

Dec. 3, 1968

T. G. HARRIGAN ETAL

3,414,802

STACKED SERIES REGULATOR

Filed April 18, 1966

2 Sheets-Sheet 1

FIG. 1

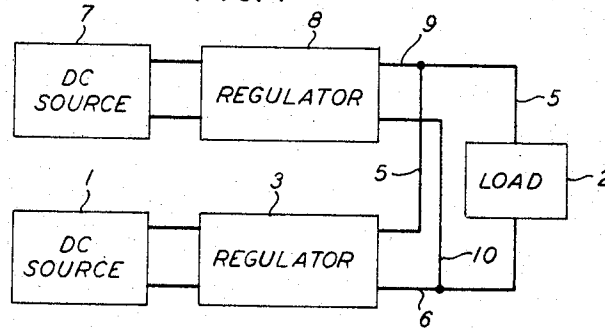


FIG. 2

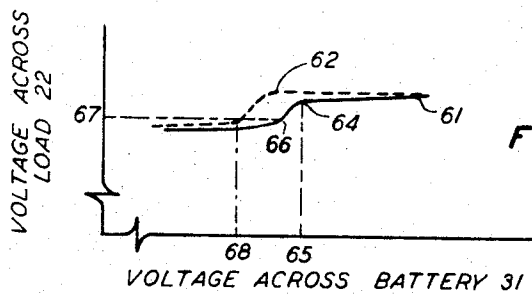
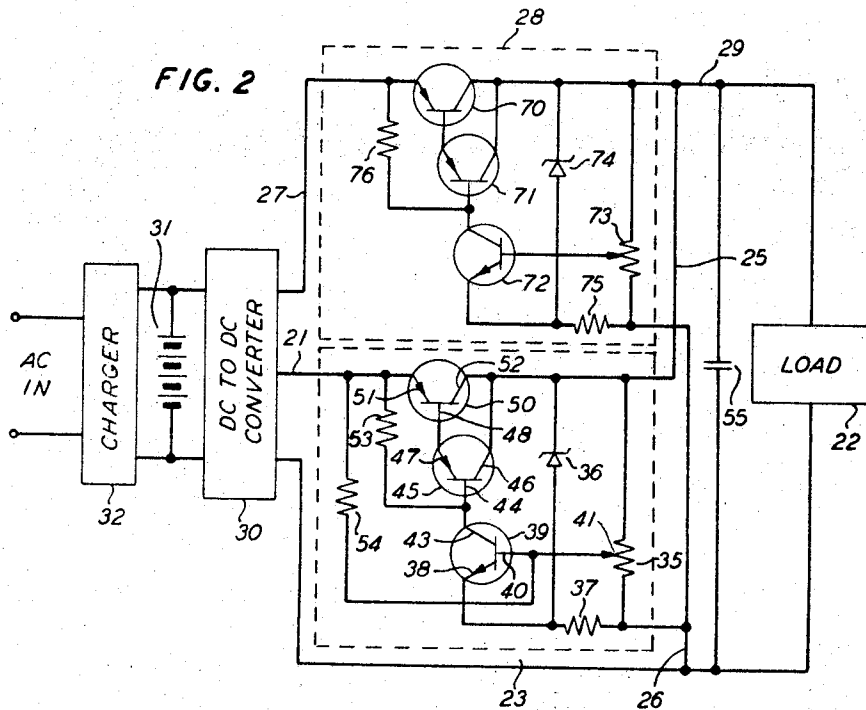


