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SERVO SYSTEM WITH QUICK-ACTION RESPONSE

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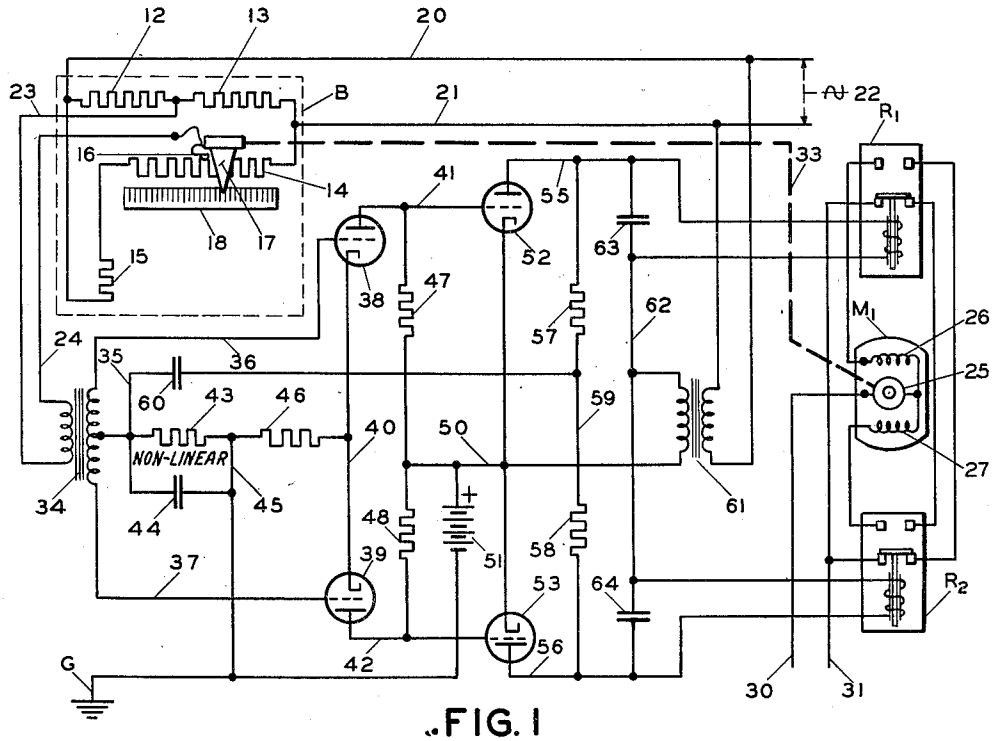


FIG. 1

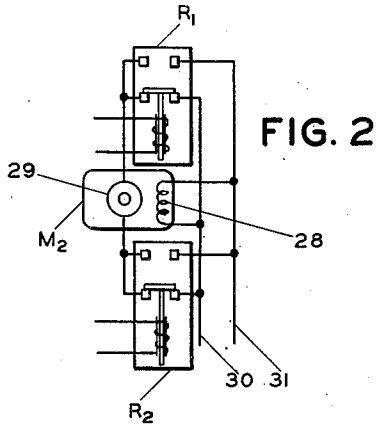


FIG. 2

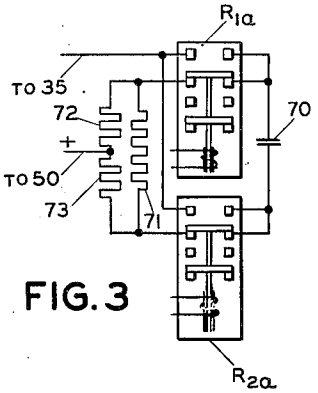


FIG. 3

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SERVO SYSTEM WITH QUICK-ACTION RESPONSE

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13 Claims. (Cl. 318—29)

This invention relates to electronic control circuits, and more especially to a system of electronically actuated electro-magnetic relays for directional operation of a reversible electric motor. In the utilization of electronic amplifying systems for rendering electromagnetic relays responsive to signals, or to potential changes, of an order of magnitude below the practical operating limits of said relays, there exists a tendency to uncertain and "chattering" performance of said relays as the output currents of the amplifying systems attain certain critical values; and in some of the circuits used in such amplifiers these effects may become cumulative, introducing a "pumping" action, partially, if not completely, defeating the purpose of the system. It is not here necessary to discuss the manifold possible causes for such phenomena, as the hereinafter to be pointed out objects of the invention are concerned not so much with eliminating these causes as with providing means for overcoming their erratic effects and promoting definite and positive action of relays or other apparatus so controlled.

