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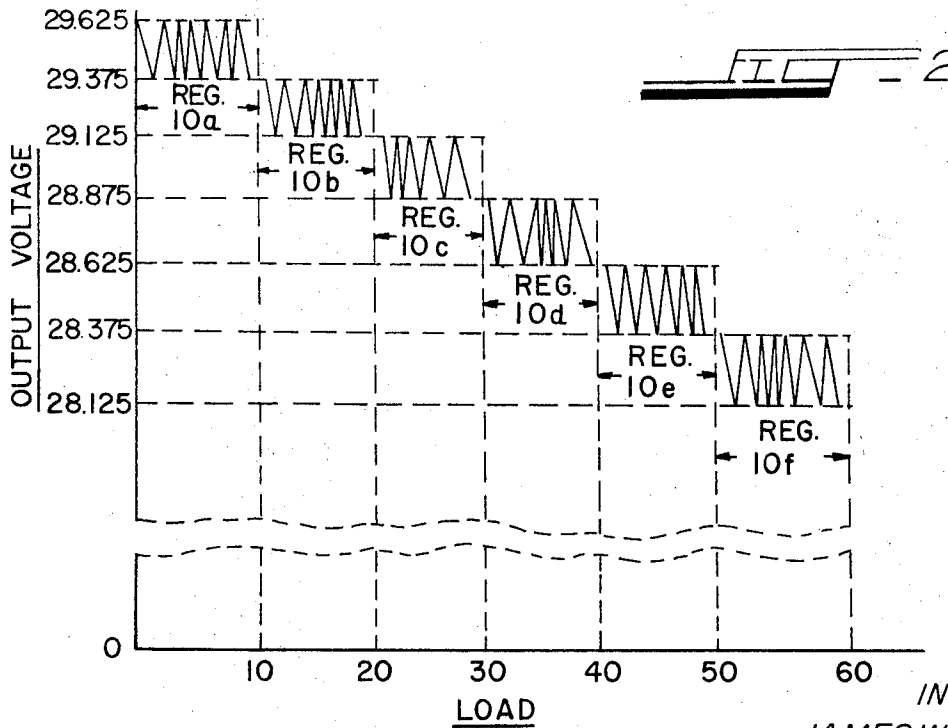
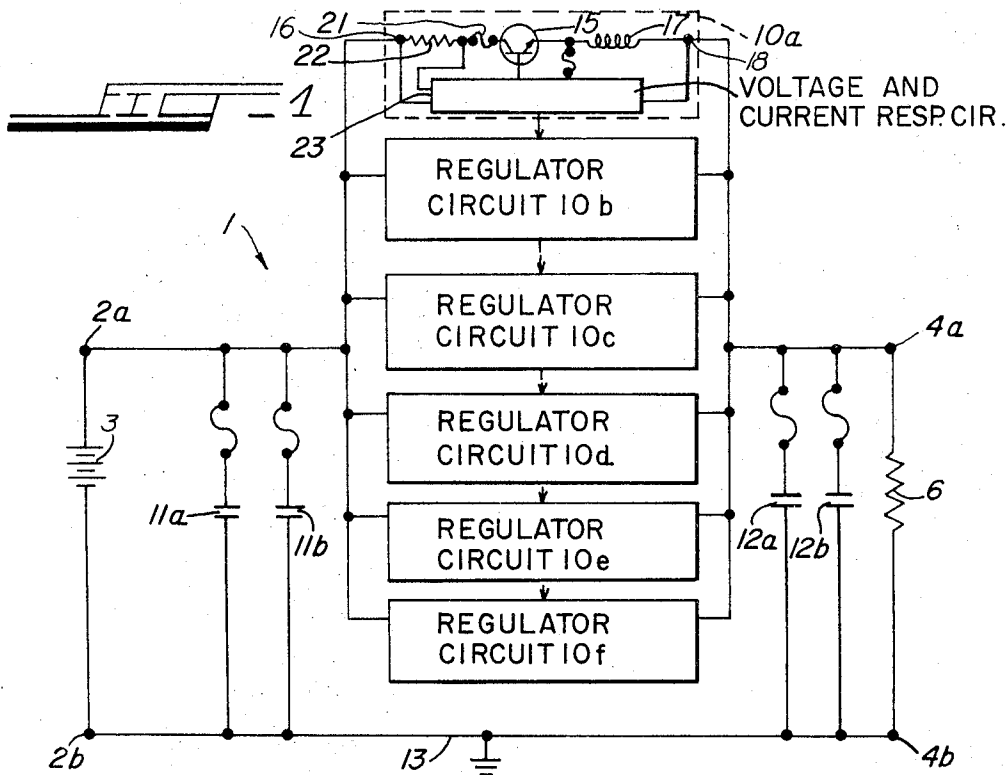
J. W. BATES

