April 26, 1949. K. R. MacKENZIE 2,468,678

REGULATOR

Filed June 28, 1946 2 Sheets-Sheet 1

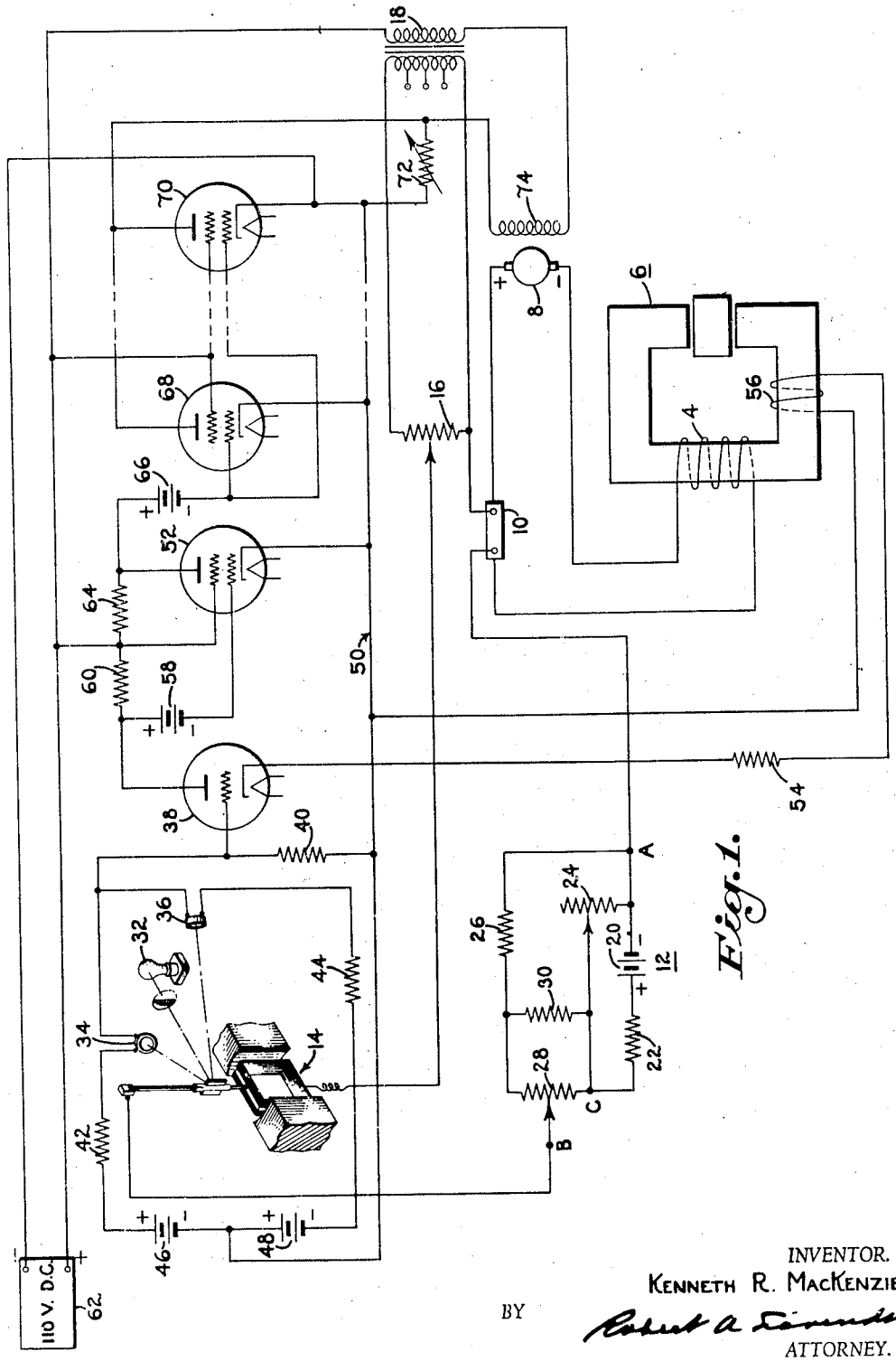


Fig. 1.