Specifically, it is an object of the present invention to provide means whereby to impart to an electronic amplifying system a threshold effect or snap-action, whereby a minor change in output current from said amplifying system in response to a small variation in the input signal will be temporarily magnified and rendered of such amplitude as will assure positive operation of the load apparatus, after which it will drop to a smaller value sufficient to maintain said apparatus in its operated condition.

It is a further object to render such means bilateral in its performance, so that it will be equally effective whether the operation of the load apparatus be effected by energization, or by de-energization, of an electric circuit.

It is a further object to provide means of the above nature and adaptable to the operation of a relay for controlling a motor, or to a combination of paired relays for controlling a reversible motor, especially in combination with a balanceable electrical network.

It is a further object to provide means of the above nature characterized by an "anticipatory" feature wherein action of the operated apparatus may be terminated prior to cessation of the initiating signal.

It is a further object to provide means which shall be characterized by the above-stated meritorious features over a wide range of initiating signal values.

In effecting the purposes of the invention, it is proposed to provide an electronic system having at least two stages of amplification, the initial stage being normally responsive to a controlling signal and the final stage adapted to actuate relay or other load devices in its output circuit. By means of an interconnection between the output circuit of the final stage and the input circuit of the initial stage, the presence of the output current is caused to produce a temporary bias upon the input of the initial stage, whereby any change in said current is attended by a tendency to amplify and prolong said change.

It is further proposed alternatively to include in said interconnection a non-linear resistance element whereby to vary the circuit characteristics according to the impressed signal voltage, thus rendering the system adaptable to its stated purposes over a wide range of signal voltage values.

As a further alternative it is proposed to provide auxiliary relay means whereby to superpose a timed pulsing characteristic upon the performance of the load apparatus.

In the drawings:

Fig. 1 is a diagrammatic representation of a control system embodying the principles of the invention as applied to a servo-actuated bridge-balancing device.

Fig. 2 is a diagram of an alternative form of a detail of the apparatus shown in Fig. 1.

Fig. 3 represents auxiliary means which may be superposed on either form of the apparatus to obtain improved performance under critical conditions.

The control system selected as suitably exemplifying the principle of the invention comprises a balanceable alternating-current bridge network shown in Fig. 1, and generally designated as B, a reversible electric motor M_1, adapted to adjust said bridge network to balance the same, a pair of interconnected relays R_1 and R_2 to control the operation of said motor, and a combination of electric and electronic components and circuits directionally responsive to unbalance potentials in said network correspondingly to actuate said relays and operate said motor in a sense to restore said bridge to a balanced condition.

The bridge network B is a conventional arrangement in common use for the determination of temperatures as effecting a temperature-sensitive branch of the network. It will be understood, however that the principle of the invention is equally applicable to positioning systems of the bridge type, wherein such a network is manually unbalanced to actuate servo-apparatus, which, while positioning an object to be moved, incidentally restores electrical balance in the network. The bridge network B is comprised of two standard resistors **12** and **13**, a calibrated resistor **14**, and a temperature-sensitive resistor **15** exposed to a temperature to be measured. Engaging the calibrated resistor **14** is a translatable contact member **16** adapted for mechanical displacement with respect to the resistor, whereby to make contact with the latter at any one of a multiplicity of points throughout its length. The contact member **16** carries an index or pointer **17** adapted to cooperate with a stationary graduated scale **18** in providing a measure of the displaced position of said contact member. The four resistors are connected into a closed loop having four junction points, and these junction points are connected alternately to a pair of conductors **20** and **21** supplied from a source **22** of alternating-current energization for the network, and to a pair of conductors **23** and **24** between which will develop a potential, or "error signal" corresponding in intensity and phase position upon the degree and the sense, respectively, of unbalance existing in the bridge network.