3,521,150

PARALLEL SERIES VOLTAGE REGULATOR WITH CURRENT LIMITING

Filed Dec. 6, 1967

4 Sheets-Sheet 1



INVENTOR.
JAMES W. BATES

BY
Wellstein, Spangenberg, Hattis & Strampel

ATTORNEYS

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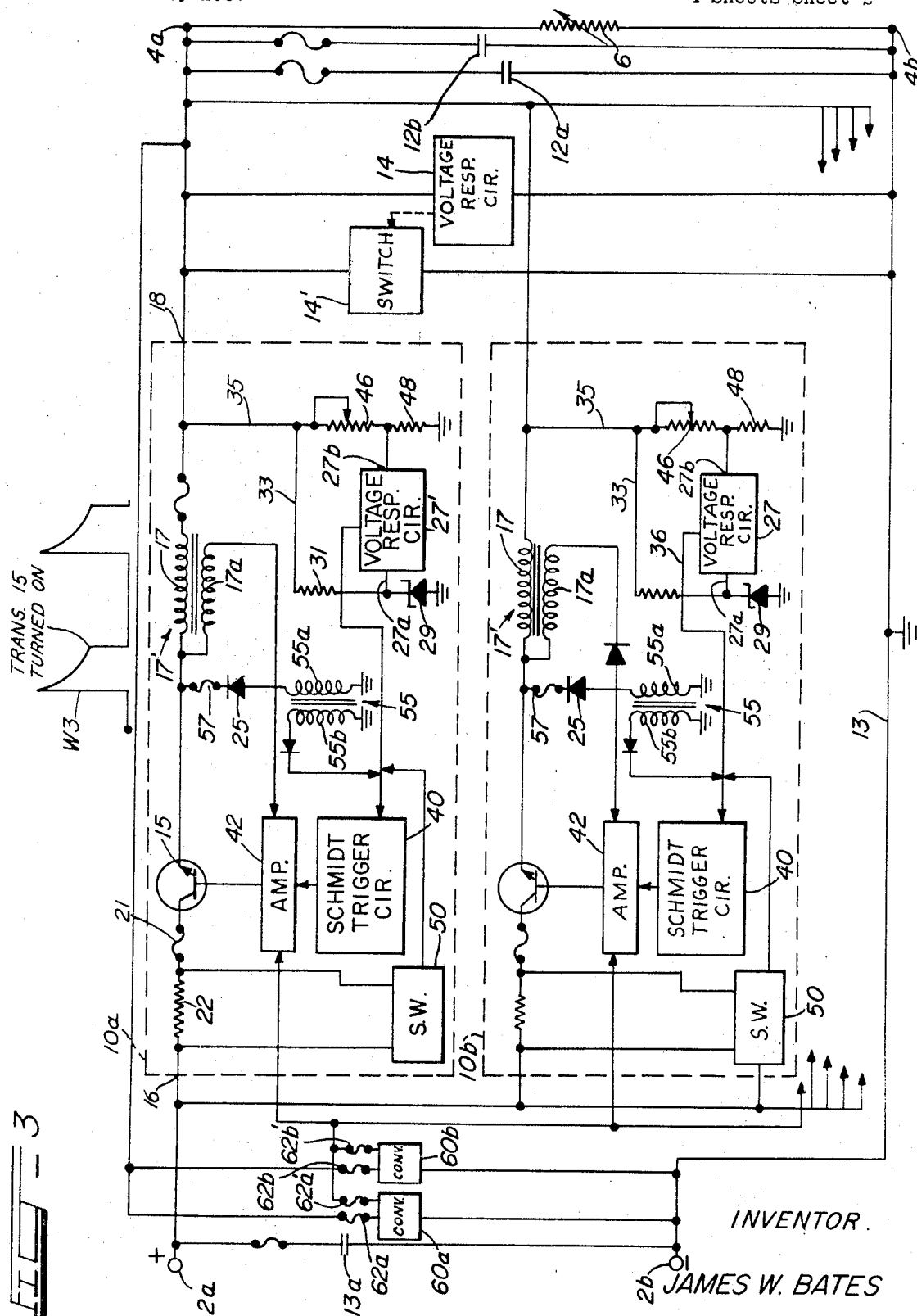
J. W. BATES

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PARALLEL SERIES VOLTAGE REGULATOR WITH CURRENT LIMITING

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4 Sheets-Sheet 2



INVENTOR.

92 JAMES W. BATES

BY Wallenstein, Spangenberg, Hattis & Strampel

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3,521,150 PARALLEL SERIES VOLTAGE REGULATOR WITH CURRENT LIMITING

James William Bates, Palos Verdes Estates, Calif., assignor to Gulton Industries, Inc., Metuchen, N.J., a corporation of Delaware

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16 Claims

ABSTRACT OF THE DISCLOSURE

A number of series voltage regulator circuits are connected in parallel between D.C. input and output terminals and each is designed to carry only a fractional part of a given maximum load current and capable of maintaining the voltage across said output terminals within given predetermined limits without the aid of the other. One of the voltage regulator circuits is initially operative to carry load current up to a given maximum current level which is a fractional part of said total load current and means are provided for rendering a number of the initially inoperative regulator circuits operative to carry load current in accordance with the demands of the load to be connected across said output terminals, wherein there can be only one operating voltage regulator circuit carrying less than its assigned maximum current.

The present invention relates to series, direct current D.C. voltage regulators. More particularly, the invention relates to a type of series regulator sometimes referred to as a pulse width regulator which uses a current control device which is alternately rendered fully conductive and fully non-conductive and where regulation is achieved by controlling the ratio of the total durations of the conductive and non-conductive periods thereof over a base period involving a number of cycles of operation of the current control device. As is conventional in most voltage regulators, an error voltage is obtained which is a function of the difference between the actual output of the regulator and a reference voltage. This error voltage is used to control the proportion of the aforesaid time base period during which the current control device is in its conductive or non-conductive state. The efficiency of a pulse width regulator is determined to a great extent by the power loss across the load terminals of the current control device. In general, as in the case where the current control device is a power transistor, power losses across the load terminals thereof are minimized when the transistor is driven into saturation and the saturation current level is at a minimum so the current which must be interrupted is at a minimum.

Where the load on a pulse width regulator is constant, it is a relatively simple matter to select a power transistor or other control device which will minimize the losses of the circuit. However, when the load of a pulse width regulator varies widely, the efficiency at low loads is markedly lower than for high loads because at low loads the current control devices of these prior circuits carry only a small percentage of their maximum rated current where they operate at maximum efficiency.

In accordance with an aspect of the invention, a number of completely independently operable voltage regulator circuits designed to carry at maximum efficiency only a fractional part of the total maximum expected load current are connected in parallel between the D.C. input and output terminals of the regulator and arranged to operate (that is carry load current) only when the load demands are such as to require their operation. For example, if the maximum expected load current is 50 am-

peres and each regulator circuit is designed to carry a maximum of 10 amperes, there are provided at least five such parallel connected voltage regulator circuits arranged so that initially only one of the voltage regulator circuits will be rendered operable to carry the first 10 amperes of required load current. As soon as the demands of the load require more than the current carrying capability of the initially operable regulator circuit, one or more other regulator circuits are automatically connected in parallel with the initially inoperable regulator circuits to supply the required load. With this arrangement, most of the aforementioned conditions for minimizing losses will be present. The aforementioned parallel voltage regulator circuit has its principal application where efficiency and reliability are of primary concern, and the cost factor is of secondary concern, as, for example, in the case of power supplies for highly sophisticated space vehicles and the like.

In accordance with another aspect of the invention, the regulator circuits operated in parallel are fused or otherwise provided with overload switches which will automatically disconnect a short circuited regulator circuit so that the D.C. voltage supply cannot feed directly into the short circuit or indirectly therein through the outputs of the voltage regulator circuits connected in parallel therewith. To this end, fuses or other overload protecting means are located within each of the regulator circuits so that the presence of an overload current therein will interrupt the short circuited portions of the regulator circuit involved and disconnect the same from the D.C. voltage supply and the other regulator circuits. So that the regulator can carry a maximum load current even with a disconnected voltage regulator circuit, there is preferably provided at least one more regulator circuit in the aforesaid parallel circuit than that required by the maximum load current requirements involved.