FIG. 3

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FIG. 4

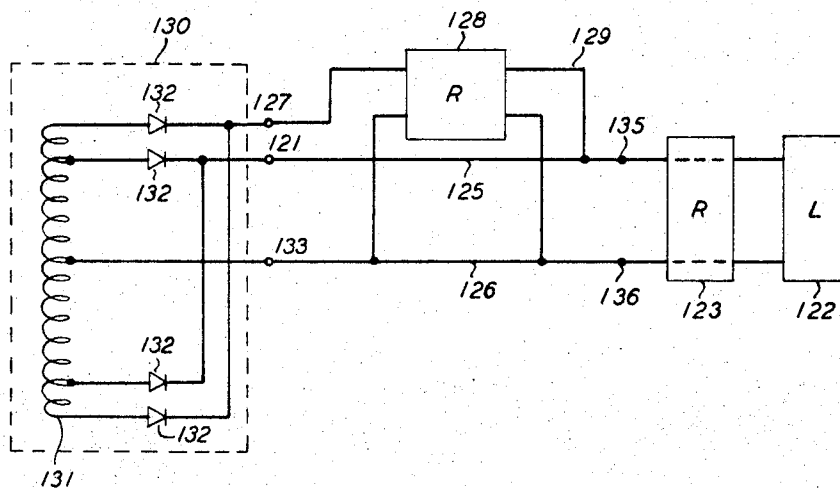
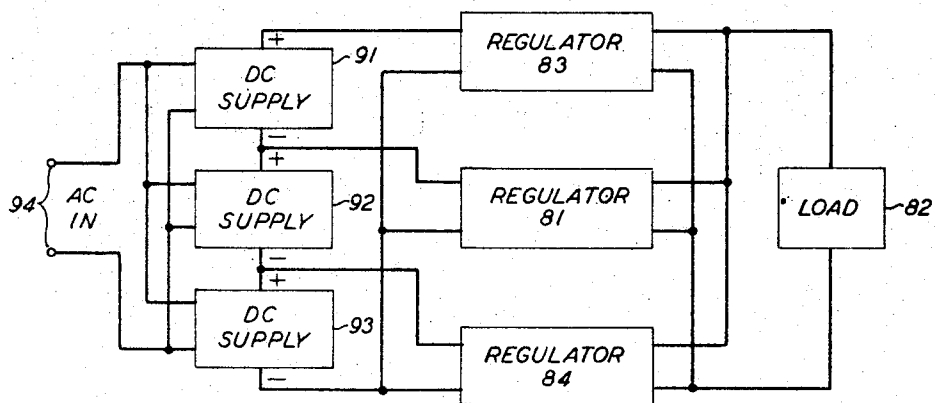


FIG. 5



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3,414,802

STACKED SERIES REGULATOR

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ABSTRACT OF THE DISCLOSURE

An efficient voltage regulating system comprises two variable series impedance regulators with outputs in parallel. The first regulator operates efficiently with a minimum voltage drop across it when the input voltage is normal. The second regulator, operating from a higher input voltage, is adjusted to supply a slightly lower output voltage than the first regulator supplies. The second regulator is therefore normally cut-off and operates only when the output voltage falls because of a larger drop in the input voltage than the first regulator can absorb. Where a slight step in load voltage is undesirable the output of the second regulator is connected to the first regulator's input. Where large excursions in input voltage are bidirectional three regulators are connected with their outputs in parallel.

This invention relates to the field of voltage regulated power supplies, particularly to the series regulating types. In the electronic arts direct current is commonly supplied at a constant regulated voltage to a variable load from an unregulated source through a series regulator of either the switching or the nonswitching type.

In the switching type regulator a switch is interposed between the source and the load. The percentage of time that the switch is closed, transmitting current to the load, is varied to maintain a constant voltage at the load. The switch must operate, of course, at a fast enough rate to accommodate contemplated changes in the load and in the source. When the switch is closed there is virtually no voltage drop across it; when the switch is open no current flows through it. Consequently, there is virtually no power lost in the switch itself, and the device is very efficient. On the other hand, since the current is supplied in pulses, extensive filtering is required both at the input and the output, and the output impedance is relatively high. In addition, the size and weight of this type regulator tend to be relatively large.

In the nonswitching or variable impedance type series regulator an impedance element such as a transistor or vacuum tube is interposed between the source and the load. The impedance of the element is varied to maintain a constant voltage at the load. Since the response of vacuum tubes and transistors is virtually instantaneous, very little filtering is needed. In fact, the device itself is a type of electronic filter. In addition, the size and weight can be made relatively small. The major drawback, however, is poor efficiency. All of the load current passes through the impedance element, and all of the voltage difference between the highest input voltage and the lowest output voltage is dropped across it. Under the common condition of a high input voltage and a low voltage high current load an appreciable voltage appears across the regulator at a high current. This results in a high power loss and very poor efficiency.