The reversible motor M_1, which may be of any one of a variety of types and forms known to the art is shown in Fig. 1 as of the split-field class, wherein an armature **25** is free to revolve in the field produced by either of two magnet windings **26—27** of mutually opposed polarity, and therefore to have a direction of rotation depending upon which of said windings is energized. Operation of the motor M is subject to the actuated position of the two relays R_1 and R_2, each of these having a set of normally-open and a set of normally-closed contacts. To the common, or armature, terminal of the motor M is connected a conductor **30** forming one side of a suit-

able source of power supply for the motor. The field winding 26 of the motor is connected through the normally-open contacts of the relay R_1 and the normally-closed contacts of the relay R_2 in series to a conductor 31 forming the other side of said power circuit; and the winding 27 is connected through the normally-open contacts of relay R_2 and the normally-closed contacts of relay R_1 in series also to said conductor 31.

From inspection of the diagram it will be seen that with both relays de-energized, as indicated in the drawing, both field windings of the motor will be open-circuited, and the motor will remain at rest. If the relay R_1 be energized, closing its normally-open and opening its normally-closed contacts, a circuit will be completed from the conductor 30 through the armature of the motor, the winding 26, the normally-open contacts of relay R_1, and the normally-closed contacts of relay R_2 to the conductor 31, energizing the motor for operation in a selected direction. Similarly, if the relay R_2 be energized, the winding 27 of the motor wil be energized, causing the motor to operate in the opposite direction. With electrical connections as shown in Fig. 1, simultaneous energization of the relays R_1 and R_2 will cause the motor circuit to be interrupted by the concurrent opening of their normally-closed contacts, so that neither of the motor circuits will be completed and the motor will remain de-energized. This electrical interlocking may if desired be replaced, or supplemented, by mechanical interlocking means whereby it is rendered impossible for more than one of the relays at a time to complete its operating circuit. As a further alternative, use may be made of the system shown in Fig. 2, wherein the split-field motor M_1 of Fig. 1 is replaced by a motor M_2 having a single field winding 28 and an armature 29. With connections as shown, between the armature, the relays R_1 and R_2 and the supply conductors 30 and 31, the field winding 28 being connected directly to said last-named conductors, it will be seen that operation of the motor will be directionally responsive to whichever of said relays is energized. If both relays are concurrently energized, or are concurrently de-energized as indicated in Fig. 2, the armature 29 will be short-circuited; and, with the field 28 excited, there will be obtained a powerful dynamic braking effect, tending to prevent overshooting of the motor in operation. The connection shown in Fig. 2, or its equivalent, is common in the control of small motors; and, when used on a direct-current system, the field magnet with its winding 28 may be—as it frequently is—replaced by a permanent magnet.

Other effective methods of actuating a reversible motor from a pair of relays are well known in the art of control, and for them no invention is herein claimed. As indicated in Fig. 1, a suitable mechanical connection 33 is provided between the armature of the motor and the movable contact member 16 in the bridge B, whereby operation of the motor may be utilized to affect the electrical balance condition of said bridge.

The circuitry whereby the relays R_1 and R_2 are made selectively responsive to conditions of unbalance in the bridge network B, and for which invention is claimed, may be described as follows: An input transformer 34 is provided with a primary winding adapted to be responsive to potentials evolving from unbalance conditions in the bridge network B and having its terminals directly connected to the conductors 23 and 24. The secondary winding of the transformer 34 is provided with a center tap 35, and has its terminals connected to conductors 36 and 37. A pair of electronic discharge devices (triodes) 38 and 39 are provided each with a cathode, an anode and a control electrode. The cathodes, rendered emissive by heating means not shown in the drawing, are connected to a common conductor 40. The control electrodes are connected respectively to the conductors 36 and 37 and the anodes (plates) to conductors 41 and 42.

The center tap 35 of the secondary winding of transformer 34 is connected, in series with a resistor 43, having in parallel therewith a capacitor 44, to a conductor 45, which may be directly connected to a ground point G. The conductor 40 is connected, in series with a cathode biasing resistor 46, to the ground conductor 45. Between the conductors 41 and 42 are connected in series two equal resistors 47 and 48 having their common junction connected to a conductor 50. Between the conductor 50 and the ground conductor 45 is connected a suitable battery or equivalent source of uni-directional electromotive force 51, whereby to render the former conductor positive with respect to the latter, and to provide a polarizing potential for the electronic system.