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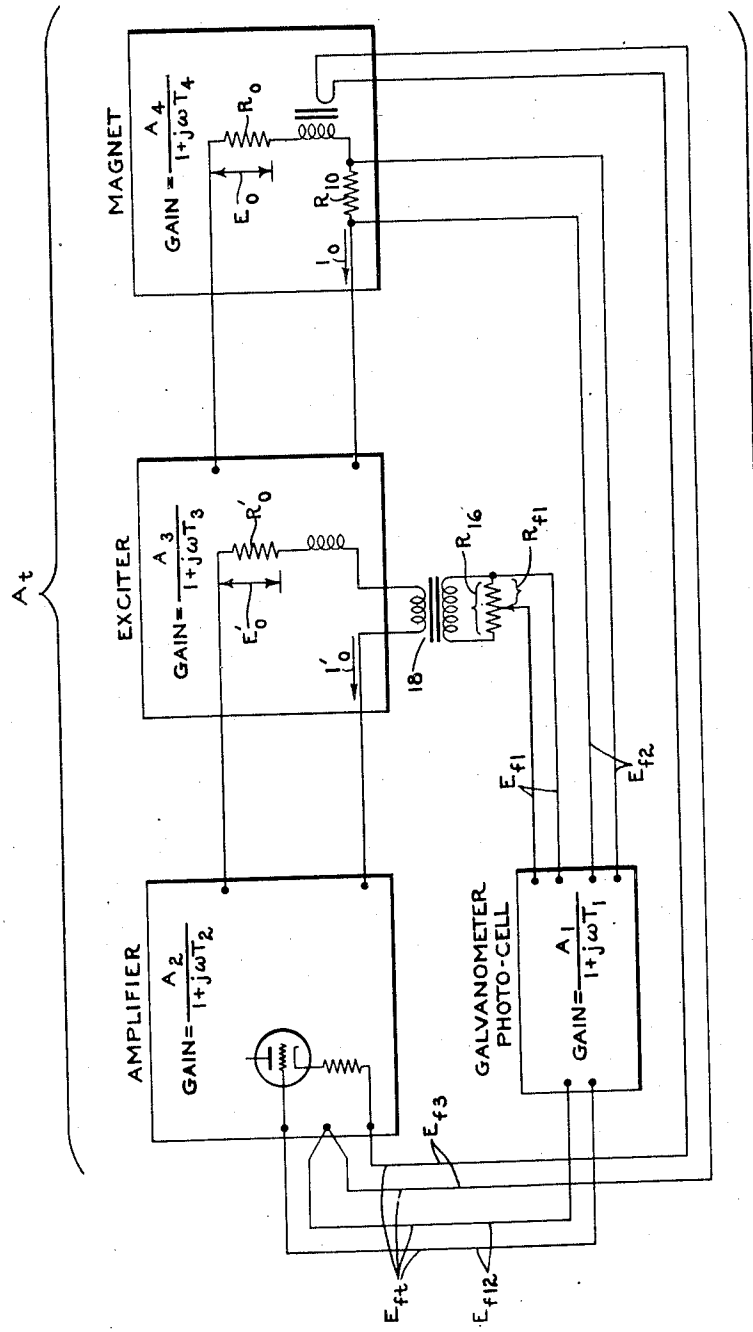


Fig. 2.

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REGULATOR

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5 Claims. (Cl. 175—335)

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This invention relates to electromagnet regulators and more particularly to electromagnet regulators of the type in which the current through the magnetic coil is regulated to produce a constant magnetic field.

