 volts. PUT **228** turns on, thereby forward biasing the base-emitter junction of transistor **226**. As before, a collector current begins to flow in the collector of transistor **226**, thereby providing a reverse bias to Darlington transistor **212** included in devicee **500**.

The circuit operation is identical to that of FIG. **37**, except that by utilizing capacitor **267** and resistor **268** and diode **264**, the length of time that a forward bias is applied to the base-emitter junction of transistor **254** is increased, thereby insuring that a turn-off pulse that is sufficiently long in time will be applied to turn-off Darlington transistor **212** of device **500**.

Now referring to FIG. **39**, another embodiment of the electronic switching circuit of the present invention is illustrated. Electronic switch **510** includes a switching circuit, voltage sensing turn-on circuit and a current sensing turn-off circuit, such as illustrated and described for FIG. **5** and FIG. **6**.

FIG. **39** shows electronic switch **510** being used to supply ballast control to lamp **250**. A dc power source (not shown) is connected to the input. Inductor **244**, which may be identical to inductor **60** of FIG. **6**, is in series with switch **510** and diode **242**, which may be identical to diode **78**, and is connected from the output of switch **510** to the return power connection.

In order to prolong the life of ballast lamp **250**, double-pole, double-throw (DPDT) relay **298** interchanges the terminals of the lamp so that the same terminal does not have the same polarity of direct current applied to it at all times. The rate of interchange may be determined by either an ac driven relay device **370**, a dc driven relay or DPDT relay **298** may be operated manually at periodic intervals.

FIG. **40** illustrates a switching arrangement for applying ac current to a lamp load. Ballast lamp **450** is connected to capacitor **442**, which, in turn, is connected to coil **440**. Electronic switches **446** and **448** are connected together, the junction therebetween being connected to coil **440**. Although illustrated merely as switches, preferably both switches **446** and **448** are electronic switches **510**, previously described. When switch **446** is closed, switch **448** is open and when switch **446** is open, switch **448** is closed. Hence, operation is synchronous and complementary. These switches are driven by an electronic ac drive **370**, similar (but of higher frequency) to that used in the FIG. **39** configuration. Together these components comprise electronic drive **444**.

In operation of the FIG. **40** circuit, the switching of switches **446** and **448** so as to alternately provide current paths I_1 and I_2 to lamp **450** applies ac current to the lamp via LC oscillation.

Conventional ballast lamps require a relatively high voltage, on the order of several hundred volts, to sustain their operation. Utilizing an electronic switch **510**, a low dc voltage may be used to operate the ballast lamp when utilized in conjunction with an autotransformer **332**, such as shown in FIG. **41**.

The circuit is connected thusly: the input of electronic switch **510** is connected to the dc power input; the output of electronic switch **510** is connected to the common winding of autotransformer **332**; the second terminal of the primary of autotransformer **332** is connected to the return of the dc input; the anode of diode **42** is connected to the first terminal of ballast lamp **250**; the second terminal of the secondary of autotransformer **332** is connected to the cathode of diode **242** and the first end of inductor **244**; and the second end of inductor **244** is connected to the second terminal of ballast lamp **250**.

The autotransformer has a turn ratio of N to **1**, wherein N signifies the number of turns in the secondary of the autotransformer for each turn in the primary thereof. The autotransformer is chosen so that the turns ratio N to **1** increases the dc input voltage to such a level as to maintain proper operation of the ballast lamp.

FIG. **42** shows a utilization of the basic electronic switch to provide starting voltage to a ballast lamp **250**. Ordinarily, a starting voltage is established with additional electronics which creates a starter pulse. Utilizing the switch as shown in FIG. **42**, however, this starting and continuous operation following starting can be accomplished using the same components without additional electronics.

Electron switch **510** as shown comprises the basic switching circuit described in FIGS. **32**, **33** or **34**, plus turn-off means and turn-on means, such as previously described for FIGS. **5** and **6**. The output of this switch is connected to the cathode of diode **242** and to one terminal of the primary of transformer **292**; the other terminal of the primary of transformer **292** is connected to one terminal of the secondary of transformer **292**, a first end of capacitor **294** and a first end of resistor **290**; the second terminal of the secondary of transformer **292** is connected to one terminal of ballast lamp **250**; the second terminal of ballast lamp **250** is connected to the second end of capacitor **294**, the second end of resistor **290** and the anode of diode **242**. In normal operation, a positive voltage is supplied to the input of electronic switch **510** and the return of this positive voltage is applied to the anode of diode **242**.

Initially, there is no charge on capacitor **294**. When the turn-on means of electronic switch **510** closes the switch, the entire voltage of the power supply appears across the primary of transformer **292**. The reason for this is that there is no voltage on capacitor **294** initially. The voltage then occurring on the secondary of transformer **292** is N times the supply voltage, wherein N is the turns ratio of transformer **292**. This secondary volt-

age provides the necessary instantaneous high voltage to start lamp **250** into operation.

If the common connection of the primary and the secondary of transformer **292** is connected directly to the return of the power supply, then all the current from the power supply would flow directly back to the supply via the return. Inclusion of capacitor **294** allows a momentary short circuit to exist to the power supply return when switch **510** is initially closed. Shortly after the switch closure, the voltage on capacitor **294** begins to increase, thereby blocking the flow of current from the power supply directly back to the return of the power supply and effective turning the primary and secondary of transformer **292** into a series choke with lamp **250.** Therefore, current is supplied in the secondary of the transformer for operation of lamp **250.**

When the turn-off means of electronic switch **510** closes, switch capacitor **294** immediately discharges through resistor **290** in order that the momentary short circuit described above between the transformer and power supply return may be achieved on the next closure of the switch.