The prior art approaches a solution to the inefficiency of the otherwise desirable series nonswitching regulator in two ways. First, when a large variation in output voltage is desired, means have been used for lowering the source voltage as the load voltage is lowered. Commonly a variable autotransformer at the input is coupled me-

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chanically to the potentiometer which adjusts the output voltage. The second common approach attacks an effect of the poor efficiency rather than the cause. In the case of a transistor regulator an instantaneous large power absorption can result in permanent damage to the transistor. Many devices have been designed which protect the transistor by absorbing this power elsewhere, but these, of course, do not improve the efficiency.

In applications where the source voltage is relatively constant with only an occasional large excursion and where the equipment is in constant use, there is a real need for a series regulator which can operate efficiently and yet accommodate the occasional large input excursion. Such an application is commonly found in a telephone system. In order to provide continuous service in the event of a power blackout, the system continually operates on storage batteries under a trickle charge; normally the voltage at the batteries is relatively constant. When there is a power failure, however, the charging voltage disappears and the battery voltage drops. An efficient regulator is found in our invention, the stacked series regulator.

An object of this invention is to provide a very efficient voltage regulating circuit with all the advantages of series nonswitching regulation and without the major disadvantage of low efficiency.

Another object is to provide a series voltage regulating circuit ideally suited to supply current from a normally well regulated source such as storage batteries.

A still further object of this invention is to provide a series voltage regulating circuit in applications where generated heat or cost of wasted power must be kept to a minimum.

In its simplest form the invention comprises two ordinary series regulators operating with outputs in parallel. The first regulator is designed to operate with a minimum voltage across it when the input voltage is normal. This allows it to operate very efficiently. The second regulator, operating from a higher input voltage, is adjusted to supply current at a slightly lower output voltage than the first regulator supplies. This second regulator, because of its higher drop, is not so efficient when operating, but is normally cut off. During the infrequent periods when the input voltage to the first regulator drops below the value at which the regulator can continue to regulate, the output voltage drops slightly causing the second regulator to become operative. Thus the system operates with good efficiency most of the time, protects for the occasional extreme excursion, and has all the advantages of series nonswitching regulation.

In the event that the slight step in output voltage necessary to activate the normally cut off regulator is undesirable, a similar embodiment can be used. In this embodiment the output of the second regulator is connected to the first regulator's input rather than its output. Now, when the first source voltage drops to some predetermined point above that at which the first regulator loses regulation, the second regulator begins to pass current, maintaining the input voltage to the first regulator. The system output voltage therefore remains substantially constant, even during the large input excursion.

Where the normal regulation of the first source is within the tolerance required by the load, the first regulator may be eliminated entirely. In this case, during normal operation, the load is supplied directly from the first source with no power consumed in a regulator. When the load voltage, which is the first source voltage, drops beyond the normal minimum, the second regulator takes over and maintains the load voltage.

Finally, where the input voltage is apt to rise considerably as well as fall, still another embodiment of our in-

vention utilizes a third regulator to handle the large positive excursion. This regulator is adjusted to regulate at a slightly higher output voltage than the first regulator and is supplied from a lower voltage DC source. All three DC sources are supplied from a single system input. During normal operation, the third regulator is cut off because its source voltage is lower than the load voltage. During a large positive voltage excursion on the system input, the source voltage to the third regulator rises, allowing that regulator to pass current and take over the regulation at the slightly higher load voltage.

A more complete understanding of the invention may be obtained from a study of the following detailed description of several specific embodiments. In the drawings:

FIG. 1 is a block diagram of the invention in its simplest form;

FIG. 2 is a schematic diagram of one preferred embodiment of the invention;

FIG. 3 is a plot of output voltage against input voltage for two typical loads on the system of FIG. 2;

FIG. 4 is a block diagram of an alternative embodiment of the invention with a different arrangement of regulators; and

FIG. 5 is a block diagram of an alternative embodiment utilizing three regulators.