In accordance with still another aspect of the invention, means is provided for disconnecting a short circuited regulator circuit under no load conditions when short circuit currents cannot normally flow. To this end, the regulator has means for sensing an abnormally high output voltage of the regulator which would indicate a short circuit condition and means for automatically disconnecting the initially operative regulator circuit. The latter means preferably includes an artificial load supplying means which permits an abnormally high current to flow in the initially operative regulator circuit so that the overload protecting means therein will operate to disconnect the regulator circuit from the D.C. voltage supply and the other regulator circuits.

Another aspect of the invention relates to the manner in which the various regulator circuits are rendered sequentially operable under the various load conditions. This is most advantageously achieved by providing current limiting means in each regulator circuit, and designing the various regulator circuits to regulate at progressively lower voltage levels.

Other features and advantages of the present invention will become apparent upon making reference to the specification to follow, the claims and the drawings wherein:

FIG. 1 is a simplified block diagram of the voltage regulator system of the invention;

FIG. 2 illustrates the voltage ripple voltage waveforms at the output of the preferred voltage regulator system of the invention provided by the various voltage regulator circuits of FIG. 1;

FIG. 3 is a simplified diagram of the invention, partially in block form, illustrating the different component parts of each parallel connected voltage regulator circuit of the preferred regulator system of the present invention;

FIG. 4 is a schematic diagram of the preferred circuit for each of the parallel connected voltage regulator circuits shown in FIG. 3; and

FIG. 5 is a circuit diagram of a preferred artificial load supplying circuit used in the circuit of FIG. 4.

Referring now more particularly to FIG. 1, the voltage regulator system there shown and identified by reference numeral 1 includes a pair of input terminals 2a and 2b across which is connected a source 3 of D.C. current which may be a battery or the like, and a pair of output terminals 4a and 4b across which a variable load 6 is connected. The voltage regulator system 1 is designed to deliver a regulated voltage across the output terminals 4a and 4b with a widely varying D.C. input voltage. For example, let it be assumed that the voltage regulator system 1 is to maintain the voltage across the output terminals 4a and 4b between 28.1 and 29.6 volts for a varying input voltage of 30-40 volts over a varying load of from 0 to 50 amperes. (However, it should be understood that the present invention is not limited to any particular set of input and output voltage and current conditions and the exemplary values are given only for purposes of explanation of the operation of the invention.) In the exemplary voltage regulator system illustrated, a number of parallel connected voltage regulator circuits 10a, 10b, 10c, 10d, 10e and 10f are respectively connected in parallel between one of the input terminals 2a and one of the output terminals 4a. The input terminal 2a is shown connected to the positive terminal of the source of D.C. voltage 3, it being understood that the polarities shown could be inverted with corresponding changes made in the voltage regulator circuits to be described. One or more fused output filter capacitors 12, 12b, etc. are connected between the output terminals 4a and 4b. Similarly, one or more fused input filter capacitors 11a, 11b, etc. may be connected across the input terminals 2a and 2b. The negative input and output terminals 2b and 4b are shown connected to a common bus 13.

Each of the voltage regulator circuits 10a . . . 10f is designed to carry a fractional part of the maximum load current. In the example given, each of the voltage regulator circuits 10a, 10b, etc. is designed to carry a maximum current of 10 amperes, so that the six voltage regulator circuits can supply a total of 60 amperes to the load 6. However, to improve the reliability of the circuit, it will be assumed that the maximum load current will be 50 amperes so one of the regulator circuits can act as a replacement for a defective regulator circuit which would be automatically removed from the circuit in a manner to be described.

In accordance with the invention, the voltage regulator circuits 10a . . . 10f are so designed and adjusted that only one of the regulator circuits, for example, regulator circuit 10a, will be initially operative to control the voltage across the terminals 4a and 4b and to carry load current when the total load current is at or less than the current handling capacity of the regulator circuit, namely 10 amperes. When the load current flowing in the regulator circuit 10a exceeds this limit, one or more of the other regulator circuits will become operative to carry the required load current and to effect control over the voltage across the output terminals 4a and 4b. All operating voltage regulator circuits but one will be carrying a maximum load current so that maximum efficiency is achieved.

Each of the voltage regulator circuits 10a . . . 10f includes a current control device, such as a power transistor 15, and a filter inductance 17 connected in series between the input 16 and the output 18 of the voltage regulator circuit. Also, to protect against a short circuit across the load terminals of the current control device 15, a fuse 21 or similar circuit opening and protecting means is provided between the input 16 and the input side of the associated filter inductance 17. A short circuit appearing across the current control device 15 of a regulator circuit will increase the voltage across the output terminals to about that of the input D.C. voltage, and, assuming there is a

significant load connected across the output terminals 4a and 4b, a sufficiently large abnormal current will flow through the fuse 21 to blow the same thereby to disconnect the defective regulator circuit from the other regulator circuits. Other fuses or circuit protecting means to be described are preferably added to the voltage regulator circuits for interrupting other short circuit paths which may occur in a regulator circuit and disconnecting the short circuited portion of the regulator circuit from the other regulator circuits and the D.C. input to the voltage regulator system.

Various means may be used for automatically rendering the proper number of voltage regulator circuits operative to carry the required load current involved. For example, each voltage regulator circuit may be provided with a sensing element which senses the presence of a maximum desired current therein, such as the ten ampere exemplary value, and initiates operation of one or more other voltage regulator circuits to carry the additional required load current. However, one of the specific aspects of the invention is in a very simple and inexpensive means for automatically rendering the proper number of regulator circuits operative to carry the required load current. This means involves the provision of means in each voltage regulator circuit for limiting the current flow to the maximum fractional part of the load current which is to be handled by each regulator circuit. The current limiting means in each voltage regulator circuit may include a sensing element through which load current of the circuit flows, such as a resistor 22 in series with the current control device 15. When a maximum desired current flows through the sensing element, a control signal is produced which operates a voltage and current responsive circuit 23 controlling the conduction of the current control device 15 to render the device non-conductive until the current flowing in the output portion of the voltage regulator circuit involved drops to a given lower level, whereupon the conduction of the current control device 15 will resume. The voltage and current responsive circuit 23 is also responsive to the voltage across the output terminals 4a and 4b so as to render the associated current control device 15 non-conductive when the voltage across the output terminals 4a and 4b rises to a given upper voltage control level. When the current control device 15 is then rendered non-conductive, the voltage across the output terminals 4a and 4b will drop and when it reaches a given lower voltage control level, the current control device 15 is again rendered conductive to cause the voltage across the output terminals 4a and 4b to rise to the aforementioned upper voltage current control level where the regulation process described is repeated.