FIG. **43** illustrates the utilization of the electronic switch in accordance with the present invention as a low-power switching circuit to control a high-powered transistor. The circuit of FIG. **43** is connected thusly: terminal **435** is connected to the collector of Darlington transistor **212** and to the first end of resistor **252;** the second end of resistor **252** is connected to the first end of resistor **214,** to a first end of resistor **216,** to a first end of capacitor **401,** and to a first end of resistor **409;** the second end of resistor **409** is connected to the collector of npn transistor **411** and to the first end of diac **224;** the second end of resistor **214** is connected to the anode of diode **213;** the cathode of diode **213** is connected to the collector of npn transistor **204** and to the base of pnp transistor **200;** the emitter of transistor **200** is connected to the second end of resistor **216;** the emitter of Darlington transistor **212** is connected to the second end of capacitor **401,** to a first end of resistor **403,** to a first end of resistor **407,** to a first end of resistor **413,** to a first end of resistor **421,** to a first end of resistor **417,** and to a first end of capacitor **415;** the second end of resistor **413** is connected to the anode of PUT **228;** the cathode of PUT **228** is connected to the base of transistor of npn transistor **226;** the gate of PUT **228** is connected to the second end of resistor **417** and to a first end of resistor **419;** the collector of transistor **226** is connected to the emitter of transistor **411,** to the emitter of transistor **406,** to the cathode of diode **431,** to a first end of resistor **405** and to the base of Darlington transistor **212;** the second end of resistor **407** is connected to the base of transistor **411;** the second end of resistor **403** is connected to the base of transistor **406;** the second end of diac **224** is connected to the collector of transistor **200,** the collector of transistor **406,** the base of transistor **204** and the anode of diode **429;** the emitter of transistor **204** is connected to the second end of resistor **405;** the cathode of diode **429** is connected to the anode of diode **431;** the emitter of transistor **226** is connected to the second end of capacitor **415** and to the anode of diode **423;** and the cathode of diode **423** is connected to the second end of resistor **419,** the second end of resistor **421** and to output terminal **427.**

Note that the turn-off circuit of FIG. **43** may also be any of the many turn-off circuits shown and described elsewhere herein, such as in FIGS. **10, 11** and **35.** Note also that diac **224** may also be a Zener diode (in which case transistor **411** is not necessary) or one of the latch devices shown in FIGS. **12–18,** e.g., a SBS, SUS, 4-layer diode, PUT or SCR (in which cases transistor **411** is necessary).

Furthermore, resistor **419** may be replaced with a Zener diode or with any of the devices shown in FIGS. **12–18.**

The discussion of operation of the circuit of FIG. **43** begins by assuming that no current from terminal **425** is flowing through Darlington transistor **212.** All of the dc current applied to terminal **435** flows through resistor **252,** thereby increasing the voltage on capacitor **401.** When the voltage of capacitor **401** exceeds the forward breakover voltage of diac **224,** the base-emitter junction of transistor **204** is forward biased. Current therefore flows through resistor **214,** through diode **213,** and into the collector of transistor **204.** At this time the voltage across diode **213** and resistor **214** increases, thereby providing a forward bias to the base-emitter junction of transistor **200.** Transistor **200** turns on and current flows out of the emitter of transistor **200.** At this time a forward bias is provided to the base-emitter junction of Darlington transistor **212.** Current from capacitor **401** goes through transistors **204** and **200** and the emitter and base of transistor **212.**

This forward bias causes Darlington transistor **212** to turn on, and the dc input current from terminal **435** flows through Darlington transistor **212** into the first end of resistor **421.** At this time the voltage on capacitor **415** begins to increase, which increase continues until the anode-to-gate voltage of PUT exceeds 0.5 volts. This anode-to-gate voltage is determined by resistor **421** and by the resistor divide network comprised of resistors **417** and **419.** Of course, in alternate turn-off arrangements, a Zener diode or other component(s) may determine this anode-to-gate voltage.

When PUT **228** begins to conduct, the emitter-base junction of transistor **226** is forward biased, thereby turning on transistor **226,** the turn on of transistor **226** allowing the voltage on capacitor **415** to reverse bias the emitter-base junction of Darlington transistor **212.**

When transistor **226** is turned on, current may flow from capacitor **415** through resistor **403,** thereby forward biasing the emitter-base junction of transistor **406** and also forward biasing the emitter-to-base junction of transistor **411** through resistor **407.**

Each of these transistors turns on and the voltage appearing at the collector of transistor **406** is very nearly equal to the voltage appearing at the collector of transistor **411.** At this time, there is in effect a short circuit across diac **224,** and therefore no current will flow through diac **224** or other device, such as illustrated in FIGS. **12–18.** Collector current flowing in transistor **406** is the collector current from transistor **200** drawn away from the base of transistor **204,** thereby reverse biasing the emitter-base junction of transistor **204.** The voltage on resistor **405** causes reverse bias of transistor **204.** One way of viewing this is that the shorting of transistor **406** instantaneously applies the voltage on resistor **405** across the emitter-base junction of transistor **204.** The turning off of transistor **204** reverse biases the emitter-base junction of transistor **200,** which also turns off. At this time (i.e., when transistor **212** is off), current begins once more to flow through resistor **252,** and the cycle repeats. The turn-off pulse is applied to the emitter-base junction of transistor **212** and to transistor **204** and diode **224** until capacitor **415** discharges

below approximately 1.5 volts, which is long after transistor **212** is actually off.

Certain modifications of FIG. **42** may be made to modify the operation of the circuit, in addition to these previously mentioned. For example, diodes **429** and **431** are included to make operation of the switching components operate in conjunction with constant current means. If they are not included in the circuit, then operation is in conjunction with variable current means, as in the more general case described herein in conjunction with many other embodiments of the invention, for example, FIG. **6.**

FIG. **44** illustrates an alternative embodiment of a basic switch and turn-off means in accordance with the present invention. The circuit is connected thusly: a first end of resistor **214** is connected to a first end of resistor **217** into a first end of resistor **216;** the second end of resistor **214** is connected to the anode of diode **202;** the cathode of diode **202** is connected to a second end of resistor **217,** to the base of pnp transistor **200** and to the collector of npn transistor **204** (or, alternatively, a Darlington pair; the second end of resistor **216** is connected to the emitter of transistor **200;** the collector of transistor **200** is connected to the base of transistor **204,** to the first end of resistor **210,** to the first end of resistor **229** and to the first end of resistor **233;** the emitter of transistor **204** is connected to the second end of resistor **210,** to the anode of Zener diode **221,** to the first end of capacitor **226** and to the first end of resistor **238;** the second end of resistor **229** is connected to the emitter of transistor **227;** the second end of resistor **233** is connected to the anode of diode **231;** the cathode of diode **231** is connected to the base of transistor **227** and to the collector of transistor **223;** the collector of transistor **227** is connected to the anode of Zener diode **221,** to the base of transistor **223** and to the first end of resistor **330;** the emitter of transistor **223** is connected to the second end of resistor **330;** to the second end of capacitor **236** and to the anode of diode **240;** the cathode of diode **240** is connected to the second end of resistor **238.**

