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CURRENT REGULATOR

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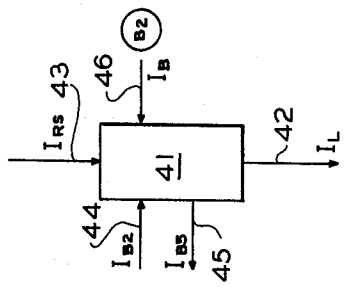



FIG. 2

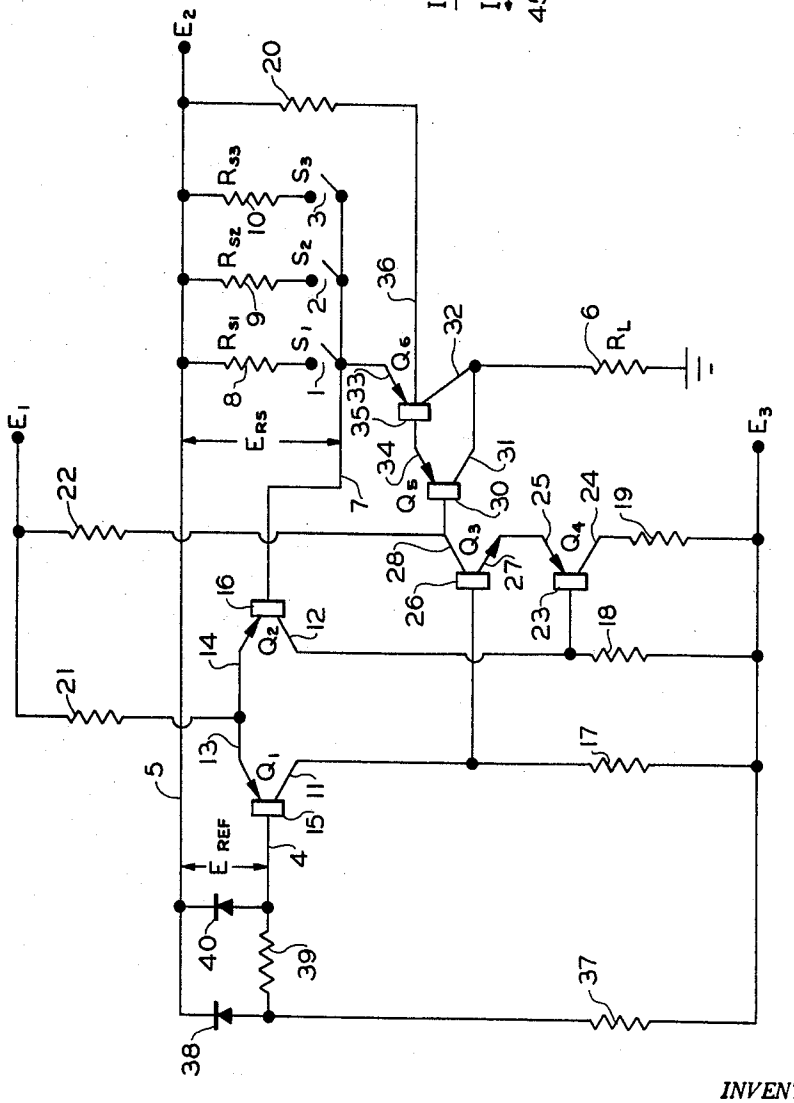



FIG. 1

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# CURRENT REGULATOR

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This invention relates to means for providing an output current having an amplitude which is selectively adjustable in precise steps.

There has been proposed heretofore a variety of means for supplying precise currents which are equal to a preset value or numerical input information. Typical prior devices employ a digital potentiometer or voltage dividing network having selective switch taps for providing an output which may be adjusted in discrete steps corresponding to the numerical input. The input to the potentiometer or tapped network is derived from a fixed and/or stabilized reference source. Typically this reference source is an automatically regulated current, or regulated voltage, power supply. A disadvantage inherent in this technique is that selective switching to obtain amplitude adjustment of the output may introduce undesirable changes in the impedance of the output circuit. Also, prior circuits are generally undesirably effected by changes in the type of output load from purely resistive to reactive loads.

