

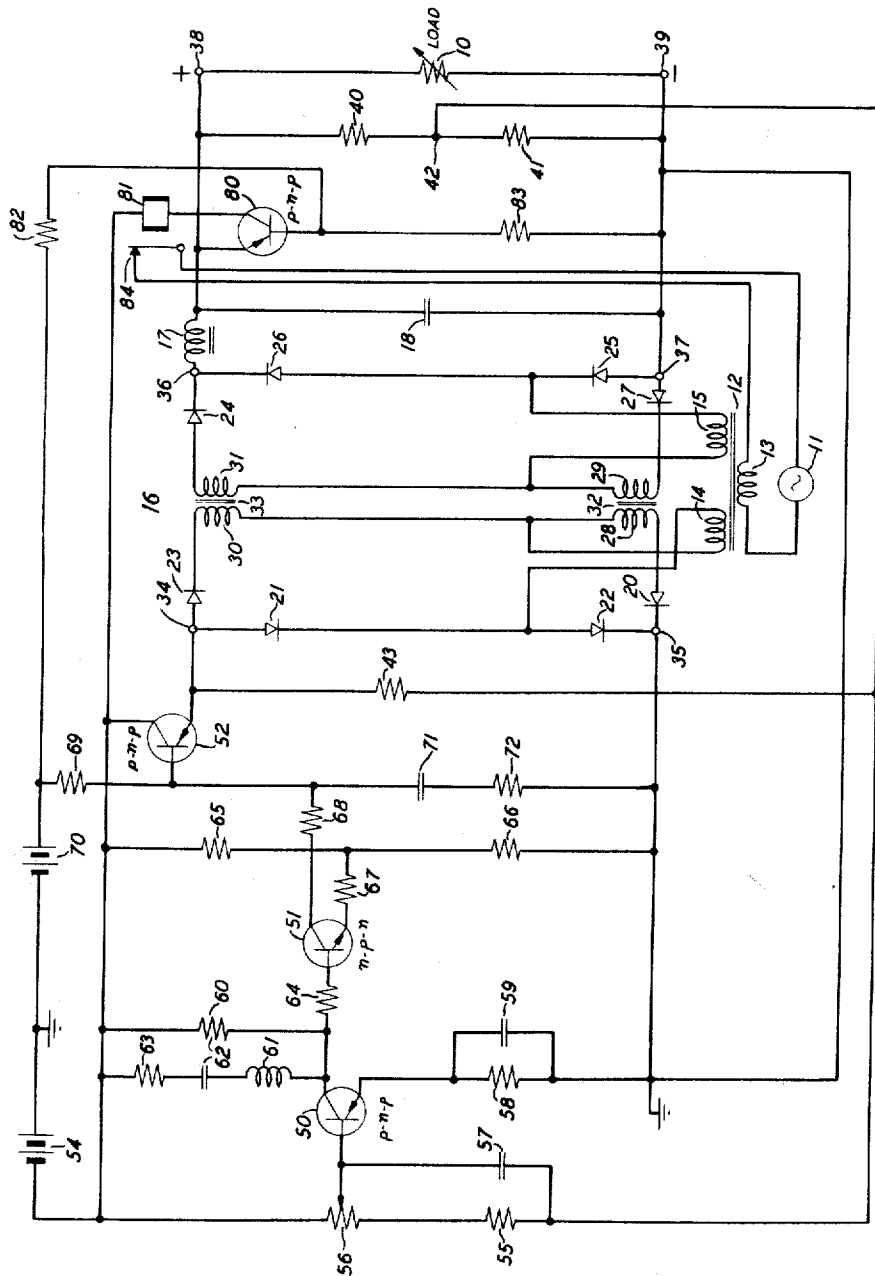
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CURRENT SUPPLY APPARATUS

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CURRENT SUPPLY APPARATUS

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This invention relates to current supply apparatus and particularly to a transistor-amplifier controlled magnetic-amplifier for regulating the supply of current to a load under control of load voltage changes.