For purposes of this discussion it is assumed initially that transistor **204** is turned on, i.e., current is flowing through the emitter and collector of transistor **204.** This current creates a voltage drop across resistor **238** and the voltage on capacitor **236** begins to increase. Zener diode **221** begins to conduct when the voltage on capacitor **236** exceeds the reverse breakdown voltage of Zener diode **221** plus the base-to-emitter voltage drop of transistor **223.** The base-emitter junction of transistor **223** will be forward biased and this forward biased turns on transistor **223.** At this time the voltage on the collector of transistor **223** is decreased with respect to the emitter. The base-to-emitter junction of transistor **227** is forward biased by the voltage drop across diode **231** and resistor **233.** When this occurs, current flows from capacitor **236** through resistor **210** through resistor **229,** through transistor **227,** and through transistor **223** to the second end of capacitor **236.** Current also flows through resistor **233,** diode **231** and transistor **223.** These currents flow until the voltage across resistor **229** approaches zero.

When transistor **223** is turned on, the base-to-emitter junction of transistor **204** is reversed biased, and, therefore, transistor **204** turns off. When current has ceased to flow (i.e., the voltage across resistor **229** is approximately zero) transistor **223** and **227** will turn off. When transistor **204** is once again turned on by means not shown, the turn-off operation begins again.

FIG. **45** depicts a simplified combination of the high speed switching device of FIG. **34,** a turn-on means **270** and a turn-off means **272** which may be utilized as an electronic fuse **505.** The circuit is connected thusly: the first end of resistor **334** is connected to the first end of resistor **270** and to the input dc current source; the second end of resistor **334** is connected to the anode of diode **202;** the second end of resistor **270** is connected to the emitter of pnp transistor **200;** the cathode of diode **202** is connected to the base of transistor **200** and to the collector of Darlington transistor **212;** and the collector of transistor **200** is connected to the base of Darlington transistor **212.** Connected in parallel with the emitter and base of Darlington transistor **212** are the turn-on means **270,** turn-off means **272** and an external load connected to terminal **276.** When power is initially applied to electronic fuse **505,** the turn-on means may supply current to the base of Darlington transistor **212,** causing the Darlington transistor to turn on. This turn-on means **270** may either be manual or automatic. Transistor **200** maintains this on condition of the Darlington transistor **212** and current flows into the junction of resistors **334** and **270** through the Darlington transistor **212** to the load. Whenever the load current is such that the sensing device of turn-off means **272** senses an overload of current, a turn-off pulse is applied to the base of Darlington transistor **212.** This causes Darlington transistor **212** and transistor **200** to turn off, thereby interrupting the flow of current from the source of the load.

This interruption of current flow happens in a matter of microseconds. Hence, electronic fuse **505** is an improvement over standard fuses utilized in most electronic circuitry today that take on the order of milliseconds to activate.

In order to resume applying current to the load, turn-on means **270** must again be activated. If the overload current still exists at this time of reactivation, electronic fuse **505** will again interrupt the flow of current from the source to the load.

Although device **505** is illustrated incorporating turn-on and turn-off means internal thereto, of course, one or both such means may, if desired, be externally connected.

Manual reset may be provided by closing an external connection at turn-on means **270.** For example, in the circuit incorporating a diac (e.g., a diac similar to diac **58** in FIG. **6**), the external connection may merely be a bypass for the switch.

FIG. **46** is an illustration of an alternate embodiment of the use of a solid state switching circuit useful as an electronic fuse **505** described in FIG. **45** with respect to an ac circuit. The circuit of FIG. **46** is connected thusly; terminal **285** is connected to the cathode of diode **284** and to the anode of diode **281;** the cathodes of diodes **281** and **282** are connected together; the cathode of diode **283** is connected to the anode of diode **282** and to the first end of load **287;** and the second end of the load is connected to external terminal **286.**

Electronic fuse **505** is connected between the junction of the anode of diode **283** and diode **284** thusly: terminal **274** of the figure shown in FIG. **45** is connected to the junction of the cathodes of diodes **281** and **282;** and terminal **276** of the FIG. **45** circuit is connected to the junction of the anodes of diodes **283** and

284. The diode arrangement is commonly referred to as a full-wave bridge rectifier and the electronic fuse 505 of FIG. 45 is connected across the terminals that are commonly referred to as the dc output terminals.

An ac voltage is applied between terminals 285 and 286. During the positive half cycle of this ac voltage, current flows through diode 281, through the switching device, through diode 283 into the load. During the negative half cycle of the ac voltage, current flows through the load, through diode 282, into the sensing device, through diode 284, into terminal 285.

The voltage at terminal 274 and 276 is a full-wave rectified sine wave. The high speed switching device therefore has essentially dc current flowing through it while ac current is being supplied to the load. The high speed switching device includes a sensor which can be set to monitor anything; for example, the amount of current flowing through it. If for example, the current should exceed a certain level, Darlington transistor 212 in device 505 will turn off, thereby breaking the flow path for the current from source to load. Therefore with this configuration, we have not only an improvement in fusing techniques using this electronic switch, but fuse 505 is able to trip on dc current still supplying ac to the load.

The connection shown in FIG. 46 is with respect to a single phase hook-up. Of course, in a three-phase hook-up, each phase may be separately fused in a similar manner. Moreover, if a three phase input is used to establish rectified dc power for circuit use, such as shown in FIG. 6, circuit 505 may be connected directly in series with a dc output line therefrom to effectively fuse the overall power input.

In FIG. 47 the basic switch is utilized as an electronic fuse 505 and turn-off means 272 of FIG. 46 comprises in FIG. 47 resistor 230, resistor 350, PUT 278, transistor 226 and operational amplifier 352. The turn-on mean of FIG. 45 is not shown in FIG. 47.