According to the present invention quantizing or discrete adjustment in accordance with the selective input is accomplished by operating upon the control signal input to the voltage or current regulator, thus obviating selective switching in the output network for current amplitude adjustment.

All solid-state elements are employed in the circuitry of the regulator.

It is, therefore, an object of the invention to provide a novel solid-state current regulator.

Another object of the invention is to provide a novel solid-state current regulator capable of being selectively adjusted in discrete increments to provide an output current having a precisely regulated amplitude.

Still another object of the invention is to provide a novel digital-to-analog converter for accepting a parallel code input and supplying an output current having an amplitude corresponding to the coded input.

Yet another object of the invention is to provide novel and improved means for supplying a continuously regulated output current, independent of the type of output load, from an unregulated current source.

These and other objects of this invention will be more readily understood upon consideration of the following specification and drawings in which:

FIGURE 1 is a schematic diagram of the circuit of the invention.

FIGURE 2 is a block diagram illustrating the output circuit of the invention including the current inputs thereto.

A practical circuit diagram is illustrated in FIGURE 1. Unlike voltage regulators in which the voltage at the output terminals is sensed, a current is passed through a resistor and the voltage developed across the resistor is compared with a voltage reference. Any voltage difference between the voltage reference and the voltage across the measuring resistor is then amplified and applied to the base of the regulator transistor so that the transistor is a series regulating transistor which completes the regulating feedback connection by controlling the current flow. The result is that this transistor attempts to pass a current which will keep the voltage across $R_{S1}$–$R_{S3}$ closely equal to the reference voltage $E_{REF}$. The numerical input to the circuit comprises incremental resistance changes effected by selectively closing combinations of switches



S1–S3 shown at 1–3. These switches selectively connect current measuring resistors $R_{S1}$–$R_{S3}$ into the circuit. The magnitude of the output current appearing across load resistor $R_L$, shown at 6, is proportional to the voltage $E_{RS}$ appearing across lines 5 and 7 as determined by the total resistance switched into the regulator circuit by combination of closures of switches S1–S3. The accuracy of the output current through the load resistor $R_L$, indicated at 6, is the same as the accuracy of the signal voltage $E_{RS}$ appearing across lines 5 and 7.

The voltage $E_{RS}$ appearing across lines 5 and 7 and developed across resistors 8–10 is compared to the reference voltage $E_{REF}$. It should be understood that any desired number of resistors may be employed in the switching circuit and that the circuit is not limited to three resistors such as 8–10 and their respective switches 1–3. That is to say, the number of resistors and switches employed is determined by the desired adjustment resolution. It being obvious to those skilled in the art that by increasing the number of selectable resistances, there will be a direct increase in the resolution of adjustment in the regulator output current appearing across resistor 6.

The voltage $E_{RS}$ is compared with the voltage $E_{REF}$ and the difference voltage appears between the collectors 11 and 12 of transistors Q1 and Q2 respectively forming an emitter-coupled comparison, or difference amplifier. The reference voltage on line 4 is applied to the base 15 of the transistor Q1 and the signal voltage $E_{RS}$ on line 7 is applied to base 16 of transistor Q2 for amplification. Transistors Q3 and Q4 form a "complementary" push-pull pair which convert the "push-pull" input from collectors 11 and 12 of transistors $Q_1$ and $Q_2$ applied at bases 26 and 23, respectively, to a single-ended output signal at collector 28 of $Q_3$ and $Q_4$ isolate the source of the differential voltage (i.e. $E_{REF}$ and $E_{RS}$) from the output stages employing transistors Q5 and Q6 which are connected in a circuit similar to the Darlington configuration. Transistors Q3 and Q4 also provide current amplification of the absolute differential signal obtained from transistors Q1 and Q2. The signals appearing at the base 30 of transistor Q5 tend to return the original differential signal to zero.

By returning the collector 31 of transistor Q5 to the collector 32 of transistor Q6, a much larger percentage of the emitter current of transistor Q6 is delivered to the load resistor 6. The use of a double-base transistor tetrode Q6 provides high frequency response and increases the usable gain of the circuit over that which would be obtainable with a transistor triode.