An object of the invention is to provide improved means for coupling a transistor-amplifier to a magnetic-amplifier.

Another object is to provide a magnetic-amplifier ripple-filter combination having a relatively small time constant.

Another object of the invention is to provide improved regulated rectifying apparatus which is compact, light and rugged, which is capable of supplying relatively large output current and having a relatively low output ripple component and a high speed of response.

In a specific embodiment of the invention herein shown and described for the purpose of illustration, regulated rectified current is supplied from a magnetic-amplifier to a load through a filter for suppressing alternating current or ripple components. Load voltage changes are impressed upon a transistor-amplifier to control the current flowing through a coupling resistor connected to its output. The voltage across the coupling resistor and in series therewith a portion at least of the load voltage in opposition to the voltage across the coupling resistor are impressed upon the input of the magnetic-amplifier. An increase of load voltage, for example, in the input circuit of the transistor-amplifier causes the current through the coupling resistor to decrease, thereby reducing the voltage drop across the coupling resistor. This decrease of voltage across the coupling resistor tends to cause the voltage across the load connected to the output of the magnetic-amplifier to decrease, thereby minimizing the initially assumed increase of load voltage. Since the load voltage or portion thereof impressed upon the magnetic-amplifier input is opposed to the voltage across the coupling resistor, an increase of this component of the magnetic-amplifier input voltage, that is, the portion of the load voltage, also tends to reduce the load voltage.

It is thus seen that there are provided two negative feedback paths from the load current to the input of the magnetic-amplifier. One of the feed back paths is through the transistor-amplifier and the other is a direct feedback path. The two feedback voltages are of opposite polarity in the input circuit of the magnetic-amplifier, the one voltage decreasing and the other increasing in response to an increase of load voltage, and vice versa. During normal operation, the feedback comprising the transistor-amplifier is more effective in minimizing load voltage changes than the direct feedback because of the amplification of the load voltage changes in the transistor-amplifier. However, the limit of the operating range of the transistor-amplifier is reached when the current flowing through the coupling resistor and the last amplifier stage of the transistor-amplifier is reduced to a minimum value. Thereafter, if the load voltage should increase further, the load voltage increase is limited due to the action of the direct feedback circuit.

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The direct feedback from the load circuit to the input of the magnetic-amplifier also has the desirable effect of compensating, in part at least, for the voltage drop across the coupling resistor due to the magnetizing current flowing through the control windings of the magnetic-amplifier and through the coupling resistor. A coupling resistor having relatively large resistance may therefore be used with the result that impedance matching of the transistor-amplifier and the magnetic-amplifier is improved, that the required gain of the transistor-amplifier is decreased, and that the required control current range of the magnetic-amplifier is reduced.

A further advantage of using the direct feedback path is that it considerably reduces the time required for the circuit to respond to a change of load voltage for the purpose of minimizing the change of load voltage. The transistor-amplifier has a negligibly low time constant and the magnetic-amplifier per se has a time constant of the order of a half-cycle period of the alternating-current source from which current is supplied to the magnetic-amplifier. However, the ripple filter in the output of the magnetic-amplifier has a fairly large inductance so that the time constant of the magnetic-amplifier-filter combination is fairly large when the direct feedback is not used. The effect of the direct feedback path is to reduce the time constant. Tests have shown that the time constant may be reduced from a period of about three and one-half cycles of the alternating-current supply source to a period of about one and one-half cycles by the use of the direct negative feedback path.

The invention will now be described in greater detail with reference to the accompanying drawing the single figure of which is a schematic view of a regulated current supply circuit embodying the invention.