When Darlington transistor 212 is on, dc current flows into terminal 274, through Darlington transistor 212, and out terminal 276 of electronic fuse 505. This current creates a voltage drop across resistor 350. When the voltage drop across resistor 350 is in excess of a predetermined maximum limit, the output of operational amplifier 352 will be such that the difference between it and the voltage on the anode of PUT 228 will be 0.5 volts or greater. When this occurs, the base-to-emitter junction of transistor 226 is forward biased, thereby turning it on and a reverse bias is placed on the base-to-emitter junction of Darlington transistor 212, thereby turning it off. Resistor 350 is, therefore, utilized as a current sensing device.

FIG. 48 illustrates another embodiment of the solid state switching circuit utilized as an electronic fuse 505, including an alternate embodiment of the turn-off means. In FIG. 48, the turn-on means for Darlington transistor 212 is not shown.

In normal operation, current would be flowing into terminal 274 through transistor 212 and out terminal 276 of device 505. When sensor 362 detects an out of tolerance condition of the device it is monitoring, the trigger means 364 is activated and the anode-to-gate voltage of PUT 228 will exceed 0.5 volts. At this time, the base-to-emitter junction of transistor 226 is forward biased, and a reverse bias is therefore placed on the base-to-emitter junction of Darlington transistor 212, thereby turning it off. In order to resume normal operation, Darlington transistor 212 would be turned on either a manual or automatic turn-on means that is not shown in FIG. 48. For noise immunity or electrical isolation, the sensor 362 may be electronically isolated from electronic fuse 505.

A floating dc voltage, nominally about 6 volts dc, is connected across capacitor 356 and to the output of the circuits shown in FIGS. 47 and 48. The precise value of this voltage is not critical.

Now referring to FIG. 49, an embodiment of the basic switch arrangement is illustrated utilized in conjunction with a light emitting diode to create a bi-stable light emitting circuit. The circuit is connected thusly: the anode of Zener diode 205 is connected to the collector of pnp transistor 200 and to the base of npn transistor 204; the emitter of npn transistor 204 is connected to the first end of resistor 203; the second end of resistor 203 is connected to the anode of Zener diode 205 and to ground; the collector of npn transistor 204 is connected to the base pnp transistor 200 and to the cathode of light emitting diode (LED) 201; the emitter pnp transistor 200 is connected to the first terminal of resistor 216; and the second end of resistor 216 is connected to the anode of LED 201 and to a positive voltage, for example, normally +5 volts for digital circuit applications, Alternatively, a Darlington pair may be substituted for transistor 204.

In operation, LED 201 is turned on and turned off by application of input pulses to the cathode of Zener diode 205. When a positive input pulse greater in magnitude than the base-to-emitter forward voltage of transistor 204 is applied to the cathode of Zener diode 205, the base-emitter junction of transistor 204 is forward biased and transistor 204 conducts. Transistor 204 being forward biased provides a path for current flow from the +5 volts supply through the LED, into the collector and out the emitter of transistor 204, and through the resistor 203 to ground. An analysis of the voltage loop formed by Zener diode 205, transistor 204 and resistor 203 shows that the current through resistor 203 will remain constant. The reason for this is that the voltage across the Zener diode is constant and the base-to-emitter voltage drop of transistor 204 is constant. Therefore, the voltage across resistor 203 remains constant. The collector current of transistor 204 is constant since the emitter current is constant; therefore, the current through light emitting diode 201 remains constant.

When current initially begins to flow through LED 201, the base-emitter junction of transistor 200 is forward biased, thereby providing a flow of current on the +5 volt supply through resistor 216, through the emitter and collector of transistor 200 to the base of transistor 204 and to the cathode of Zener diode 205. When the input pulse is removed, the voltage at the cathode of Zener diode 205 is sufficient to hold the Zener diode in conduction. The current flowing from the collector of transistor 200 is sufficient to maintain the conduction of both npn transistor 204 and Zener diode 205.

When a negative pulse is applied to the cathode of Zener diode 200, Zener diode stops conducting and the reverse bias is applied to the base-emitter junction of transistor 204, thereby turning off transistor 204. Since the turn off of transistor 204 instantaneously reverse biases the base-emitter junction of transistor 200, transistor 200 also turns off, thereby ceasing to supply current to the base of transistor 204. At this time, LED 201 ceases to emit light, i.e., it is turned off.

The circuit of FIG. **50** is identical to the circuit of FIG. **49** except that Zener diode **205** and LED **201** have been interchanged. With this circuit, a constant current is again supplied to LED **201**, since the current to resistor **203** will again remain constant.

The circuit of FIG. **50** provides a lower input impedance circuit to the driving pulse applied at the anode of the LED than does the circuit of FIG. **49**. The reason for this is that LED **201** wants to draw current before the voltage across it is equal to its full forward voltage drop. It may be noted from FIG. **49** that the main current carrying device was npn transistor **204**, since it supplied current to the LED. In FIG. **50**, however, the main current carrying device is the pnp transistor.

FIG. **51**, illustrates a suitable circuit for use as an interface between digital logic and the bi-stable LED for turning on or off the devices of FIGS. **49** and **50**. Note that the input from the digital-like logic circuit applied to the input terminal of the FIG. **51** circuit is a square wave. The output is the on and off pulses for application to the FIG. **49** and FIG. **50** circuits.

While particular embodiments of the invention have been shown and described, it will be understood that the invention is not limited thereto, since many modifications may be made and will become apparent to those skilled in the art.

What is claimed is:

1. A regulating ballast circuit for a high intensity discharge lamp, comprising

dc voltage input means,

switching circuit means connected to said input means including means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance, the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from said dc voltage means when said switching circuit is in the off condition,

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition, and

inductor means for maintaining current through the lamp connected to said switching circuit, the effective current therethrough being approximately constant independent of the frequency of turn on and turn off of said switching circuit.

2. A regulating ballast circuit as set forth in claim **1**, wherein said dc voltage input means includes pairs of rectifying diodes connected to input lines from a three phase ac power source.

3. A regulating ballast circuit as set forth in claim **1**, wherein said high gain means of said switching circuit includes a Darlington pair of transistors.

4. A regulating ballast circuit as set forth in claim **3**, wherein said variable current means includes a transistor, the base of which is connected to the series connection point between a diode and the collector circuit of said Darlington pair, said dc voltage input means being respectively connected through said first and second resistances to said transistor and to said Darlington pair, current flow through said transistor being limited by the current gain established by said first and second resistances.