The invention contemplates the use of a shunt resistance in series with the magnet coil for producing a signal, a galvanometer-photocell arrangement feeding a direct-coupled amplifier for amplification of the signal, and a generator controlled by the amplifier for energizing the field of the magnet. It is well known that in a regulating system of this type the time delays introduced into the loop by the inductance of various circuit components such as a magnet coil or a generator or by the inertia of a galvanometer coil tend to produce instability and overshooting in the regulation characteristic unless measures are taken to counteract their effect. It is customary to use a damping circuit wherein a signal dependent upon the rate of change of the current to be regulated is inserted in the regulator amplifier to counteract or dampen the normal regulating action, thereby preventing overshooting of the correcting signal. However, the present invention contemplates the use of a new and novel method of damping whereby improved stability and freedom from overshooting is obtained and whereby, also, the galvanometer is protected from excessive excursions from its operating point caused by transient signals of high magnitude.

Accordingly, it is an object of the invention to provide an improved magnet regulator in which maximum stability and minimum overshooting are obtained.

It is another object of the invention to provide an improved magnet regulator for use with a galvanometer-photocell arrangement whereby the galvanometer is protected from mechanical shocks due to the presence of high energy electrical transients.

Further objects and advantages of the invention will be apparent to one skilled in the art from the following drawings, specification, and claims.

Figure 1 of the drawings illustrates a preferred embodiment of the invention comprising a magnet to be regulated, a network for comparing a signal derived from the magnet current against a standard voltage, a galvanometer-photocell arrangement, a direct-coupled amplifier, a plurality of variable impedance tubes, and a generator for exciting the magnet, the variable impedance tubes being connected in series with the generator field circuit to control the generator excitations; and

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Fig. 2 is a schematic diagram employed to facilitate explanation of the invention.

Considering first the connections of the drawings in detail, an electromagnet 6 is energized by a generator 8 through a shunt resistor 10, this shunt resistor having substantially zero temperature coefficient to eliminate drift due to heating. One end of resistor 10 is also connected to point A of the standard voltage network 12, point B of the standard voltage network 12 being connected to one end of the coil of the galvanometer 14. The other end of resistor 10 is connected to one end of the parallel combination of potentiometer 16 and the secondary of damping transformer 18, these latter two components comprising one of the damping circuits. The variable contactor of potentiometer 16 is connected to the other end of the coil of galvanometer 14, completing the galvanometer circuit.

The above-mentioned standard voltage network is energized by a standard battery 20, the positive terminal of which is connected to one end of resistor 22 and the negative terminal of which is connected to one end of variable resistor 24, to one end of resistor 26 and to the above-mentioned point A. The other end of the resistor 22 is connected to one end of potentiometer 28, to one end of resistor 30 and to the variable contactor of variable resistor 24. The other end of the potentiometer 28 and the other end of resistor 30 are connected to the other end of resistor 26. Thus, variable resistor 24 and potentiometer 28 provide, respectively, a coarse and fine control of the standard voltage appearing between points A and B, variable resistor 24 varying the total current flowing through resistor 22 and hence varying the potential of point C with respect to point A, and potentiometer 28 allowing a further variation of the potential appearing between point B and point A.

This variable standard voltage is compared with the potetnial drop developed across resistor 10 by the magnet current, and the difference voltage is applied to the moving coil of galvanometer 14. It is noted that no additional voltage is inserted in the galvanometer circuit by potentiometer 16 in the steady-state condition, since a damping voltage is generated across the secondary of transformer 18 only when there is a change of current through the primary thereof. A beam of light from a light source 32 is reflected by the mirror of galvanometer 14 to the photocells 34 and 36 which are connected in a balanced bridge

circuit, one terminal of each photocell being connected to the control grid of vacuum tube 38 and to one end of grid resistor 40, and the other terminal of each of the photocells 34 and 36 being connected, respectively, through resistor 42 and resistor 44 and through battery 46 and battery 48 to the common bus 50. The other end of resistor 40 is also connected to the common bus 50. The circuit arrangement is such that a deflection of the galvanometer coil from the center position will cause the potential impressed upon the input of vacuum tube 38 to either increase or decrease, depending upon the direction of deflection of the coil.