Referring now to the drawing, rectified current is supplied to a load 10 from an alternating-current supply source 11 through a circuit comprising a transformer 12 having a primary winding 13 and two secondary windings 14 and 15, a magnetic amplifier generally designated by the numeral 16 and a ripple filter comprising a series inductor 17 and a shunt condenser 18. The magnetic amplifier is of the general type shown on page 170 of a book by William A. Geyger entitled "Magnetic Amplifier Circuits" and in Fig. 5, page 181, of an article by A. E. Maine entitled "High Speed Magnetic Amplifiers" published in "Electronic Engineering" for May 1954. The magnetic amplifier comprises a plurality of rectifier elements 20, 21, 22, 23, 24, 25, 26 and 27, a first saturable reactor having a control winding 28 and a load winding 29 and a second saturable reactor having a control winding 30 and a load winding 31. The windings 28 and 29 are wound upon a closed core 32 of magnetic material and the windings 30 and 31 are wound upon a similar core 33. Each core should preferably have high resistivity, low coercive force, high saturation flux density, a nearly as possible rectangular hysteresis loop and high stability of magnetic characteristics. The magnetic-amplifier has a pair of input terminals 34 and 35 and a pair of output terminals 36 and 37. Output terminal 36 of the magnetic-amplifier is connected through filter inductor 17 to the positive load terminal 38 and output terminal 37 is directly connected to the negative load terminal 39 which is grounded. A voltage divider comprising resistors 40 and 41 having a common terminal 42 is connected across the load. Connected to the input terminals of the magnetic-amplifier is a current path which may be traced from the terminal 34 through a coupling resistor 43 to the positive terminal 42 of resistor 41 and from the negative terminal of resistor 41 to the input terminal 35.

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The currents flowing through the windings 29 and 31 saturate the cores 32 and 33, respectively. The control currents supplied to windings 28 and 30 set up magneto-motive forces which reduce the flux in the cores, respectively, that is, each control current resets the flux in the core to thereby control the average load current. The amount that the flux is reduced below saturation is proportional to the voltage-time integral applied to the control winding. During a half-cycle period of one polarity, current flows from one terminal of transformer winding 14, through a series circuit comprising control winding 28, rectifier element 20 to the input terminal 35, through resistors 41 and 43 to terminal 34 and thence through rectifying element 21 to the other terminal of winding 14. During the same half-cycle period, current flows from one terminal of transformer winding 15 through a series circuit comprising load winding 31, rectifier element 24, inductor 17, the load and rectifier element 25 to the other terminal of transformer winding 15. During a half-cycle period of opposite polarity, current flows from a terminal of transformer winding 14, through a series circuit comprising rectifier element 22, resistors 41 and 43, rectifier element 23 and control winding 30 to the other terminal of transformer winding 14. During the same half-cycle period, current flows from a terminal of transformer winding 15 through a series circuit comprising rectifier element 26, inductor 17, load 10, rectifier element 27 and load winding 29 to the other terminal of transformer winding 15. It is thus seen that the current flowing through control winding 28 during a half-cycle period of one polarity causes the resetting of the flux in core 32 to control the current supplied to the load circuit through winding 29 during the following half-cycle period of opposite polarity. During the half-cycle period when load current is flowing through load winding 29, current is supplied to control winding 30 to reset the flux in the core 33 to control the current supplied to the load circuit through winding 31 during the next half-cycle period.

During normal operation the variable direct voltage across resistor 43 is larger than the relatively constant direct voltage across resistor 41 so that input terminal 34 is negative with respect to input terminal 35. This input control voltage between terminals 34 and 35 therefore is in opposition to the voltage pulse from transformer winding 14 in the circuit for supplying control current to control winding 28 or 30. As the voltage across input terminals 34, 35 increases, for example, the reduction of flux below saturation in the core 32, for example, decreases with the result that the core 32 saturates earlier during the next half-cycle period to cause the average current supplied to the load circuit through winding 29 to increase. Similarly, the current supplied to the load circuit through reactor winding 31 increases in response to an increase of control voltage across input terminals 34, 35, and vice versa.