5. A regulating ballast circuit as set forth in claim **4**, wherein said diode has a forward voltage drop approximating the base-to-emitter drop of said transistor.

6. A regulating ballast circuit as set forth in claim **5**, wherein said diode is shunted by a resistor to provide decreased charge storage time of said diode.

7. A regulating ballast circuit as set forth in claim **1**, wherein said high gain means includes a first transistor having a first leakage current reduction resistor connected from the base to emitter thereof and said variable current means includes a second transistor having a second leakage current reduction resistor connected from the base to emitter thereof.

8. A regulating ballast circuit as set forth in claim **1**, wherein said turn-on means includes a capacitor connected to said dc voltage input means and a threshold semi-conductor device connected to said switching circuit, such that a voltage build up of predetermined amount of said capacitor causes a current pulse through said threshold semi-conductor device to turn on said switching circuit.

9. A regulating ballast circuit as set forth in claim **8**, wherein said semi-conductor device is a diac.

10. A regulating ballast circuit as set forth in claim **8**, wherein said semi-conductor device is a silicon bi-lateral switch.

11. A regulating ballast circuit as set forth in claim **8**, wherein said semi-conductor device is a silicon unilateral switch.

12. A regulating ballast circuit as set forth in claim **8**, wherein said semi-conductor device is a 4-layer diode.

13. A regulating ballast circuit as set forth in claim **8**, wherein said semi-conductor device includes a programmable unijunction transistor.

14. A regulating ballast circuit as set forth in claim **8**, wherein said semi-conductor device includes a silicon controlled rectifier.

15. A regulating ballast circuit as set forth in claim **8**, wherein said semi-conductor device includes a programmable unijunction transistor and a Zener diode.

16. A regulating ballast circuit as set forth in claim **8**, wherein said semi-conductor device includes a silicon controlled rectifier and a Zener diode.

17. A regulating ballast circuit as set forth in claim **1**, wherein said turn-off means includes a resistance means connected to supply operating current to said inductor and a charging capacitor and a delay circuit sensing the operating current from said switching circuit, and a semi-conductor device such that an operating current of a predetermined amplitude causes said semi-conductor device to conduct, the charge on said capacitor generates a turn-off pulse to said switching circuit.

18. A regulating ballast circuit as set forth in claim **17**, wherein said semi-conductor device is a silicon bilateral switch.

19. A regulating ballast circuit as set forth in claim **17**, wherein said semi-conductor device is a silicon unilateral switch.

20. A regulating ballast circuit as set forth in claim **17**, wherein said semi-conductor device is a 4-layer diode.

21. A regulating ballast circuit as set forth in claim **17**, wherein said semi-conductor device includes a gated semi-conductor, the operating current of predetermined amplitude actuating the gate thereof.

22. A regulating ballast circuit as set forth in claim 17, wherein said semi-conductor device includes a programmable unijunction transistor.

23. A regulating ballast circuit as set forth in claim 17, wherein said semi-conductor device includes a silicon controlled rectifier.

24. A regulating ballast circuit as set forth in claim 17, wherein said semi-conductor device includes a programmable unijunction transistor and a Zener diode.

25. A regulating ballast circuit as set forth in claim 17, wherein said semi-conductor device includes a silicon controlled rectifier and a Zener diode.

26. A regulating ballast circuit as set forth in claim 1, wherein said turn-off means is preset for turn-off at a preselected maximum operating current level and the turn-on means is preset for operation for a nominal output from said voltage means and said lamp such that the ratio of on-time to off-time determines duty cycle regulation of constant effective current through said lamp.

27. A regulating ballast circuit as set forth in claim 1, wherein said switching circuit, turn-on means and turn-off means comprise a two-terminal network, said input means connected to said first and second load resistances through a first terminal and said inductor being connected to said turn-off means through a second terminal.

28. A switching circuit for connection to a dc source, comprising:

means exhibiting high gain over a wide range of applied operating currents,

a first load resistance connected to said high gain means, and

variable current means regeneratively connected to said high gain means having a second load resistance,

and including compensating means for eliminating load current as a factor in determining turn-off current gain,

the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit.

29. A switching circuit as set forth in claim 28, wherein said high gain means includes a first transistor having a first leakage current reduction resistor connected from the base to emitter thereof and said variable current means includes a second transistor having a second leakage current reduction resistor connected from the base to emitter thereof.

30. High speed switching means for connection to a dc source, comprising

a switching circuit, including

means exhibiting high gain over a wide range of applied operating currents,

a first load resistance connected to said high gain means, and

variable current means regeneratively connected to said high gain means having a second load resistance, the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit, and

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from the dc source when said switching circuit is in the off condition.

31. High speed switching means for connection to a dc source, comprising

a switching circuit, including

means exhibiting high gain over a wide range of applied operating currents,

a first load resistance connected to said high gain means, and

variable current means regeneratively connected to said high gain means having a second load resistance, the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit, and

turn-off mans connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition.

32. High speed switching means for connection to a dc source, comprising

a switching circuit, including

means exhibiting high gain over a wide range of applied operating currents,

a first load resistance connected to said high gain means, and

variable current means regeneratively connected to said high gain means having a second load resistance, the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from the dc source when said switching circuit is in the off condition, and

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition.

33. High speed switching means as set forth in claim 32, wherein said high gain means of said switching circuit includes a Darlington pair of transistors.

34. High speed switching means as set forth in claim 33, wherein said variable current means includes a transistor, the base of which is connected to the series connection point between a diode and the collector circuit of said Darlington pair, said dc source being respectively connected through said first and second resistances to said transistor and to said Darlington pair, current flow through said transistor being limited by the current gain established by said first and second resistances.

35. High speed switching means as set forth in claim 34, wherein said diode has a forward voltage drop approximating the base-to-emitter drop of said transistor.

36. High speed switching means as set forth in claim 35, wherein said diode is shunted by a resistor to provide decreased charged storage time of said diode.

37. High speed switching means as set forth in claim 32, wherein said high gain means includes a first transistor having a first leakage current reduction resistor connected from the base to emitter thereof and said variable current means includes a second transistor having a second leakage current reduction resistor connected from the base to emitter therof.