The various voltage regulator circuits 10a . . . 10f in the preferred form of the invention are automatically rendered operative to accommodate the necessary load current by virtue of the additional fact that the various upper and lower control levels associated with the various voltage regulator circuits progressively form the upper and lower limits of contiguous voltage bands, such as illustrated in FIG. 2. (The highest voltage control level of the highest voltage band and the lowest voltage control level of the lowest voltage band there illustrated are respectively 29.625 volts and 28.125 volts in FIG. 2 to provide the overall required regulation in the example of the invention being described.) Initially, under low or no load conditions, only the regulator circuit 10a which provides regulation over the highest voltage band will be operating because initially the output voltage will be at a maximum and it can rise to the upper voltage control level of the highest voltage band (29.625 volts) before all of the current control devices 15 will be non-conductive whereupon the output voltage drops to the lower voltage control level of the uppermost band (29.375 volts) where only the voltage and current responsive circuit 23 of voltage regulator circuit 10a will operate to render the

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associated current control device conductive. This will cause the output voltage to rise again to the upper voltage control level of 29.625 volts. The current limiting means in each regulator circuits assures the operation of the proper number of voltage regulator circuits because as soon as all operating voltage regulator circuits are operating in their current limiting mode as described, any increase in the load (i.e. decrease in load resistance) will automatically produce a lower voltage across the output terminals which will ultimately reach the lower voltage control level of an inoperative voltage regulator circuit operable in the next lowest voltage band whereupon the last mentioned voltage regulator circuit will begin to carry load current and control the voltage across the output terminals between the limits of this voltage band. Once a new voltage regulator circuit becomes operative, the other operating voltage regulator circuits cease regulating the voltage across the output terminals 4a and 4b because the output voltage remains at or below the associated lower voltage control levels where conduction of the associated current control devices will be determined only by the current limiting action of said other operating regulator circuits as explained above.

Refer now to FIG. 3 which illustrates, partially in block form, various component parts of circuits constituting the voltage regulator circuits 10a . . . 10f. Each regulator circuit includes a conventional flyback or commutator rectifier 25 connected between the input side of the filter inductance 17 and ground. The negative input and output terminals 2b and 4b of the regulator system are connected to bus 13 as indicated. When the current control device of the associated voltage regulator circuit is rendered non-conductive, the flyback rectifier 25 provides a path for current flow so the energy stored in the inductance 17 is transferred to the output capacitors 12a, 12b etc.

When a voltage regulator circuit is not current limiting, the conduction of the associated current control device 15 is controlled by a voltage responsive circuit 27 which may be a differential amplifier which effectively compares a D.C. reference voltage fed to an input 27a thereof and a voltage fed to an input 27b which is a measure of the output voltage of the regulator system. The reference voltage is generated by a circuit including a Zener diode 29 connected between the input 27a and bus 13 and a resistor 31 connected by conductors 33 and 35 to the output 18 of the voltage regulator circuit which, in turn, is connected to the output terminal 4a of the regulator system. From the voltage at the input terminal 27a an error signal is generated by the voltage responsive circuit 27 which is proportional to the difference between the voltage on the terminals 27b and 27a which signal is coupled by a conductor 36 to a Schmitt trigger circuit 40. The Schmitt trigger circuit feeds a signal to an amplifier 42 which renders the current control device 15 non-conductive when the error signal is at a given upper level and renders the current control device conductive when the error signal is at a lower level. The voltage present at the input terminal 27b of the voltage responsive circuit 27 for a given voltage at the regulator system output terminal 4a is determined by the adjustment of a variable resistor 46 forming part of a voltage divider network including a resistor 48 connected between the input terminal 27b and bus 13. The variable resistor 46 is connected between the input terminals 27b and the conductor 35 which is coupled to the regulator circuit output terminal 18. The adjustments of the variable resistances 46 of the various voltage regulator circuits establishes the different upper voltage control levels of the various voltage bands in FIG. 2.

To speed up the process of rendering a current control device 15 non-conductive, the inductance 17 of each voltage regulator circuit forms a primary winding of a transformer 17' having a secondary winding 17a in which is generated a transistor turn-off voltage when the rate of change of the current in the inductance reverses in polar-

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ity as a result of the initiation of a non-conductive condition in the associated current control device or power transistor 15. This voltage is fed back to the amplifier 42 and/or the power transistor 15 to speed-up the turn-off process.

When the current flowing through the current control device 15 reaches a limiting value, such as 10 amperes, the resulting voltage developed across resistor 22 (which is a very small resistor which does not dissipate very much power) rises to a value which triggers a switch 50 which, in turn, feeds a control voltage to the input of the Schmitt trigger circuit 40 which sets the circuit 40 to a condition where the signal fed to the amplifier 42 will render the current control device 15 non-conductive. As the current control device 15 is rendered non-conductive, the current flowing through the flyback rectifier 25 will have the waveform W3 (FIG. 3). The primary winding 55a of a transformer 55 is connected in the line between bus 13 and the flyback rectifier 25 so that a voltage is produced in the secondary winding 55b of the transformer 55 which also follows the waveform W3. The secondary winding 55b is coupled to the input of the Schmitt trigger circuit 40. The voltage induced in the secondary winding 55b is initially of a polarity and magnitude to maintain the previously set condition of the Schmitt trigger circuit 40 to keep the current control device 15 non-conductive for a given period until the current flowing through the flyback rectifier 25 drops to a lower level where the voltage and current induced to the secondary winding 55b will drop to a lower level where the Schmitt trigger circuit 40 resets to the condition where the current control device 15 is rendered conductive.

To protect against short circuit currents due to a shorting of the flyback rectifier 25, a fuse 57 or other overload protecting means is placed in circuit with the flyback rectifier 25 so that any such short circuiting of the flyback rectifier will cause fuse 57 to blow, thereby to disconnect the short circuit involving from the output 18 of the voltage regulator circuit involved.