There is provided an amplifier comprising transistors 50, 51 and 52 for controlling the current supplied to resistor 43 in response to load voltage changes. Transistors 50 and 52 are of the p-n-p type and transistor 51 is of the n-p-n type. The voltage impressed upon the input terminals 34, 35 is thus controlled to minimize the changes of load voltage. A battery 54 having its positive terminal connected to ground represents a source of constant reference voltage which may be obtained by any suitable means such as a regulated rectifier similar to the one shown in the drawing or the breakdown voltage of a silicon alloy junction diode. A voltage equal to the sum of the voltage of the reference source 54 and a portion at least of the load voltage, specifically, the portion of the load voltage across resistor 41 is impressed across a voltage divider comprising in

series a resistor 55 and a potentiometer 56, condenser 57 being provided in a path connecting the positive terminal of resistor 41 and the adjustable tap of potentiometer 56. The base of transistor 50 is connected directly to the tap of potentiometer 56. The emitter of transistor 50 is connected through a resistor 58 shunted by a condenser 59 through ground to the positive terminal of battery 54. A portion of the voltage across potentiometer 56, which is proportional to the load voltage, and in opposition thereto the constant reference voltage of battery 54 are impressed upon a circuit connecting the base and emitter of transistor 50. Part of the collector current of transistor 50 flows through a resistor 60 to the negative terminal of battery 54 and the remaining part to the base of transistor 51. If desired, of course, a current source other than the source 54 may be provided for supplying the collector-emitter currents of transistors 50, 51 and 52, the source 54 being used only as a reference standard voltage source for transistor 50. A current path in parallel with resistor 60 comprises in series an inductor 61, a condenser 62 and a resistor 63, this current path being provided for suppressing transients.

The collector of transistor 50 is connected through a resistor 64 to the base of transistor 51. A voltage divider comprising resistors 65 and 66 is connected across the battery 54 and the emitter of transistor 51 is connected through a resistor 67 to the common terminal of resistors 65 and 66. The collector of transistor 51 is connected through resistors 68 and 69 in series to the positive terminal of a battery or other current source 70 the negative terminal of which is grounded. The base of transistor 52 is connected to the common terminal of resistors 68 and 69 and through a condenser 71 and a resistor 72 in series to ground. The emitter of transistor 52 is connected through the resistor 43 to the positive terminal 42 of resistor 41. The collector of transistor 52 is connected to the negative terminal of battery 54.

A circuit comprising a p-n-p type transistor 80 and an electromagnetic relay 81 is provided for protecting the load from excessive voltage under an abnormal operating condition. A voltage divider comprising resistors 82 and 83 in series is connected across the battery 70 and the base of transistor 80 is connected to the common terminal of resistors 82 and 83. The emitter of transistor 80 is connected to the positive load terminal 38 and the collector of the transistor is connected through the winding of relay 81 to the negative terminal of battery 54. If the load voltage should become excessive, current flowing into the emitter and out of the base of transistor 80 will increase to cause a sufficient increase of current flowing out of the collector of transistor 80 and through the winding of relay 81 to cause it to operate. The contacts 84 of relay 81 are thus opened to interrupt the circuit connecting the primary winding 13 of transformer 12 to the alternating-current supply source 11. The supply of rectified current to the load 10 is thus interrupted.

The voltage regulating action of the current supply circuit may be understood by initially assuming an increase of load voltage. An increase of the portion of the load voltage across resistor 41 produces an increase of voltage across the portion of potentiometer 56 between the adjustable tap and the negative terminal of the constant voltage source 54. As a result, the base of transistor 50 becomes relatively more positive or less negative with respect to its emitter potential to thereby decrease the current flowing into the emitter. The collector current of transistor 50 flowing through resistor 60 is thus decreased to make the base of transistor 51 relatively less positive or more negative with respect to its emitter. The current flowing into the base and out of the emitter of transistor 51 decreases. The collector current of transistor 51 flowing through resistor 69 likewise decreases. The base of transistor 52 thus becomes relatively more positive or less negative with respect to its emitter and

the emitter and collector currents of transistor 52 are each decreased.