38. High speed switching means as set forth in claim 32, wherein said turn-on means includes a capacitor connected to the dc source and a threshold semi-conductor device connected to said switching circuit, such that a voltage build up of predetermined amount on said capacitor causes a current pulse through said

threshold semi-conductor device to turn on said switching circuit.

39. High speed switching means as set forth in claim **38,** wherein said semi-conductor device is a diac.

40. High speed switching means as set foth in claim **38,** wherein said semi-conductor device is a silicon bilateral switch.

41. High speed switching means as set forth in claim **38,** wherein said semi-conductor device is a 4-layer diode.

42. High speed switching means as set forth in claim **38,** wherein said semi-conductor device is a silicon unilateral switch.

43. High speed switching means as set forth in claim **38,** wherein said semi-conductor device includes a programmable unijunction transistor.

44. High speed switching means as set forth in claim **38,** wherein said semi-conductor device includes a silicon controlled rectifier.

45. High speed switching means as set forth in claim **32,** wherein said turn-off means includes a resistance means connected to supply operating current to the output thereof and a charging capacitor and a delay circuit sensing the operating current from said switching circuit, and a gated semi-conductor device, such that when the gate causes said semi-conductor device to conduct, the charge on said capacitor generates a turn-off pulse to said switching circuit.

46. High speed switching means as set forth in claim **45,** wherein said gated semi-conductor device includes a programmable unijunction transistor.

47. A regulating ballast circuit as set forth in claim **45,** wherein said gated semi-conductor device includes a silicon controlled rectifier.

48. High speed switching means as set forth in claim **32,** wherein said turn-off means includes a resistance means to supply operating current to the output and a capacitor chargeably connected to said resistance means, and semi-conductor means, a voltage build-up predetermined amount on said capacitor causing said semi-conductor means to conduct, generating a turn-off pulse to said switching circuit.

49. High speed switching means as set forth in claim **48,** wherein said semi-conductor means includes a silicon bi-lateral switch.

50. High speed switching means as set forth in claim **48,** wherein said semi-conductor means includes a 4-layer diode.

51. High speed switching means as set forth in claim **48,** wherein said semi-conductor means includes a silicon unilateral switch.

52. High speed switching means as set forth in claim **32,** wherein said turn-on means includes constant current source means.

53. High speed switching means as set forth in claim **52,** wherein said constant current source means includes a field effect transistor.

54. High speed switching means as set forth in claim **52,** wherein said constant current source means includes an npn transistor and a Zener diode.

55. High speed switching means as set forth in claim **52,** wherein said constant current source means includes a pnp transistor and a Zener diode.

56. High speed switching means as set forth in claim **32,** wherein said turn-on means includes a diode for reverse biasing said high gain means during turn-off.

57. High speed switching means as set forth in claim **32,** wherein said turn-on means includes inductor means for reverse biasing said high gain means during turn off.

58. An encapsulated high-speed switching circuit, comprising:

first transistor means exhibiting high gain over a wide range of applied operating currents,

second transistor means, complementary to said first transistor means, connected at a first common connection to said first transistor means as a variable current source and having a second terminal suitable for connecting to a second load resistor, the ratio of said first and second load resistors determining the turn-off current gain of said switching circuit,

a diode connected to the base of said second transistor means and having a first terminal suitable for connecting to a first load resistance,

said diode having a forward voltage drop approximating the base-to-emitter drop of said second transistor means,

a second common connection between said first and second transistor means connected to a third terminal,

said first transistor means connected to a fourth terminal,

said third and fourth terminals providing connections for applying turn-on and turn-off signals to said high speed switching circuit.

59. An encapsulated high speed switching circuit as set forth in claim **58,** wherein the values of said first and second resistors are zero, the voltage across said diode and across the base-emitter junction of said second transistor being equal, so that the ratio of the currents through said diode and into the emitter of said second transistor determines the turn-off current gain of the circuit.

60. The encapsulated high speed switching circuit as set forth in claim **58,** wherein said high gain transistor means includes a Darlington pair of transistors.

61. The encapsulated high speed switching circuit as set forth in claim **58,** wherein said first transistor means includes an npn transistor and said second transistor means includes a pnp transistor.

62. The encapsulated high speed switching circuit as set forth in claim **58,** wherein said diode is shunted by a first resistor to provide decreased charged storage time of said diode.

63. The encapsulated high speed switching circuit as set forth in claim **62,** wherein said first transistor means includes a first leakage current reduction resistor connected from the base-to-emitter of a transistor included therein and said second transistor means includes a second leakage current reduction resistor connected from the base-to-emitter of a transistor included therein.

64. An encapsulated high speed switching circuit as set forth in claim **58,** wherein said first and second resistors are connected together and including a third terminal connected to the junction therebetween, and wherein the values of said first and second resistors are zero, the voltage across said diode and across the base-emitter junction of said second transistor being equal, so that the ratio of the currents through said diode and into the emitter of said second transistor determines the turn-off current gain of the circuit.

65. An encapsulated high speed switching circuit, comprising:

first transistor means exhibiting high gain over a wide range of applied operating currents,

second transistor means, complementary to said first transistor means, connected at a first common connection to said first transistor means as a variable current source,

a diode connected to the base of said second transistor means,

a first load resistance connected to said diode,

a second load resistor connected to said second transistor means, the ratio of said first and second load resistors determining the turn-off current gain of said switching circuit,

said diode having a forward voltage drop approximating the base-to-emitter drop of said second transistor means,

a second common connection between said first and second transistor means connected to a first terminal,

said first transistor means connected to a second terminal,

said first and second terminal providing connections for applying turn-on and turn-off signals to said high speed switching circuit.

66. A regulating ballast circuit for a high intensity discharge lamp, comprising

dc voltage input means,

switching circuit means connected to said input means including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance, the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit means for generating a turn-on input thereto dependent in time on the level of output from said dc voltage means when said switching circuit means is in the off condition,

turn-off means connected to said switching circuit means for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit means is in the turned on condition, and

high frequency switching means for applying ac current to the lamp, including

inductor means connected to said switching circuit means, and

relay switching means for providing current through said lamp in a first direction and then in the opposite direction.

67. A regulating ballast as set forth in claim **66,** wherein said relay switching means connects said inductor in series with said lamp first one side of said lamp and then on the other side of said lamp.