The function of resistors 8–10 in the circuit of emitter 33 of transistor Q6 is to determine the magnitude of the current that is to be regulated. These resistors can be either manually selected by means of switches 1–3 or may be controlled by solid-state switching as will be obvious to those skilled in the art. By selecting the resistance values of resistors 8–10 which are weighted according to a binary code, a large number of discrete current levels may be obtained by combining a relatively small number of individual switches and corresponding resistors. For example, by using nine resistors (rather than the three resistors 8–10) having resistance values which are related according to the binary number system, 512 discrete current levels may be obtained by suitably combining the nine resistors via switches 1–3 in the base circuit 16 of transistor Q2 and the emitter circuit 33 of transistor Q6.

The operating potential for transistors Q1 and Q2 is obtained from the positive terminal of an external power supply $E_1$ via emitter bias resistor 21. The collector of transistor $Q_1$ is referenced to the negative power supply terminal $E_3$ via resistor 17. Similarly, the collector 12 of transistor $Q_2$ is referenced to the negative power sup-

ply terminal $E_3$ via resistor 18. The differential amplifier comprising transistors $Q_1$ and $Q_2$ is direct-coupled to cascaded-amplifier stages employing transistors $Q_3$ and $Q_4$. Operating potentials for transistors $Q_3$ and $Q_4$ are obtained from positive power supply terminal $E_1$ via resistor 22 and negative power supply terminal $E_3$ via resistor 19.

The voltage level at the bases 23 and 26 may vary independently from the amplified output of transistors $Q_3$ and $Q_4$; it is the differential signal between the collectors 11 and 12 which is amplified. The potential at the juncture between collector 28 and base 30 is fixed.

The reference voltage $E_{REF}$ is derived from the external power supply potentials appearing between positive terminal $E_2$ and negative terminal $E_3$ via a zener diode voltage-regulating circuit. The zener diode reference-voltage circuit comprises zener diodes 38 and 40 having their cathodes connected in common to line 5 terminating at positive terminal $E_2$ of the external power supply. The magnitude of supply voltage $E_2$ will be less than that of $E_1$. The anode of zener diode 40 serves as the negative termnial of the reference supply $E_{REF}$ and is connected to base 15 of transistor $Q_1$ via line 4. The anode of diode 38 terminates at the negative power supply terminal $E_3$ via resistor 37 and is also connected to the anode of diode 40 via resistor 39. The reference voltage $E_{REF}$ appearing across lines 4 and 5 will not exceed the zener voltage of diode 40 and will be somewhat less than the potential difference appearing between positive power supply terminal $E_2$ and negative power supply terminal $E_3$.

The differential output signal appearing between the collector 28 of transistor $Q_3$ and collector 24 of transistor $Q_4$ is applied as an input signal to the base 30 of transistor $Q_5$, which in conjunction with direct-coupled transistor tetrode $Q_6$ comprises the series regulating element in the current output circuit. The input signal to the regulator appears between the base 30 of transistor $Q_5$ and ground. The active base 35 of transistor $Q_6$ is direct-coupled to the emitter 34 of $Q_5$. Collectors 31 and 32 of transistors $Q_5$ and $Q_6$, respectively, are tied together; the output current flows from the collectors 31 and 32, through the load resistor 6 ($R_L$) to ground. The auxiliary base 36 of transistor $Q_6$ obtains its bias potential from positive power supply terminal $E_2$ via resistor 20. The signal current $I_{RS}$ from switches $S_1$–$S_3$, to the series regulator element, is injected via the emitter 33 of $Q_6$.

The signal that appears at the base 30 of transistor $Q_5$ is in a direction that tends to reduce the original differential signal to zero.

The usually high gain obtained by the use of a transistor tetrode ($Q_6$) shortens the response time of the circuit and increases the usable gain. In practical circuits, current changes may be performed at a 10 kc. rate. An additional advantage of employing a transistor tetrode is that the operating bias, obtained from the bias network, may be kept to a desirably low level as compared with the signal level.

FIGURE 2 represents a block diagram of the output circuitry 41 and the input currents thereto.