The circuit connecting the emitter and collector electrodes of transistor 52 may be traced from the grounded negative load terminal, through resistor 41, through resistor 43 to the emitter, from the collector to the negative terminal of battery 54 and from the positive terminal of battery 54 back to ground. There is thus impressed across input terminals 34, 35 of the magnetic-amplifier a voltage equal to the difference of the voltage drop across resistor 43 and the portion of the load voltage across resistor 41. The decreased voltage across resistor 43 resulting from the assumed increase of load voltage causes the input voltage of the magnetic-amplifier to decrease, the increased voltage across resistor 41 being small relative to the decreased voltage across coupling resistor 43. The integral with respect to time of the voltage across the control windings 28 and 30 is therefore increased to cause the flux in cores 32 and 33 to be reset below the saturation value by an increased amount. The average currents supplied through the load windings 29 and 31 to the load circuit is therefore decreased to cause the initially assumed increase of load voltage to be minimized.

It is seen that the input voltage of the magnetic-amplifier is changed in the same direction in response to either a decrease of voltage across resistor 43 or an increase of voltage across resistor 41. During normal operation the voltage change across resistor 43 is larger than the voltage change across resistor 41 because of the amplification of the amplifier comprising transistors 50, 51 and 52. Therefore, the negative feedback through the transistor-amplifier is normally relatively more effective in minimizing load voltage changes. However, if for some reason the transistor-amplifier should fail to function to decrease the current through resistor 43 in response to an increased load voltage, the direct negative feedback from the load circuit to the magnetic-amplifier input will function to limit the increase of load voltage. The limit of the operating range of the transistor-amplifier is reached when the emitter current of transistor 52 is reduced to zero or a minimum value. If, thereafter, a further increase of load voltage should occur, the direct negative feedback from the load circuit to the magnetic-amplifier input will be effective to limit the load voltage.

The voltage across resistor 43 is due not only to the current flowing into the emitter of transistor 52 but also to the control currents flowing through the control windings 28 and 30 of the magnetic-amplifier. The voltage supplied from the load circuit in series opposition to the voltage drop across resistor 43 in part at least compensates for the portion of the voltage drop across resistor 43 due to the control currents flowing in windings 28 and 30. This is a desirable effect since it makes possible an increased change of voltage across the input terminals 34, 35 of the magnetic-amplifier. Furthermore, employing the direct feedback from the load circuit makes possible an increase of the resistance of resistor 43 to improve the efficiency of the combination of the transistor-amplifier and the magnetic-amplifier. Another advantage of the direct negative feedback to the magnetic-amplifier input is that it increases the speed of response of the circuit, compensating for or canceling in large part the delay introduced by the filter inductance 17 in the load circuit.

What is claimed is:

1. Current supply apparatus for controlling the supply of rectified current from an alternating-current supply source to a load circuit including a load comprising a magnetic amplifier having an input circuit and an output circuit, said magnetic amplifier output circuit being coupled to said load circuit to supply said rectified current thereto, said input circuit comprising a control winding and rectifying means for rectifying currents supplied to said input circuit, a resistor, means for supplying cur-

rent from said supply source through said resistor to said magnetic amplifier input circuit, means for impressing upon said magnetic amplifier input circuit a portion at least of the load voltage in series opposition to the voltage drop across said resistor, thereby compensating in part at least for the voltage drop produced across said resistor due to the magnetizing current of said magnetic amplifier flowing through said resistor, and means for minimizing load voltage changes comprising means responsive to load voltage changes for further controlling the current flow through said resistor.

2. A current supply circuit in accordance with claim 1 in which said means for further controlling the current flow through said resistor comprises a transistor having an emitter, a collector and a base, means for supplying current through a current path comprising in series said resistor and the emitter-collector path of said transistor, and means responsive to load voltage for supplying to the emitter-base path of said transistor a current having variations corresponding to load voltage changes.