In the embodiment of the invention shown in FIG. 1, a DC source 1 supplies current to a load 2 through a series regulator 3 via a pair of conductors 5 and 6. In like manner, a DC source 7 can supply current to load 2 through a series regulator 8 via a pair of conductors 9 and 10. Source 7 is of higher voltage than source 1 and regulator 8 is set to supply current at a slightly lower output voltage than is regulator 3. Normally, therefore, when source 1 is operating close to its nominal voltage, virtually all of the current to load 2 is supplied by source 1 through regulator 3. Regulator 8, in attempting to reduce the load voltage, has a very high impedance, cutting off the current from source 7.

When the voltage of source 1 falls off, the impedance of regulator 3 decreases in an attempt to maintain the voltage at the load. When this impedance is at a minimum and the voltage of source 1 continues to fall, the voltage at the load must then fall. When the load voltage, which is the output voltage of regulator 8 as well as regulator 3, falls a slight amount to that value to which regulator 8 was set, the impedance of regulator 8 begins to fall. The load voltage is then maintained at the slightly lower level by current from source 7 until the voltage of source 1 again rises.

In the preferred embodiment of FIG. 2, an output tap 21 of a DC to DC converter 30 supplies current to a load 22 through a series regulator 23 via a pair of conductors 25 and 26. In like manner, an output tap 27 can supply current to load 22 through a series regulator 28 via a conductor 29 and conductor 26. Tap 27 supplies a higher voltage than does tap 21. Converter 30 is supplied by a battery 31 which is kept under constant charge by a charger 32 operating from the AC power line.

Series regulators 23 and 28 are typical of those well known in the art and their operation will be described. The invention is not limited to the use of these particular regulators, of course, as it will operate equally well with any DC series voltage regulator circuit. A potentiometer 35 is in parallel with the load 22 hence sees the same voltage. A series circuit consisting of a Zener diode 36 and a resistor 37 is also in parallel with the load. The Zener diode is poled so that it is back biased by the load voltage and the value of resistor 37 is chosen so that avalanche current continually flows in the diode. Under these conditions, the voltage across the diode is constant, independent of changes in the voltage across the load 22. The emitter 38 of an NPN transistor 39 is connected to the junction between Zener diode 36 and resistor 37. The base 40 of transistor 39 is connected to the adjustable tap 41

of potentiometer 35. Any change of output voltage across load 22 therefore appears undiminished at emitter 38 and some proportion of this change appears at base 40. If because of a change in current in load 22 or a change in voltage across battery 31 the voltage across load 22 tends to drop, the voltage at emitter 38 drops the same amount while that at base 40 drops a lesser amount. This causes a slight increase in base-emitter voltage of transistor 39 and hence a slight increase in base-emitter current. The collector 43 of transistor 39 is connected to the base 44 of a PNP transistor 45. The collector 46 of transistor 45 is connected to conductor 25; the emitter 47 is connected to the base 48 of a PNP transistor 50. The emitter 51 of transistor 50 is connected to tap 21; the collector 52 is connected to conductor 25. Biasing resistor 53 is connected between tap 21 and base 44, and biasing resistor 54 is connected between tap 21 and base 40.

The slight increase in base-emitter current of transistor 39 causes by transistor action a larger increase in collector-emitter current. In like manner this causes a larger increase in collector-emitter current in transistor 45 and in turn a still larger increase in collector-emitter current in transistor 50. The collector-emitter impedance of transistor 50 is thereby reduced, offsetting the original drop in output voltage at load 22. Should the output voltage tend to rise, the impedance of transistor 50 is increased through a similar chain of events of opposite polarity. The output voltage at load 22 is therefore well regulated over a range of input and output conditions.

This invention departs from the prior art, however, in that the range of input voltage over which regulator 23 maintains the output voltage is purposely made very small. It is important to the efficiency objective of the invention that the voltage of tap 21 be so chosen in relation to the desired output voltage that the voltage drop across transistor 50 be never very large. In fact, the collector-emitter impedance of transistor 50 is at an effective minimum when the voltage of battery 31 is at its normal minimum with battery charger 32 operating. This condition can be better explained with additional reference to the curves of output voltage against input voltage of FIG. 3.