It will be recalled that a fuse 21 is provided in series with the current control device 15 so that the short circuiting thereof will increase the current flowing through the fuse 21 to a value well above the maximum limit (10 amperes) of the voltage regulator circuit which would blow the fuse 21. However, this action would not occur under very low or no load conditions because the current resulting from the shorted current control device would not necessarily result in a current flow exceeding this limit. For maximum reliability, therefore, it is important to provide a means for artificially providing a large load on the regulator circuit under small load or no load conditions when the current control device 15 becomes short circuited. To this end, an output voltage responsive switch control circuit 14 is connected across the output terminals 4a and 4b which circuit closes an associated switch 14' also coupled across the output terminals 4a and 4b when the voltage across the output terminals 4a-4b rises to a value, like 30 volts in the example being given, which is above the normal regulated upper limit of the voltage across the output terminals. The presence of a voltage across the output terminals 4a-4b above this limit would normally indicate a short circuited current control device. In this event, the closure of the switch 14' will cause a sufficient abnormal current to flow through the fuse 21 to blow the same.

If a short circuit develops across the current control device 15 of any operating voltage regulator circuit when more than one regulator circuit is carrying load current, the load current carried by the other operating regulator circuits will be diverted to the defective regulator circuit so that the fuse 21 of the defective regulator circuit will readily blow.

As previously indicated, for maximum efficiency it is desirable that a power transistor 15 be driven into a fully saturated state when it is conducting. To insure the driv-

ing of a power transistor 15 used as the current control device 15 into such a fully saturated state, it has been found desirable to provide a source of forward biasing voltage in the drive circuit of the power transistor when the drive circuit is a Darlington drive circuit, as fully described in copending application Ser. No. 387,457 filed Aug. 4, 1964, now Pat. No. 3,368,139. To obtain such a forward biasing voltage in the circuit of FIG. 3, one and preferably a number of parallel connected converter circuits 60, 60a, etc. are provided which are energized from the input terminals 4a and ground to provide first an alternating current and then a filtered and isolated D.C. output voltage fed to the amplifier 42 to increase the drive to the base circuits of the various power transistors 15. The provision of a number of converter circuits connected in parallel and each capable of supplying part of the total supplemental drive current increase the reliability of the system. The converter circuits are each designed so that a short circuit developing in one converter circuit will blow a fuse 62a, 62b etc. in the input or a fuse 62a', 62b' etc. in the output thereof which will disconnect the converter circuit involved from the other converter circuits. The current capacity of the converter circuits must be in excess of the total required current so the converter circuit can supply the required current with one converter circuit in an inoperative state.

Although the particular circuitry for the various portions of the regulator circuits shown in box form in FIG. 3 may vary widely, reference should now be made to FIG. 4 which, among other things, illustrates the preferred circuitry for the regulator circuits. It should be noted that the power transistor 15 of each regulator circuit in FIG. 3 has been replaced by two similar NPN power transistors 15' and 15'' connected in parallel so that lower current rated power transistors can be used. Resistors 63, 64 and 65 are connected with the base electrodes of transistors 15' and 15'' for maintaining the proper balance of current flow through the transistors. The amplifier 42 in FIG. 3 is formed by a series of transistors 67, 68 and 69 and associated resistors. The emitter-collector circuit of the transistor 69, which is a PNP transistor, is connected in series with the outputs of the converter circuits 60a, 60b etc. and the base to collector circuits of the power transducers 15' and 15'' to form a forwardly biased Darlington circuit as disclosed in said copending application Ser. No. 387,457, now Pat. No. 3,368,139.

The outputs of the converter circuits 60a, 60b etc. provide a source of forward biasing D.C. voltage which reduces the voltage drop across the power transducers 15' and 15'' to reduce the conduction losses therein. Thus, as illustrated in FIG. 4, the emitter electrode of transistor 69 is connected to the juncture of resistors 63 and 64 connected to the base electrodes of the transistors 15' and 15'', and the collector electrode of the transistor 69 is connected to a resistor 70 which, in turn, is connected by a conductor 72 to a common bus 74a, extending to the various outputs of the inverter circuits 60a, 60b etc. through associated output fuses 62a', 62b' etc. As shown in FIG. 4, the output of each of the converter circuits includes a terminal 77 at which a D.C. voltage of positive polarity appears relative to the voltage at a terminal 79. A capacitor 81 is connected across the terminals 77 and 79. The terminal 79 extends to the positive input bus 13' which is common to the various converter circuits and is connected to input terminal 2a. The terminals 77 and 79 of each converter circuit constitute an output terminal of a full wave rectifier circuit 85 which is energized from the secondary winding 87a of a transformer 87 whose primary windings 87b, 87c and 87d and NPN transistors 88 and 89 together with various resistors and rectifiers form a more or less conventional D.C. to A.C. converter circuit 90. The D.C. to A.C. converter circuit 90 is energized from input conductors 91 and 93 extending respectively to the output terminal bus 91' and bus 13 of the voltage regulator system.

The transformer 87 of each converter circuit has a secondary winding 87e which energizes a second full wave rectifier circuit 95 which produces a D.C. voltage across a capacitor 97 connected between the aforementioned output terminal 77 and another terminal 100. The terminal 100 is connected by a conductor 101 to a bus 102, in turn connected by conductors 103, 103', 103'' etc. to the various voltage regulator circuits. Each conductor 103, 103', 103'' etc. is connected through a resistor 104 to the emitter electrode of the associated transistor 68 which is a PNP transistor whose collector electrode is connected to the base electrode of the transistor 69 to act as a base drive means therefor. The outputs of the converter circuits 60a, 60b etc. taken across the capacitors 97 and the emitter to collector circuit of each voltage regulator circuit transistor 68 form a Darlington type circuit for the emitter-collector circuit of the associated transistor 69 which is substantially identical to the Darlington circuit formed by each transistor 69 and the converter circuit output taken across the capacitors 81 thereof which aids in driving the power transistors 15' and 15''.