As an introduction to the analysis of the diagram of FIGURE 2, the operation of the circuit of FIGURE 1 will be summarized. Connected between the positive power supply terminal 5 and line 7 are a plurality of branch circuits each containing a switch and a series resistor. These branch circuits, together with the collector-to-emitter resistance of transistor $Q_6$, and the load resistance $R_L$ form a plurality of circuits connected in parallel across power supply E2. The total resistance in resistance in these circuits may correspond to the coefficients of the radix of any desired number system. Assuming that a number system having a radix of two is used (i.e. binary), then the circuit including S1 will have a total resistance of R, the circuit including S2 a total resistance of 2R, the next circuit a total resistance of 4R and, by extension of the branch circuits, the $n^{th}$ a total resistance of $2^{n-1}R$. The current through the load $R_L$ is the sum of all the currents produced in these parallel circuits by voltage $E_{RS}$; therefore, the output current $I_L$ is the analog of the binary number set into switches S1–S*n*. Ideally, the load current $I_L$, appearing at terminal 42, should equal the reference signal current $I_{RS}$, supplied at terminal 43; this being the circuit that is controlled. However, in practical circuits, the effect of the base currents of the series regulator transistors and the signal input transistor of the differential amplifier introduce a predictable sum which, of course, must be added to the output current $I_L$. These base currents flow through the auxiliary base of the tetrode transistor ($I_B$ at terminal 46), the base transistor Q5 ($I_{B5}$ appearing at terminal 45) and the base of transistor $Q_2$ ($I_{B2}$ appearing at line 44). Changes in the sum of these three currents with respect to the change in $I_{RS}$ is extremely small.



It will be appreciated that the output curent $I_L$ may be used directly in which case load resistor $R_L$ would be an external impedance or current $I_L$ can be transformed to discrete voltage by the use of a precision fixed resistor as the load resistor 6. In this instance, the potential difference appearing across $R_L$ would be discrete voltage steps. The magnitude of the signal available from the collector circuit of the output stage is limited only by the rating of the transistors employed. Practical circuits may be constructed having a current range of a few milliamperes to several amperes. In all cases, the performance of the regulator is substantially independent of the type of load (i.e. inductive, capacitive, or resistive).

Although this invention has been described with respect to a particular embodiment thereof it is not to be so limited, as changes and modification may be made therein which are within the full intended scope of the invention, as defined in the appended claims.

What is claimed is:

1. A selectively adjustable current regulator comprising;
   - an unregulated supply of direct current,
   - a source of fixed reference voltage source,
   - a plurality of resistances connected to said unregulated supply, the resistance in each of said circuits corresponding to coefficients of the radix of a number system,
   - a selective switching means connected in series with each of said resistances for selectively paralleling said resistances to obtain a selected signal voltage from said unregulated supply,
   - a comparison means connected to said fixed reference voltage and to said selected signal voltage and responsive to said signal and said reference for providing a difference voltage representing the difference therebetween,
   - a load impedance, and
   - circuit means connected between said unregulated supply and said load impedance responsive to the selected signal voltage and the difference voltage for maintaining a constant current through said load impedance, said constant current corresponding to the sum of the selected coefficients of the radix of the number system.

2. A selectively adjustable current regulator comprising:
   - a source of direct current,
   - a zener diode regulated constant reference voltage source,
   - a plurality of resistance circuits connected to said unregulated source, the resistance in each of said circuits corresponding to coeffcients of the radix of a number system,
   - switching means connected in series with each of said resistance circuits for selectively connecting said circuits in parallel to obtain a selected signal voltage from said source of direct current,

differential means connected responsive to said constant reference voltage source and to said source of selected signal voltages and responsive thereto for providing a difference voltage representing the difference therebetween,

a load impedance, and

amplifier means connected to said differential means and to said load impedance and being responsive to said difference voltage for maintaining a constant current through said load impedance, the amplitude of said constant current corresponding to the sum of the selected coefficients of the radix of the number system.

3. A selectively adjustable current regulator comprising:

an unregulated supply of direct current,

a zener diode regulated constant reference voltage source,

a plurality of resistance circuits connected to said unregulated supply, the resistance in each of said circuits corresponding to coefficients of a number system radix,

switching means connected in series with each of said circuits for selectively paralleling said circuits to obtain a selected signal voltage from said unregulated supply,

an emitter-coupled transistor difference amplifier having its inputs connected to said constant reference voltage and to said switching means, respectively, for providing a difference voltage,

a load impedance, and

means connected with said load impedance said selected signal voltage and with said difference amplifier and being responsive to said difference voltage for maintaining a constant current through said load impedance, said constant current corresponding to the sum of the selected coefficients of the number system radix.