3. In combination, a magnetic amplifier comprising a control winding and a load winding both wound upon a core of magnetic material, means for supplying rectified current from an alternating voltage supply source through a first circuit comprising said load winding and a load circuit during half cycle periods of one polarity only of said alternating voltage, a resistor, means for supplying rectified current from said supply source through a second circuit comprising said resistor and said control winding during half cycle periods of opposite polarity only of said source, thereby setting the flux in said core to control the current flowing through the load winding and the load circuit during half cycle periods of said one polarity, means for impressing a portion at least of the load voltage upon said second circuit in series with said resistor and in opposition to the voltage drop across said resistor, thereby compensating in part at least for the voltage drop produced across said resistor due to the current supplied therethrough to said control winding, and means for supplying an additional unidirectional current to said resistor for controlling the load voltage.

4. A current supply circuit comprising a magnetic-amplifier having an input and an output for supplying rectified current from an alternating-current supply source to a load circuit coupled to said output, said load circuit comprising a load, a ripple filter having series inductance and shunt capacitance in said load circuit, means for impressing upon said input a first voltage having variations corresponding to load voltage changes for minimizing said changes of load voltage, and means for impressing upon said input a portion at least of said load voltage in series opposition with respect to said first voltage for reducing the delay of said current supply circuit in responding to said variations of said first voltage.

5. In combination, an amplifier comprising a plurality of transistors including an input transistor and an output transistor each of said transistors having a plurality of electrodes including a base, an emitter and a collector, a circuit connecting the emitter and base of said input transistor comprising a source of substantially constant voltage and in opposition thereto a source of voltage having variations corresponding to load voltage changes, a circuit connecting the emitter and collector of said input transistor comprising a first resistor and in shunt relation thereto, a series path comprising an inductor, a capacitor and a second resistor, a magnetic-amplifier having a pair of input terminals and a pair of output terminals, means for supplying to said magnetic-amplifier current from a supply source of alternating current, a filter having series inductance and shunt capacitance connected to said output terminals, a load connected across said capacitance, a current path con-

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nected to said pair of input terminals comprising a third resistor and a portion at least of the voltage across said load, and a circuit connecting the emitter and collector of said output transistor comprising said current path, the portion at least of the load voltage being opposed to the voltage drop across said third resistor produced by the current flowing therethrough.

6. A combination in accordance with claim 5 in which there are provided an additional transistor having an emitter, a base and a collector, an electromagnetic relay having a winding and a pair of contacts, a current path connected across the load comprising the emitter and base of said additional transistor, a circuit connecting the emitter and collector of said additional transistor comprising said relay winding, means comprising said additional transistor responsive to abnormally high load voltage for supplying operating current to said relay winding and means responsive to the operation of said relay to disconnect said magnetic-amplifier from said alternating-current supply source.

7. Current supply apparatus for controlling the supply of rectified current from an alternating-current supply source to a load circuit including a load, comprising

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a magnetic amplifier having an input and an output, a transistor amplifier having an input and an output, means for coupling said magnetic amplifier output to said load circuit, a first means for minimizing load voltage changes comprising means for impressing upon said magnetic amplifier input a portion at least of said load voltage, and a second means for minimizing load voltage changes comprising said transistor amplifier, means for coupling said transistor amplifier output to said magnetic amplifier input and means for impressing a portion at least of said load voltage upon said transistor amplifier input.

References Cited in the file of this patent

UNITED STATES PATENTS

15	2,100,715	Jenks	Nov. 30, 1937
	2,511,219	Pogorzelski	June 13, 1950
	2,525,451	Graves	Oct. 10, 1950
	2,751,545	Chase	June 19, 1956
	2,759,142	Hamilton	Aug. 14, 1956
20	2,770,770	Lufcy	Nov. 13, 1956
	2,774,930	Bixby	Dec. 18, 1956
	2,790,127	Hamilton	Apr. 23, 1957
	2,810,877	Silver	Oct. 22, 1957