68. A regulating ballast as set forth in claim **67,** and including a flyback diode to provide a conductive path for current through said inductor when said switching circuit means is turned off.

69. A regulating ballast circuit for a high intensity discharge lamp, comprising

inductor meanas for maintaining operating current through the lamp,

a flyback diode connected across the lamp and said inductor means,

a terminal for connecting to a standard dc voltage source for applying dc current through the combination of the lamp and said inductor means,

switching circuit means connected in the return path of the series combination of the lamp and said inductor means, including

means exhibiting high gain over a wide range of operating currents and having a first load resistance,

and variable current means regeneratively connected thereto having a second load resistance,

the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from said standard dc voltage source when said switching circuit is in the off condition, and

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition.

70. A regulating ballast circuit as set forth in claim **69,** wherein said external means is a dc variable control voltage source.

71. A regulating ballast circuit as set forth in claim **69,** wherein said turn-off means includes a resistance means and a charging capacitor connected to said external means for sensing the operating current from said switching circuit, and a gated semi-conductor device connected to said resistance means and said capacitor such that when the gate causes semi-conductor device to conduct, the charge on said capacitor generates a turnoff pulse to said switching circuit.

72. A regulating ballast circuit as set forth in claim **71,** wherein said turn-off means includes a time constant delay means for providing noise immunity and for preventing a false turn-off input because of the presence of an extraneous voltage with respect to time.

73. A regulating ballast circuit for a high intensity discharge lamp, comprising

dc voltage input means,

switching circuit means connected to said input means including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance, the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from said dc voltage means when said switching circuit is in the off condition,

turn-off mans connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition,

inductor means for maintaining current through the lamp connected to said switching circuit, the effective current therethrough being approximately constant independent of the frequency of turn on and turn off of said switching circuit, and

double-pole, double-throw relay means connecting said inductor means to the lamp so that the terminals of the lamp may have polarity reversals ap-

plied thereto.

74. A regulating ballast circuit as set forth in claim 73, wherein said relay means includes ac drive means for causing polarity reversals at a periodic rate.

75. A regulating ballast circuit for a high intensity discharge lamp, comprising

dc voltage input means,

LC circuit means connected to the lamp,

polarity reversing electronic switching means connected to said LC circuit means and to said lamp for supplying alternately directed current paths therefrom through the lamp, and

ac drive means connected to said polarity reversing means for causing ac current to the lamp via periodic switching of said LC circuit means.

76. A regulating ballast as set forth in claim 75, wherein said polarity reversing electronic switching means comprises synchronous complementary switches, each of said complementary switches including

electronic closure means exhibiting high gain over a wide range of operating currents and having a first load resistance,

variable current means regeneratively connected to said electronic closure means having a second load resistance, the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said electronic closure means for generating a turn-on input thereto dependent in time on the level of output from said dc voltage means when said electronic closure is in the off condition, and

turn-off means connected to said electronic closure means for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said electronic closure means is in the turned on condition.

77. A regulating ballast circuit for a high intensity discharge lamp, comprising

dc voltage input means,

switching circuit means connected to said input means including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and

variable current means regeneratively connected thereto having a second load resistance, the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit means for generating a turn-on input thereto depending in time on the level of output from said dc voltage means when said switching circuit means is in the off condition,

turn-off means connected to said switching circuit means for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit means is in the on condition,

an autotransformer connected to said switching circuit means for stepping up the voltage therefrom, and

inductor means for maintaining current through the lamp connected to said autotransformer, the effective current therethrough being approximately constant independent of the frequency of turn-on and turn-off of said switching circuit.

78. A regulating ballast circuit as set forth in claim 77, and including a flyback diode connected across the lamp and said inductor.

79. A regulating ballast circuit for a high intensity discharge lamp, comprising

dc voltage input means,

switching circuit means connected to said input means including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance,

the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from said dc voltage means when said switching circuit is in the off condition,

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition,

a transformer connected to a first terminal of the lamp, and

a capacitor connected between a common connection of the primary and secondary of said transformer and the second terminal of the lamp, the starting voltage on said lamp being the stepped up full voltage supplied to said transformer, a full charge on said capacitor converting the primary and secondary of said transformer into a series choke for providing operating voltage across said lamp.

80. A regulating ballast circuit for a high intensity discharge lamp, comprising

dc voltage input means,

switching circuit means connected to said input means including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance,

the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from said dc voltage means when said switching circuit is in the off condition,

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition,

inductor means for maintaining current through the lamp connected to said switching circuit, the effective current therethrough being approximately constant independent of frequency of turn on and turn off of said switching circuit, and

said switching circuit means including a high power transistor and a low power drive circuit, such that a low voltage of predetermined value controls the operation of said high power transistor in said switching means.

81. A regulating ballast as set forth in claim **80,** wherein said low power drive circuit includes diode means for changing said variable current means into substantially constant current means.

82. A regulating ballast circuit for a high intensity discharge lamp, comprising

dc voltage input means,

switching circuit means connected to said input means including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance,

the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from said dc voltage means when said switching circuit is in the off condition,

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition,

inductor means for maintaining current through the lamp connected to said switching circuit, the effective current therethrough being approximately constant independent of frequency of turn on and turn off of said switching circuit, and

said turn-off means including a resistance means connected to supply operating current to said inductor means and a charging capacitor and Zener diode operative as low power sensing means for sensing the operating current from said switching circuit such that the exceeding of the reverse breakdown voltage of said Zener diode generates a turn-off pulse to said switching circuit.

83. A high speed electronic circuit breaker, comprising dc voltage input means,

switching circuit means connected to said input means including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance,

the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition, and

manual turn-on means connected to said switching circuit.

84. A high speed electronic circuit breaker, comprising dc voltage input means,

switching circuit means connected to said input means including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance,

the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from said dc voltage means when said switching circuit is in the off condition, and

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition.

85. A circuit breaker as set forth in claim **84,** wherein said turn-off means is preset for turn-off at a preselected maximum operating current level and the turn-on means is preset for operation for a nominal output from said voltage means.

86. A circuit breaker as set forth in claim **84,** wherein said switching circuit, turn-on means and turn-off means comprise a two-terminal network, said first and second load resistances connected to a first terminal and said turn-off means connected to a second terminal, said input means and a load being connected in series with said first and second terminals.