Curve 61 is for a higher current load; curve 62 is for a lower current load. For example, curve 61 may represent five amperes, while curve 62 represents one ampere. Both scales have been considerably amplified to illustrate the action. The upper portion of curve 61, above point 64, represents the condition where regulator 23 is functioning as described. The voltage across load 22 is maintained relatively constant as long as the voltage at battery 31 does not go below the value represented by abscissa 65. This value should be by design the minimum normally occurring voltage across battery 31 with the charger operating. At this point also regulator 28 is not supplying any current. For sake of illustration, regulator 28 is similar to regulator 23. Three transistors, 70, 71 and 72 are connected similarly to transistors 50, 45 and 39, respectively. A potentiometer 73 for adjusting output voltage corresponds to potentiometer 35; a voltage reference circuit comprising a Zener diode 74 and a resistor 75 corresponds to the circuit of Zener diode 36 and resistor 37; a bias resistor 76 corresponds to resistor 53. Transistors 70, 71 and 72 are all cut off by virtue of the setting of potentiometer 73, which controls the bias on transistor 72. Hence during over 99.9 percent of the time, when the power lines are intact, the efficiency of the system is very good.

Now should the DC input voltage across battery 31 continue to drop below abscissa 65 in FIG. 3, as in the instance of a line power failure which makes charger 32 inoperative, output voltage begins to drop because the impedance of transistor 50 can go no lower. When the output voltage drops to point 66, however, represented by ordinate 67, the emitter voltage of transistor 72 is low enough to turn on transistor 72, in turn turning on tran-

sisters 71 and 70, and regulator 28 begins to function much as did regulator 23. A further drop in battery voltage has practically no effect on output voltage because of the action of regulator 28. The difference between point 64 and point 66 can be made very small, in the order of one-tenth volt compared to an output of twenty-four volts. Contrary to regulator 23, regulator 28 may be designed with a large reserve voltage. That is, the voltage at tap 27 may be considerably higher than the desired load voltage. While this produces inefficiency, the effect on overall efficiency is slight because regulator 28 operates for such a small percentage of time.

Even in the worst condition, however, when regulator 28 is supplying all of the load current, the system is more efficient than would be a single series regulator under normal conditions. This is because during this fault condition the battery voltage, hence the voltage at tap 27, and in turn the voltage across the functioning regulator 28 are below normal.

As can be seen by curve 62, at a lighter load the crossover point from regulator 23 to regulator 28 takes place at a lower input voltage, abscissa 68. A capacitor 55 across the load is useful to reduce noise voltage.

Where the step in load voltage shown in FIG. 3 is undesirable, the circuit of FIG. 4 may be used. By way of illustration, a source 130 may comprise the multitapped secondary winding 131 of a transformer or DC to DC converter, with a rectifier 132 connected to each tap except the center tap. The cathodes of the rectifiers of symmetrical taps are connected together to provide full-wave rectified direct current at terminals 127 and 121 with the common ground terminal 133. This arrangement may be used for the sources of any of the embodiments of the invention. A series regulator 123 is supplied from terminals 121 and 133 over conductors 125 and 126. A load 122 is in turn supplied from regulator 123. As in the case of regulator 3 of FIG. 1 and regulator 23 of FIG. 2, regulator 123 is designed with a small reserve voltage. That is, if the voltage at the terminals 121 and 133 an- hence at the input of regulator 123, points 135 and 136, were to fall a small amount, below a convenient infrequent minimum, the load voltage would start to drop. The output of a series variable impedance regulator 128, however, is connected to the input of regulator 123. Terminals 127 and 133 are connected to the input of regulator 128. Regulator 128 is adjusted to supply current at a voltage less than the normal voltage appearing at tap 127, but higher than that at which regulator 123 ceases to regulate. Most of the time, therefore, when the voltage at terminal 121 is within its normal limits, regulator 128 is cut off, and current is supplied to load 122 through efficient regulator 123. When the voltage at terminal 121, which is the output voltage of regulator 128, begins to drop beyond its normal limits, however, the impedance of regulator 128 begins to drop, passing current from terminal 127 and maintaining the voltage at points 135 and 136 above that which produces a drop at load 122.