As shown in FIG. 4, the circuit for speeding up the turn-off of the power transistors 15' and 15'' of each voltage regulator circuit includes the aforementioned secondary winding 17a in which a voltage is induced by the flow of current through the inductance 17 forming the primary winding of the transformer 17'. In the preferred circuit, one end of the secondary winding 17a is connected to the input side of the primary winding or inductance 17 and the other end thereof is connected in series with a capacitor 105 which in turn is connected to a rectifier 107 arranged to pass a negative voltage to a resistor 109 in turn connected to the juncture between the resistors 63 and 64 connected to the base electrodes of the transistors 15' and 15''. As previously indicated, when the conducting power transistors 15' and 15'' of a voltage regulator circuit start to turn-off, the resulting change in current flow through the inductance 17 will hasten the turn-off of the power transistors by virtue of the coupling of the induced negative voltage to the base electrodes of the power transistors 15' and 15''. This same voltage is coupled through a resistor 111 to the base electrode of the driver transistors 69 also to render the same non-conductive more quickly. The capacitor 105 in conjunction with a resistor 113 connected across the juncture of the rectifier 107 and capacitor 105, on the one hand, and the input side of the inductance 17, on the other hand, allows the voltage induced into the secondary winding 17a to reverse bias the transistors 15' and 15'' and 69 for a short predetermined period, such as for one microsecond.

The Schmitt trigger circuit 40 in FIG. 4 includes a pair of PNP transistors 114 and 116 interconnected in a more or less conventional manner to form a circuit wherein one of the transistors 116 and the other transistor 114 are normally nonconductive. When a drive current or a D.C. voltage is initially fed to the base electrode of the transistor 116 which is at or above a given upper control level, the transistor 116 becomes and remains conductive (i.e. become set) and the other transistor 114 becomes and remains non-conductive until the voltage or drive current at the base electrode of the transistor 116 drops below a lower control level where the circuit resets to its initial condition.

The base electrode of NPN transistor 67 is connected to the juncture of resistors 117 and 119 connected between the collector electrode of PNP transistor 114 and the common negative bus 13. Thus, the transistors 67 and 114 are normally conductive to render the drive transistors 68 and 69 operative to drive the power transistors 15' and 15'' into their heavily conducting states, and the setting of the Schmitt trigger circuit renders transistors 114, 67, 68, 69, 15' and 15'' non-conductive.

Normally, the transistor 116 is under control of the voltage responsive circuit 27 of FIG. 3 which in FIG. 4 is comprised of a pair of NPN transistors 118 and 120.

As illustrated, the aforementioned Zener diode 29 is connected between the base electrode of transistor 118 and ground or the common negative bus 13 and the aforementioned resistor 48 is connected between the base electrode and ground or the common negative bus 13. The emitter electrodes of transistors 118 and 120 are connected through a common resistor 123 to the common negative bus 13. The collector electrode of transistor 120 is connected by a conductor 127 to the base electrode of transistor 116. It is apparent that when the D.C. voltage across the output terminals 4a and 4b reaches a given level which is the adjusted upper voltage control level of the voltage regulator circuit involved, a voltage is presented at the base electrode of transistor 120 which will increase the collector current of transistor 120 to a point where it will drive the transistor 116 of the Schmitt trigger circuit 40 to its conductive state to stop the conduction of the power transistors 15' and 15". When the voltage across output terminals drops to a given lower voltage control level, the drive current to base electrode of the conducting transistor 116 will drop to a value where the transistor 116 returns to its initially non-conductive state and transistor 114 returns to its initially conductive state to reestablish the voltage conditions which drives power transistors 15' and 15" into conduction.

As previously indicated, when the current flow through the power transistors 15' and 15" reach a level which is an upper limit for the voltage regulator circuit involved, the resulting voltage across the resistor 22 in series with the power transistor will operate the switch 50 which sets the Schmitt trigger circuit 40 to a power transistor turn-off condition. In FIG. 4, the switch 50 is formed by a PNP transistor 130, a NPN transistor 147 and related circuit elements. A resistor 132 is connected between the emitter electrode of the transistor 130 and the anode of a rectifier 134 whose cathode is connected to the base electrode of the transistor 130. A pair of conductors 136 and 138 respectively connect the input and output sides of the current sensing resistor 22 to the emitter and base connected ends of the resistor 132. A pair of resistors 140 and 142 are connected between the base electrode transistor 130 and bus 13. The collector electrode of the transistor 130 is connected to bus 13 by a pair of resistors 144 and 146. The rectifier 134 establishes a forward bias between the base and emitter electrodes of the transistor 130 so that the small voltage produced when the maximum permitted current 22 flows through the resistor 22 added in series with the voltage across the rectifier 134 will cause the transistor 130 to conduct to a degree which generates a voltage across the resistor 146 which drives the base electrode of a NPN transistor 147 whose emitter electrode is connected to bus 13 and whose collector electrode is coupled through a resistor 148 to the base electrode of the Schmitt trigger circuit 40 to set the trigger circuit to its power transistor turn-off condition. A Zener diode 149 is connected between the anode of the rectifier 134 and the juncture of resistors 140 and 142 providing a constant current to the rectifier 134 to stabilize the operation of the circuit.

As previously indicated, as soon as the transistors 15' and 15" become non-conductive, current will begin to flow in the primary winding 55a in the flyback rectifier circuit to develop a voltage in the secondary winding 55b which will keep the Schmitt trigger circuit 40 for a short period in its set state which effects the turn-off of the power transistors 15' and 15". In the circuit of FIG. 4, a positive voltage passing rectifier 150 is connected between one end of the secondary winding 55b and one end of a resistor 151 whose opposite end is connected to the common negative bus 13. The rectifier 150 is connected by a conductor 152 to one end of a resistor 154 whose other end is connected to negative bus 13. The positive end of the resistor 154 is connected

to a rectifier 156 arranged to pass a positive voltage to the base electrode of the NPN transistor 147 which provides drive current to the Schmitt trigger circuit transistor 116. As the transistors 15' and 15" are driven to a non-conductive state, the resulting positive voltage induced across winding 55b is coupled through rectifier 150 and rectifier 156 to the base electrode of the transistor 147 to maintain the drive on transistor 147 which keeps transistor 116 conductive to keep the power transistors 15' and 15" in their non-conductive state until the voltage induced in the secondary winding 55b reduces to a level (see waveform W3 in FIG. 3) that is insufficient to keep the transistor 116 in a conductive state.