The cathode of vacuum tube 38 is connected through resistor 54 and damping coil 56 to the common bus 50, this arrangement comprising a second damping circuit. The anode of vacuum tube 38 connects through coupling battery 58 to the control grid of vacuum tube 52, and through resistor 60 to the positive terminal of a D. C. power supply 62. The cathode of vacuum tube 52 connects to the common bus 50 and the screen grid of vacuum tube 52 connects to the positive terminal of the D. C. power supply 62. The anode of vacuum tube 52 connects through resistor 64 to the positive terminal of the D. C. power supply 62 and through a coupling battery 66 to the control grids of a plurality of paralleled vacuum tubes, indicated in the drawings as 68 and 70 for simplicity. Thus, vacuum tubes 38 and 52 comprise a two-stage direct-coupled amplifier for controlling vacuum tubes 68 and 70 in response to the signal from the photocell bridge.

The anodes of tubes 68 and 70 are connected to one end of variable resistor 72 and to one end of the generator field coil 74, the other end of the field coil 74 being connected through the primary of transformer 18 to the positive terminal of the D. C. voltage supply 62. The negative terminal of supply 62 connects to the cathodes of tubes 68 and 70, to the other end of variable resistor 72, and to the common bus 50. It is apparent then, that tubes 68 and 70 are in effect variable impedance devices controlling the generator field current in response to the signal applied to their grids. Variable resistor 72, which is connected between the anodes and cathodes of tubes 68 and 70, by-passes an adjustable portion of the field current around these tubes so that they are not required to handle the entire field current.

The connections of the drawings having thus been described, the operation of the regulating circuit will first be considered for the steady-state condition in which case the two damping circuits do not affect the operation.

Assuming that the various vacuum-tube filaments have been energized and that the D. C. power supply 62 has been turned on, the regulating circuit will assume a certain equilibrium condition dependent upon the setting of the standard voltage controls 24 and 28. In other words, the generator 8 will furnish the magnet coil 4 a value of current such that the resultant potential drop across resistor 10, when combined with the set value of standard voltage appearing between points A and B of the standard voltage network, will just sustain the galvanometer deviation required to give this same magnet current, the galvanometer 14 acting upon the generator 8 through the photocells 34 and 36, the amplifier tubes 38 and 52, and the variable impedance tubes 68 and 70. Now if any slow change appears in the current of magnet coil 4, the difference signal applied to galvanometer 14 will vary from the equilibrium value, causing a redistribution of the light falling on photocells 34 and 36. The resultant voltage change appearing at the grid of tube 38 is amplified by tubes 38 and 52 and impressed upon the control grids of vacuum tubes 68 and 70, varying their impedance accordingly. This impedance change in turn controls the field current of generator 8, since the generator field winding 74 is energized through tubes 68 and 70. The resulting change in output voltage of generator 8 will oppose the original change and restore the magnet coil current to substantially its original value, thereby maintaining a constant magnetic field.

Considering now the transient case in which the damping circuits become effective, a sudden change in the magnetic field strength of magnet 6 would generate a voltage in the damping coil 56, this voltage being applied through resistor 54 to the input circuit of tube 38. The circuit arrangement is such that this damping voltage would oppose the normal correcting signal derived from resistor 10 via the galvanometer circuit. Thus the effective signal appearing between the grid and cathode of tube 38 is reduced for sudden changes in the magnetic field, and the normal tendency of the correcting signal to overshoot is consequently greatly minimized. Similarly, a sudden change of generator field current would energize transformer 18, causing a voltage to appear across resistor 16. A portion of this voltage, dependent upon the setting of the variable contactor of resistor 16, appears in the galvanometer coil circuit. The polarity of this signal is such that the correcting signal effective in the galvanometer circuit is greatly decreased, thereby tending to reduce or dampen the tendency to overshoot. Further, this last-mentioned damping circuit also prevents excessive excursions of the galvanometer due to transient signals, since a damping signal appears across resistor 16 and is effective in the galvanometer coil circuit as soon as the galvanometer coil starts to deviate from its equilibrium position.