In the event that the load can tolerate the normal voltage range of the primary source 121, and must be protected from only a major excursion, it is possible to eliminate regulator 123 entirely as shown by the dotted lines in FIG. 4. This is the most efficient embodiment of the invention in that there is no power lost in regulation during normal operation. There is no change in the operation of regulator 128.

For applications where the infrequent large excursions in input voltage tend to be bidirectional, a third regulator may be added, as shown in block diagram FIG. 5. In this circuit, for sake of illustration, three DC power supplies 91, 92 and 93 are each powered by a common AC input line 94. The output circuits of the three supplies are connected in series. A load 82 is connected across the parallel connected output circuits of three regulators 81, 83 and 84. The input circuit of regulator 83 is connected

between the positive output terminal of supply 91 and the negative output terminal of supply 93; the input circuit of regulator 81 is connected between the positive output terminal of supply 92 and the negative output terminal of supply 93; the input circuit of regulator 84 is connected between the positive and negative output terminals of supply 93. The invention is not limited, of course to this supply voltage polarity, as the opposite polarity would work equally well. During the preponderance of time, when the AC input voltage is within normal limits, the efficient regulator 81 supplies current to load 82 from the source made up of supply 93 in series with supply 92. Similarly to previously discussed circuits, regulator 83 is adjusted to supply current at a slightly lower voltage than is regulator 81. When the AC input voltage drops beyond the regulating range of regulator 81, regulator 83 becomes active and supplies current to load 82 from the source made up of supplies 91, 92 and 93 in series. Regulator 84 is adjusted to supply current at a slightly higher voltage than is regulator 81. Consequently, the true impedance of regulator 84 is at a minimum as long as the load voltage is normal or lower. The only reason that regulator 84 does not supply current is that DC supply 93 is not of a high enough voltage. When the AC input voltage in line 94 rises appreciably, therefore, the voltage at DC supply 93 rises, allowing regulator 84 to take over and supply the load.

It is to be understood that the above-described arrangements are illustrative of the applications of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A direct current voltage regulating system comprising a first direct current variable impedance type series voltage regulator having input and output terminals, a first direct current source connected to said input terminals, a second direct current variable impedance type series voltage regulator having input and output terminals, and a second direct current source connected to the input terminals of said second regulator, wherein the output terminals of both regulators are connected in parallel, said second direct current source is of higher voltage than said first source, and said second regulator provides current at a slightly lower output voltage than said first regulator.

2. A direct current voltage regulating system as in claim 1 wherein said sources comprise a direct current to direct current converter having an input circuit and multiple output voltage taps, a direct current storage battery connected to said converter input circuit, and charging means connected to said battery for maintaining the voltage thereof.

3. A direct current voltage regulating system as in claim 1 comprising in addition a third direct current series voltage regulator having input and output terminals and a third direct current voltage source connected to the input terminals of said third regulator, wherein the output terminals of said third regulator are connected in parallel with those of said first and second regulators, and said third regulator provides current at a slightly higher voltage than does said first regulator.

4. A direct current voltage regulating system as in claim 1 wherein said first and second direct current series voltage regulators each comprise input and output terminals, adjustable sensing means connected across said output terminals for sensing a portion of the voltage there appearing, voltage reference means, comparison means connected between said sensing means and said reference means for producing an output voltage proportional to the difference between said sensing means and said reference means, and current control means connected between one input and one output terminal responsive to the output voltage of said comparison means.

5. A direct current voltage regulating system comprising a first variable impedance type series regulator having input and output terminals and adapted to maintain a constant voltage at said output terminals, a load connected to said output terminals, a first direct current source having a nominal voltage range connected to said input terminals, a second variable impedance type series regulator having input and output terminals and adapted to maintain an adjustable constant voltage at its output terminals, a second direct current source connected to said last-named input terminals, and means connecting the output terminals of said second regulator to the input terminals of said first regulator, wherein the voltage magnitude of said second source is greater than that of said first source and said second regulator supplies current at a lower voltage magnitude than said nominal voltage range.

6. A direct current voltage regulating system as in claim 5 wherein said first and second source comprises the rectified outputs of a multitap transformer.

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