It will be recalled that a switch 14' (FIG. 3) is provided which is closed by the voltage responsive means 14 when a short circuit develops across the load terminals of a current control device 15. The closure of switch 14' could provide a short circuit across the output terminals 4a and 4b or could switch in a finite load resistance thereacross to maintain an output voltage across the output terminals at all times. In the latter case, the load resistance must be capable of withstanding large amount of power. For example, to maintain a 28 to 30 volt output at twenty amperes requires a 28-300 watt resistor which would create a momentary undesired heating problem in certain environments. To avoid the necessity of using such a resistor to maintain the output voltage, the protection circuit shown in FIG. 4 could be utilized. In this circuit, the switch 14' is connected in series with an inductance 170 across the terminals 4a and 4b to establish a flow of current through the inductance 170 when the switch 14' closes. The voltage responsive circuit 14 is designed so that it oscillates the switch 14 between its open and closed conditions when an abnormally high voltage is present across the output terminals. When the switch 14' momentarily opens, the inductance 170 acts to maintain current flow by diverting the current through one or more diodes 172 and the primary winding of a transformer 173 to the input to the regulator circuit involved, so that current and power is effectively taken from the output of the regulator system and recirculated in the form of a pulsating current through the voltage regulator circuit involved until the fuse 21 blows. In such a circuit, there is no significant dissipation of power while the output voltage is maintained.

FIG. 5 illustrates the preferred circuitry for the voltage responsive circuit 14 which opens and closes the switch 14' under the abnormally high voltage conditions referred to. As there shown, PNP transistors 176 and 174 and associated circuit elements constitute a voltage differential amplifier similar to the voltage differential amplifier 27 in FIG. 4. The collector current of the transistor 174 provides drive for a transistor 178 whose collector electrode is connected to one end of a resistor 180 whose other end is connected to the common negative bus 13. The emitter electrode of transistor 178 is connected to the bus 13 also. The high voltage end of the resistor 180 is connected to the base circuits of a series of parallel connected NPN transistor 181 and 183 and 185 forming the aforementioned switch 14'. When transistor 178 is conducting, the transistor 181, 183 and 185 do not receive any drive current. When the voltage across output terminals 4a and 4b are normal, transistor 174 conducts to feed drive current to the transistor 178 so that transistors 181, 183 and 185 are non-conductive. When the voltage across output terminals 4a and 4b rises to an abnormally high value, transistor 174 becomes non-conductive to remove drive current to the transistor 178 which also becomes non-conductive. Then, transistors 181, 183 and 185 receive a drive voltage appearing across resistor 180. The drive voltage appearing across resistor 180 is obtained from current carried therethrough by a circuit including a conductor 197 connected to the high voltage end of resistor 180, the secondary winding 195 of a saturable core transformer 190, a conductor 196, resistor 193, fuse 191,

primary winding 189 of transformer 190, a conductor 187, inductance 170, and a conductor 188 leading to the output terminal 4a. Initially, a small current flows through resistor 180. However, the primary winding 189 of the transformer 190 carries the collector current of the transistors 181, 183 and 185. The initially small collector current flowing through the primary winding 189 generates a voltage across the secondary winding 195 which increases the drive current to the transistors 181, 183 and 185. The resultant positive feedback will progressively increase the drive of the transistors 181, 183 and 185 until the collector current of these transistors rises to a value which saturates the transformer 190. When this occurs, the transistors 181, 183 and 185 lose the reinforcing driving voltage so that the collector current of the transistors 181, 183 and 185 will decrease. When this current decreases, the voltage will develop across the inductance 170 which will cause current to flow through rectifiers 172 and the primary winding 173 of a saturable core transformer 173' in turn connected by conductor 205 to the positive input terminal 2a. The current flowing through the primary winding 173 induces a positive voltage in the secondary winding 173a of the transformer 173' which is coupled through rectifiers 206 through 208 to the base electrode of transistor 178 to drive the same into conduction which as above explained will render the transistors 181, 183 and 185 non-conductive as long as the transistor 178 continues to be driven by the positive voltage induced in the secondary winding 173a. Ultimately, the current flowing through the inductance 170, the rectifier 172 and the primary winding 173 will decay to a value which will cease to generate a positive voltage across the secondary winding 173a which will drive the transistor 178 heavily into conduction. Then, the aforementioned process will be repeated and causes a pulsating transistor drive current to build-up in the circuit feeding the base electrodes of the transistors 181, 183, and 185. The last referred to transistors will, therefore, become alternately conductive and non-conductive to effect circulation of current through the input of the defective regulator circuit until the fuse 21 thereof will blow.

It should be understood that numerous modifications may be made in the most preferred form of the invention described above without deviating from the broader aspects thereof.

I claim:

1. A series type voltage regulator system including a pair of D.C. input terminals and a pair of output terminals across which a regulated D.C. output voltage is to appear, and a number of series voltage regulator circuits connected in parallel between said D.C. input terminals and said output terminals and each designed to carry only a fractional part of a given maximum total load current, each of said voltage regulator circuits including its individual and independent voltage responsive and regulating components capable of maintaining the voltage across said output terminals within given predetermined limits, one of said voltage regulator circuits being initially operative to carry load current up to a given maximum current level which is a fractional part of said total load current and to regulate the voltage at said output terminals, and the other voltage regulator circuits being initially inoperative to carry load current, and control means for rendering a number of said initially inoperative regulator circuits operative to carry load current when the load current flowing in the initially operative voltage regulator circuit rises to said given maximum current level in accordance with the demands of the load connected across said output terminals so only one operating voltage regulator circuit carries less than its assigned maximum current.

2. The voltage regulator system of claim 1 wherein said control means includes in each of said voltage regulator circuits load current limiting means for limiting the load current flowing therethrough to a maximum current

level which is said fractional part of said given maximum total load current.

3. The voltage regulator system of claim 2 wherein the average voltage across said output terminals will decrease when a maximum fractional load current flows through all operating regulator circuits and the load connected across said output terminals is increased, and said control means further includes means in each regulator circuit responsive to a drop in the output voltage across said output terminals while all operating voltage regulator circuits are in their current limiting modes of operation for rendering another voltage regulator circuit operative.

4. The voltage regulator system of claim 3 wherein each of said voltage regulator circuits includes a current control device having load terminals coupled in series between one of said input terminals and one of said output terminals, and there is provided capacitor means coupled across said output terminals, a separate inductance associated with each voltage regulator circuit which inductance is coupled between the output side of the load terminals of the associated current control device and one of said output terminals, and each regulator circuit further having a separate flyback rectifier means coupled between the input side of the associated inductance and the other output terminal, and each regulator circuit having a separate control means for rendering the associated current control device non-conductive when the voltage across said output terminals rises to a value at and above a given upper voltage control level and for rendering the associated current control device conductive when the voltage across said output terminals drops to a value at and below a given lower voltage control level, the upper and lower voltage control levels of the various parallel connected voltage regulator circuits defining the limits of contiguous voltage bands, the difference between the highest voltage control level of the highest voltage band and the lowest voltage control voltage of the lowest voltage band being a small value relative to the absolute magnitudes of these voltage control levels.