Considering the transient case in another aspect, the damping circuits contemplated in this invention provide a means for cancelling undesirable time delays introduced into the loop by various components, whereby the controlling time constant is that one inherent in the component to be regulated, in this case the magnet itself. It is well known to the art that a regulating loop of this type, wherein the regulated device provides the one and controlling time constant of the loop, gives maximum stability and freedom from overshooting of the correction signal inasmuch as there is substantially no time delay between the time a change in the regulated quantity occurs and the time of application of the correcting signal to the regulated circuit component. The manner in which the present invention provides such a regulating loop will be considered in connection with Fig. 2, which illustrates in block form the circuit of Fig. 1. It will be shown that by proper design of the damping circuits the effective time delay between the occurrence of a signal across the magnet shunt resistor 10 and the appearance of a correcting signal across the magnet coil can be made negligible.

The characteristics of this circuit may be most readily examined by considering the expression $A\beta$ for the gain around the loop, in which A customarily represents the total gain of the loop under consideration and β represents the feedback

factor. In this case, however, the division of the circuit into the A-portion and the β-portion is made arbitrarily to facilitate the analysis. Thus, considering Fig. 2, it is observed that the total gain A_t is the product of the amplifier, exciter and magnet gains, and that the galvanometer is considered as part of the total feedback circuit β_t. It is assumed, for simplicity, that the various circuit components have linear characteristics about any operating point and that they also have simple time-constants, those of the generator and magnet being attributable to the series inductance thereof, that of the amplifier being due to shunt capacity present, and that of the galvanometer being due mainly to its mechanical characteristics. Accordingly the expression for the total gain is

$$A_t=\frac{E_{out}}{E_{in}}=\frac{E_0}{E_{ft}}=\frac{A_2A_3A_4}{(1+j\omega T_2)(1+j\omega T_3)(1+j\omega T_4)} \quad (1)$$

and the expression for the total feedback factor is

$$B_t=\frac{E_{ft}}{E_0}=\frac{E_{f12}+E_{f3}}{E_0} \quad (2)$$

in which E_{ft} is the total feedback voltage, E_0 is a fictitious output voltage developed across the equivalent magnet resistance R_0, E_{f12} is the feedback voltage developed by the galvanometer-photocell bridge, and E_{f3} is the feedback voltage developed by the damping coil **56**. Before combining Expressions 1 and 2 to obtain an expression for $A_t\beta_t$, the feedback voltages E_{f12} and E_{f3} will be obtained in terms of E_0 as follows:

$$E_{f12}=(E_{f1}+E_{f2})\frac{A_1}{1+j\omega T_1} \quad (3)$$

since both E_{f1} and E_{f2} are amplified by the galvanometer-photocell gain as indicated in Fig. 2. Also

$$E_{f2}=I_0R_{10}=\left(\frac{E_0}{R_0}\right)R_{10}=\left(\frac{R_{10}}{R_0}\right)E_0=\beta_2E_0 \quad (4)$$

where I_0 is the magnet current and R_{10}/R_0 equals the D. C. feedback factor β_2. Further

$$E_{f1}=I'_{sec}R_{f1}=\frac{E'_{sec}}{R_{16}}R_{f1}=\frac{I'_0j\omega L_{m1}}{R_{16}}R_{f1} \quad (5)$$

where I'_{sec} and E'_{sec} pertain to damping transformer **18**, R_{f1} is that portion of the resistor **16** included in the feedback circuit, and I'_0 is the exciter generator current, L_{m1} is the mutual inductance of transformer **18**, and ω is the usual $2\pi\times$ frequency. Also