4. A selectively adjustable current regulator comprising;

an unregulated source of direct current,

means for deriving a constant reference voltage from said source,

a plurality of resistance circuits connected to said source,

switching means connected in series with each of said resistance circuits for selectively paralleling said circuits to obtain a selected signal voltage from said unregulated source,

comparison means responsive to said fixed reference voltage and to said selected signal voltage for providing a difference voltage representing the difference therebetween,

a load impedance, and

a transistor regulator element in series with said load impedance, said circuit being responsive to said comparison means for providing a difference voltage and said switching means for returning said difference voltage to zero and thereby maintain a constant current through said load impedance.

5. A selectively adjustable current regulator comprising;

an unregulated source of direct current,

means for deriving a constant reference voltage from said source,

selectively variable resistance means connected to said source for providing a selected signal voltage,

differential means connected to said constant reference voltage and to said selected signal voltage and responsive thereto for providing a difference voltage representing the difference therebetween,

a load impedance, and

a transistor regulator connected in series with said load impedance, said regulator being responsive to the difference between the output from said differential means for providing a difference voltage and said selected signal voltage for returning said difference voltage to zero, thereby maintaining a constant current through said load impedance independent of changes in said load impedance.



6. A current regulator comprising:

an unregulated supply of direct current;

a plurality of branch circuits, each containing a switching means in series with a resistor, a first common input terminal connected to said unregulated supply and to each of said branch circuits, a second common output terminal connected to each of said branch circuits for providing a signal voltage;

a source of fixed reference voltage;

an emitter-coupled transistor difference amplifier having a first input line connected to said source and a second input line connected to said second common output terminal, and having an output providing a difference voltage representing the difference between said reference voltage and said signal voltage;

a load impedance; and

a transistor regulating means having a base, an emitter, and a collector, said base being connected to said unregulated supply and to said difference amplifier output, said emitter being connected to said second common output terminal, and said collector being connected to said load impedance, for maintaining a constant current through said load impedance.

7. A current regulator as defined in claim 6 wherein said source of fixed reference voltage comprises

a zener diode connected between said unregulated supply and said first input line.

8. A current regulator comprising:

an unregulated supply of direct current;

a plurality of branch circuits, each containing a switching means in series with a resistor, a first common input terminal connected to said unregulated supply and to each of said branch circuits, a second common output terminal connected to each of said branch circuits for providing a signal voltage;

a source of fixed reference voltage;

an emitter-coupled transistor difference amplifier having a first input line connected to said source and a second input line connected to said second common output terminal, and having a pair of output lines providing a push-pull difference voltage representing the difference between said reference voltage and said signal voltage;

cascaded transistor amplifier means connected to said pair of output lines for providing a single-ended output control signal;

a load impedance; and

a transistor regulating means having a base, an emitter, and a collector, said base being connected to said unregulated supply and responsive to the single-ended output control signal from said cascaded transistor amplifier means, said emitter being connected to said second common output terminal, and said collector being connected to said load impedance, for maintaining a constant current through said load impedance.

9. A current regulator comprising:

an unregulated supply of direct current;

a plurality of branch circuits, each containing a switching means in series with a resistor, a first common input terminal connected to said unregulated supply and to each of said branch circuits, a second common output terminal connected to each of said branch circuits for providing a signal voltage;

a source of fixed reference voltage;

an emitter-coupled transistor difference amplifier having a first input line connected to said source and a second input line connected to said second common

output terminal and having an output providing a difference voltage representing the difference between said reference voltage and said signal voltage;

a source of bias voltage;

a load impedance; and

a transistor tetrode having a first base, a second base, an emitter, and a collector, said first base being connected to said unregulated supply and to said difference amplifier output, said second base being connected to said source of bias voltage, said emitter being connected to said second common output terminal, and said collector being connected to said load impedance, for maintaining a constant current through said load impedance.




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