5. The voltage regulator system of claim 4 wherein the load current limiting means of each regulator circuit includes current control means for rendering the associated current control device non-conductive independently of the voltage across said output terminals when the current flowing through the associated current control device reaches said maximum current level and for re-establishing the conductivity of the associated current control device when the current flowing in the associated flyback rectifier means and inductance drops to a given lower current level.

6. The voltage regulator system of claim 5 wherein said current control means of each voltage regulator circuit includes a resistor connected between said one D.C. input terminal and the load terminals of the associated current control device, a control circuit responsive to a voltage across said resistor indicating the flow of a maximum current by initiating the non-conductivity of the associated current control device and means responsive to the decay of a maximum current in the associated flyback rectifier means and inductance for sustaining the non-conductivity of the associated current control device until the current decays to a given minimum level.

7. The series type voltage regulator system of claim 4 wherein there is provided first overload protection means in each regulator circuit in series with the load terminals of the associated current control device for opening the circuit thereto when the load terminals become short circuited under load conditions, and second overload protection means in each regulator circuit in series with said flyback rectifier means and inductance for opening the circuit to said flyback rectifier means when a short circuit develops across said flyback rectifier means.

8. The voltage regulator system of claim 1 wherein each of the voltage regulator circuits includes overload protection means responsive to the flow of a short circuit

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indicating current in the input or output portion thereof by disconnecting the short circuited portion of the regulator circuit from the other regulator circuits and said D.C. input terminals, so that a source of D.C. voltage connected to said input terminals and said other regulator circuits cannot supply current to the short circuited portion of a short circuited regulator circuit.

9. The voltage regulator system of claim 8 wherein there is at least one more regulator circuit in the parallel circuit of regulator circuits than that required by the maximum load current requirements, so maximum load current can be accommodated by the regulator system if one regulator circuit is disconnected by the associated overload protection means.

10. The voltage regulator system of claim 8 wherein each regulator circuit is provided with means responsive to an abnormally high voltage across said output terminals indicating a short circuit in the initially operative regulator circuit under no load conditions for providing an artificial circuit across said output terminal to provide a path for the flow of a short circuit current in said initially inoperative regulator circuit for operating said overload protection means therein.

11. The voltage regulator system of claim 1 wherein each of said voltage regulator circuits is provided with means for limiting the flow of load current therethrough to a given maximum current level which is a fractional part of the total load current which can be accommodated by said regulator system and means in each regulator circuit for maintaining the average voltage across said output terminals at a given level while the current flowing through the regulator circuit is less than said maximum current level, the voltage levels at which said last mentioned means of the various regulator circuits control the voltage across said output terminals progressively varying over a limited range which is a small proportion of the absolute values of the limits of said voltage range.

12. A series type voltage regulator comprising a pair of D.C. input terminals and a pair of output terminals across which a regulated D.C. voltage is to appear; and at least three independently operable series voltage regulator circuits connected in parallel between said D.C. input terminals and said output terminals, and each being designed to carry a fraction of the total load current and each of said voltage regulator circuits including overload protection means responsive to the flow of a given short circuit current in the input or output portion thereof by disconnecting the short circuited portion of the regulator circuit from the other regulator circuits and from said D.C. input terminals, so a source of D.C. voltage connected to said input terminals and said other regulator circuits cannot supply current to the short circuited portion of a defective regulator circuit.

13. A series type voltage regulator system comprising: a pair of D.C. input terminals and a pair of output terminals across which a regulated D.C. voltage is to appear; and a number of series voltage regulator circuits connected in parallel between said D.C. input terminals and said output terminals and each adapted to carry a fractional part of the total load current, each voltage regulator circuit including a current control device having load terminals coupled in series between one of said input terminals and one of said output terminals, said current control device of each regulator circuit being capable of being rapidly rendered conductive and non-conductive, means in each regulator circuit for rendering the current control device therein alternately conductive and non-conductive in accordance with the voltage fluctuations across said input terminals, filter means coupled between the output side of the load terminals of each current control devices and said output terminals for providing a relatively stable current and voltage at

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said output terminals when pulsating D.C. is fed thereto, said filter means including an inductance coupled between the output side of the load terminals of each current control device and one of said output terminals and a flyback rectifier means coupled between the input side of each inductance and the other output terminal, each of said regulator circuits having a first overload protection means connected in the circuit between said D.C. input terminals and said filter means for disconnecting the current control device from said input and output terminals if a short circuit develops across the load terminals of the associated current control device, and a second overload protection means in series with the flyback rectifier means and inductance thereof for disconnecting said flyback rectifier means from said input and output terminals if a short circuit develop across said flyback rectifier means.

14. A series type voltage regulator system comprising: a pair of D.C. input terminals and a pair of output terminals across which a regulated D.C. voltage is to appear; and a voltage regulator circuit connected between said D.C. input terminals and said output terminals, said voltage regulator circuit including a current control device having load terminals coupled in series between one of said input terminals and one of said output terminals, means for rendering the current control device therein alternately conductive and non-conductive in accordance with the voltage fluctuations across said input terminals, filter means coupled between the output side of the load terminals of said current control device and said output terminals for providing a relatively stable current and voltage at said output terminals when pulsating D.C. is fed thereto, an overload protection means connected in the circuit between said D.C. input terminals and said filter means for disconnecting the current control device from said input and output terminals if a short circuit develops across the load terminals of the current control device under appreciable load conditions, and means responsive to a voltage across said output terminals in excess of the desired regulated D.C. voltage thereat, which excess voltage would normally indicate a short circuit across said current control device under very low or no load conditions, for establishing an artificial load across said output terminals which provides artificially an appreciable load condition which operates said overload protection means.

15. The voltage regulator system of claim 14 wherein the last mentioned means include current recirculating means responsive to said excess voltage for recirculating current flowing through said artificial load through the input of the regulator circuit.

16. The voltage regulator system of claim 15 wherein the current recirculating means includes an inductance and a normally open switch connected in series across said output terminals, means responsive to said excess voltage for alternately opening and closing said switch means, and rectifier means coupled between said inductance and the input to said regulator circuit to permit the current flowing in said inductance when the switch is opened to flow through said current control device.

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LEE T. HIX, Primary Examiner

A. D. PELLINEN, Assistant Examiner

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