87. A regulating ballast circuit as set forth in claim **84,** wherein said high gain means includes a first transistor having a first leakage current reduction resistor connected from the base to emitter thereof and said variable current means includes a second transistor having a second leakage current reduction resistor connected from the base to emitter thereof.

88. A circuit breaker as set forth in claim **84,** wherein said high gain means of said switching circuit includes a Darlington pair of transistors.

89. A circuit breaker as set forth in claim **88,** wherein said variable current means includes a transistor, the base of which is connected to the series connection point between a diode the the collector circuit of said Darlington pair, said dc voltage input means being respectively connected through said first and second resistances to said transistor and to said Darlington pair, current flow through said transistor being limited by the current gain established by said first and second resistances.

90. A circuit breaker as set forth in claim **89,** wherein said diode has a forward voltage drop approximating the base-to-emitter drop of said transistor.

91. A circuit breaker as set forth in claim **90,** wherein said diode is shunted by a resistor to provide decreased charge storage time of said diode.

92. A circuit breaker as set forth in claim **84,** wherein said turn-on means includes a capacitor connected to said dc voltage input means and a threshold semi-conductor device connected to said switching circuit, such that a predetermined voltage build up on said capacitor causes a current pulse through said semi-conductor device to turn on said switching circuit.

93. A circuit breaker as set forth in claim **92,** wherein said semi-conductor device is a diac.

94. A circuit breaker as set forth in claim **84,** wherein said turn-off means includes a resistance means operably connected to supply operating current to an exter-

nal load and a charging capacitor and a delay circuit sensing the operating current from said switching circuit, and a gated semi-conductor device such that when the gate causes said semi-conductor device to conduct, the charge on said capacitor generates a turn-off pulse to said switching circuit.

95. A circuit breaker as set forth in claim **94,** wherein said gated semi-conductor device includes a programmable unijunction transistor.

96. A circuit breaker as set forth in claim **94,** wherein said turn-off means includes

a resistor operating as a current sensing device, and

an operational amplifier with its differential inputs connected across said resistor and its output connected to the gate of said gated semi-conductor device,

an excess voltage drop across said resistor causing turn-off operation.

97. A circuit breaker as set forth in claim **96,** and including an additional floating dc supply for providing additional voltage for turn-off operation.

98. A circuit breaker as set forth in claim **94,** wherein said turn-off means includes

a sensor connected to monitor an external signal, and

trigger means operated by said sensor and connected to the gate of said gated semi-conductor device, the presence of an external signal causing turn-off operation.

99. A circuit breaker as set forth in claim **98,** and including a floating dc supply for providing a dc voltage for aiding the turn-off operation.

100. A circuit breaker as set forth in claim **98,** and including isolating means between said sensor and said trigger means.

101. A circuit breaker as set forth in claim **84,** wherein said dc voltage input means is a multiple phase ac input means reduced to a common dc voltage through diode connections.

102. A high speed circuit breaker for an ac circuit including an ac source and a load, comprising

bridge means connected to the ac circuit and having ac and dc terminals, the ac source and load connected to said ac terminals,

switching circuit means connected to said dc terminals including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance,

the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-on means connected to said switching circuit for generating a turn-on input thereto dependent in time on the level of output from said dc voltage means when said switching circuit is in the off condition, and

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition.

103. A high speed circuit breaker for an ac circuit including an ac source and a load, comprising

bridge means connected to the ac circuit and having ac and dc terminals, the ac source and load connected to said ac terminals,

switching circuit means connected to said dc terminals including

means exhibiting high gain over a wide range of operating currents and having a first load resistance, and variable current means regeneratively connected thereto having a second load resistance,

the ratio of said first and second load resistances determining the turn-off current gain of said switching circuit,

turn-off means connected to said switching circuit for generating a turn-off input thereto dependent in time on the instantaneous level of the operating current when said switching circuit is in the turned on condition, and

manual turn-on means connected to said switching circuit.

104. A bi-stable switching circuit for operating a light emitting diode, comprising

high current means exhibiting high gain over a wide range of operating currents,

a light emitting diode connected as a load to said high current means and to an external bias voltage,

a constant current means regeneratively connected to said high current means having a load resistance connected to said external bias voltage,

the ratio of the current through said light emitting diode and said load resistance determining the turn-off gain of the switching circuit, and

said constant current means including a Zener diode connected to said high gain means, such that an external pulse applied thereto greater than the turn-on voltage of said high current means causing sustained conduction of said high current means, said Zener diode and said light emitting diode until the application of an opposite polarity external pulse causes nonconduction.

105. A switching circuit as described in claim **104,** wherein said high current means includes an npn transistor and said constant current means includes a pnp transistor, said npn transistor having its base connected to the collector of said pnp transistor and the cathode of said Zener diode, the collector of said npn transistor being connected to the base of said pnp transistor and said light emitting diode, said external pulse being applied to the base of said npn transistor.

106. A switching circuit as described in claim **105,** and including interface means connected to the cathode of said Zener diode to convert digital logic square wave pulses to spike pulses.

107. A bi-stable switching circuit for operating a light emitting diode, comprising

high current means exhibiting high gain over a wide range of operating currents,

a constant current means regeneratively connected to said high current means having a load resistance connected to an external bias voltage,

a Zener diode connected to said constant current means and to said external bias voltage, and

a light emitting diode connected to said high current means, the ratio of current through said light emitting diode and said load resistance determining the turn-off gain of the switching circuit, an external pulse applied to said constant current means greater than the turn-on voltage thereof causing sustained conduction of said constant current means, said light emitting diode and said Zener diode until the application of an opposite polarity

pulse causes non-conduction.

108. A switching circuit as described in claim **107,** wherein said high current means includes a pnp transistor and said constant current means includes a npn transistor, said pnp transistor having its base connected to the collector of said npn transistor and the anode of said Zener diode, the collector of said npn transistor being connected to the base of said npn transistor and the anode of said light emitting diode, said external pulses being applied to the base of said npn transistor.

109. A switching circuit as described in claim **108,** and including an interface means connected to the anode of said light emitting diode to convert digital logic square wave pulses to spike pulses.

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