$$I'_0=\frac{E'_0}{R'_0} \quad (6)$$

which, substituted in expression 5, gives

$$E_{f1}=\frac{E'_0}{R'_0}\frac{j\omega L_{m1}}{R_{16}}R_{f1}=j\omega\left(\frac{L_{m1}}{R_{16}}\right)\left(\frac{R_{f1}}{R'_0}\right)E'_0=j\omega t_1\beta_1E'_0 \quad (7)$$

where $t_1=L_{m1}/R_{16}$, the effective time constant, and $\beta_1=R_{f2}/R'_0$, the feedback factor of this feedback path. However, from Fig. 2, it is evident that

$$E_0=\frac{A_3}{1+j\omega T_3}E'_0$$

or

$$E'_0=\frac{1+j\omega T_3}{A_3}E_0 \quad (8)$$

Substituting in Expression 7 gives

$$E_{f1}=j\omega t_1\beta_1\frac{1+j\omega T_3}{A_3}E_0 \quad (9)$$

Substituting Expressions 9 and 4 for E_{f1} and E_{f2} respectively in Expression 3 gives

$$E_{f12}=\left[\beta_2E_0+j\omega t_1\beta_1\left(\frac{1+j\omega T_3}{A_3}\right)E_0\right]\frac{A_1}{1+j\omega T_1} \quad (10)$$

Also

$$E_{f3}=I_{sec}R_{f3}=\frac{E_{sec}}{R_{sec}}R_{f3}=\frac{I_0j\omega L_{m3}}{R_{sec}}R_{f3}$$
$$=\frac{(E_0/R_0)j\omega L_{m3}}{R_{sec}}R_{f3}=j\omega\left(\frac{L_{m3}}{R_{sec}}\right)\left(\frac{R_{f3}}{R_0}\right)E_0$$
$$=j\omega t_3\beta_3E_0 \quad (11)$$

where E_{sec} and R_{sec} refer to the circuit of the damping loop **56**, L_{m3} is the mutual inductance between the winding of magnet **6** and the damping loop **56**, R_{f3} is that portion of the effective resistance R_{sec} in the damping loop circuit that is operative in producing a feedback signal at the input of vacuum tube **38**, $t_3=L_{m3}/R_{sec}$ is the effective time constant of this feedback path, and β_3 is the feedback ratio for this feedback path. Substituting Equations 10 and 11 in 2 gives for the total feedback factor

$$\beta_T=\frac{\left[\beta_2E_0+j\omega t_1\beta_1\left(\frac{1+j\omega T_3}{A_3}\right)E_0\right]\frac{A_1}{1+j\omega T_1}+j\omega t_3\beta_3E_0}{E_0}=$$
$$\frac{A_1\beta_2}{1+j\omega T_1}\left[1+\frac{j\omega t_1\beta_1(1+j\omega T_3)}{A_3\beta_2}+\frac{j\omega t_3\beta_3(1+j\omega T_1)}{A_1\beta_2}\right] \quad (12)$$

Now, multiplying Equations 1 for the total gain and 12 for the total feedback factor gives

$$A_T\beta_T=\frac{A_1A_2A_3A_4\beta_2\left[1+\frac{j\omega t_1\beta_1(1+j\omega T_3)}{A_3\beta_2}+\frac{j\omega t_3\beta_3(1+j\omega T_1)}{A_1\beta_2}\right]}{(1+j\omega T_1)(1+j\omega T_2)(1+j\omega T_3)(1+j\omega T_4)} \quad (13)$$

for the transmission characteristic around the complete regulator loop. An examination of this expression will indicate that if the circuit components of the feedback networks are adjusted so that

$$\beta_1=\beta_2A_3,\ \beta_3=\beta_2A_1,\ t_1=T_1 \quad (14)$$

then Expression 13 reduces to

$$A_T\beta_T=\frac{A_1A_2A_3A_4\beta_2[(1+j\omega T_1)(1+j\omega T_3)-\omega^2T_1T_3]}{(1+j\omega T_1)(1+j\omega T_2)(1+j\omega T_3)(1+j\omega T_4)} \quad (15)$$

But the transmission falls off rapidly with increasing frequency, so that at the low frequencies for which the transmission is still appreciable the effect of shunt capacities in the amplifier is very small. Thus T_2 may be neglected. Also $T_1<<T_3$, making $\omega^2T_1T_3$ negligible compared to $(1+j\omega T_1)(1+j\omega T_3)$. Thus Equation 15 becomes

$$A_T\beta_T=\frac{A_1A_2A_3A_4\beta_2}{(1+j\omega T_4)} \quad (16)$$

which is an approximate expression for the transmission characteristic of the regulator herein described when the feedback networks are properly adjusted. This equation is recognizable as the expression for $A\beta$ of a simple closed loop with a single time constant, and when plotted on a Nyquist diagram gives 90° phase margin against singing or oscillations.

Thus, the present invention, by a novel arrangement and adjustment of a plurality of feedback loops, provides a magnet regulator that evidences the stable transmission characteristics of a simple, single time-constant loop, despite the presence of unavoidable time-constants associ-

ated with certain circuit components such as a galvanometer or motor-generator.

While there has been described in the foregoing specification what is considered a preferred embodiment of this invention, it is not desired to limit this invention to the exact details described except in so far as they may be set forth in the claims.

What is claimed is:

1. A magnet regulator comprising in combination an electromagnet having a principal winding and an auxiliary winding, a direct current generator having an armature and a field winding, means for connecting said armature to said principal winding for supplying current thereto, a resistor connected in series with said armature and said principal winding, a source of standard voltage, means for comparing the voltage drop across said resistor with the voltage of said standard voltage supply, a vacuum tube amplifier, means for energizing the input of said vacuum tube amplifier in accordance with the difference in potential between the voltage drop across said resistor and the voltage of said standard voltage supply, means connected to the output of said vacuum tube amplifier for controlling the field current to said generator field winding for maintaining the current through said principal magnet winding substantially constant, and means for connecting said auxiliary magnet winding to the input circuit of said vacuum tube amplifier for stabilizing the regulating action of the regulator around a desired current value through said principal winding.

2. An electromagnet regulator comprising in combination an electromagnet having a principal winding and a damping loop, a generator for supplying current to said principal winding, a resistor connected in series with said generator and said principal winding, a vacuum tube amplifier, means for energizing said amplifier in accordance with the voltage drop across said resistor, a series impedance connected to the output of said amplifier, the impedance of said series impedance being adapted to vary in proportion to the voltage signal applied thereto, means for connecting said series impedance in series with the field winding of said generator whereby the current to said field winding is controlled in accordance with the signal applied to the input of said amplifier, and means for connecting said damping loop in series with the cathode of the first stage of said vacuum tube amplifier.

3. An electromagnet regulator comprising in combination an electromagnet having a principal winding and a damping loop, a generator for supplying the current to said principal winding, a resistor connected in series with said principal winding, a bridge circuit including light-sensitive devices, a galvanometer having means for controlling the energization of light-sensitive devices, means for connecting the winding of said galvanometer to said resistor, a vacuum tube amplifier connected across said bridge circuit, means for connecting the output of said amplifier to control the field current of said generator for maintaining the current through said principal winding of said electromagnet substantially constant, means connecting said damping loop to the input of said amplifier, and means for applying a signal to said galvanometer winding from the output of said amplifier for damping said galvanometer.

4. An electromagnet regulator as set forth in claim 3, further characterized in that the last means thereof comprises a transformer having a primary winding connected in series with the output of the amplifier and having a secondary winding for supplying a signal to said galvanometer winding.

5. An electromagnet regulator comprising an electromagnet, means for supplying current to said electromagnet, amplifier means for receiving a signal from said electromagnet and controlling the current to said electromagnet in accordance with said signal, a first damping network comprising a loop inductively coupled to said electromagnet and connected to the input of said amplifier, and a second damping network coupled between the output and input of said amplifier, said first and second damping networks functioning to substantially eliminate oscillation of said regulator.

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