A pair of electron discharge devices 52 and 53, each having a cathode, an anode and a control electrode, the first mentioned elements being rendered emissive by means not shown in the drawings, are arranged with their cathodes connected to the conductor 50, and with their control electrodes connected respectively to the conductors 41 and 42. The anodes of the devices 52 and 53 are connected respectively to the conductors 55 and 56, between which are arranged in series two equal resistors 57 and 58 having their junction connected to a common conductor 59, and thence, in series with a capacitor 60, to the center tap 35 of the secondary of the input transformer 34. (While in the interest of simplicity the control devices 52 and 53 have been shown and described as triodes, other forms such as pentodes have been found applicable to the purposes of the invention. Since, however, the substitution of such devices for triodes is well known in the art of electronics and has no bearing on the novelty of the invention, they have been omitted from the present disclosure.)

A power transformer 61 provided with a primary and a secondary winding is arranged with the terminals of the former winding connected to the conductors 20 and 21 whereby to be excited from the same source as that which energizes the bridge network B. One terminal of the secondary winding of said power transformer is connected to the conductor 50, and the other terminal to a conductor 62, between which and the conductors 55 and 56 are respectively connected the actuating windings of the relays R_1 and R_2. In parallel with said respsective relay windings are connected capacitors 63 and 64 each adapted to bypass a substantial proportion of the alternating component of current flowing in the relay circuits.

For the purpose of analyzing the performance of the system, consideration may first be given to conditions existing with the bridge network B in a state of electrical balance and the circuit consequently in a quiescent condition. With the conductors 20—21 connected to the alternating-current source 22, the bridge network will be energized, but because of its balanced condition no signal will appear between the conductors 23—24, or upon the primary winding of the transformer 34, and therefore no alternating potential will be impressed upon the control electrodes of the triodes 38 and 39. There will therefore be no alternating component of current flowing in the anode circuits of these triodes, and consequently no signal applied to the control electrodes of the tubes 52—53.

Under the influence of the positive potential of the conductor 50 impressed upon the anodes of the tubes 38 and 39 there will, however, be a transfer of electrons, and substantially equal currents will flow through the resistors 47 and 48 to the cathodes of said tubes and common conductor 40, and thence together through the resistor 46 to the negative side of the battery 51. The resistors 47 and 48 are made of such value that the direct current flowing through them when no signal is present will develop sufficient potential drop to bias the tubes 52 and 53 to a non-conductive state and prevent the flow therethrough of alternating current due to the potential impressed between the anodes and the cathodes from the secondary winding of the transformer 61. Thus,

there will be no current flowing in the anode circuit of either of said last-named tubes, and consequently no potential across the winding of either of the relays R_1 and R_2. The anodes of the tubes **52** and **53** will therefore be at the same potential as the conductor **62** which is common to both relay windings, and thereby, through the metallic connection provided by the secondary winding of the transformer **61**, at the same mean potential as the conductor **50**, which is connected to the positive terminal of the battery **51**. There being no current in either of the resistors **57—58**, their common conductor **59** also will be at the same potential as the anodes of the tubes **52** and **53**, and thus at the potential of the conductor **50** and the positive terminal of the battery **51**. There being no current in the resistor **43**, the center tap of the secondary winding of the transformer **34** will assume the potential of the conductor **45** connected to the negative terminal of the battery **51**. Thus, so long as there is no signal potential on the control electrode of either of the tubes **38—39**, substantially the full voltage of the battery **51** will be impressed across the capacitor **60**.

It may now be assumed that, due to a change in temperature to which the thermally sensitive resistor **15** is exposed, the bridge network B becomes unbalanced, causing an "error signal" or alternating potential to appear between the conductors **23—24** and thereby to be impressed upon the primary winding of the transformer **34**, with the development of a corresponding secondary voltage of which substantially one half will be impressed between the control electrode and the cathode of tube **38** and substantially one half between the control electrode and the cathode of tube **39**. Because the control electrodes of the tubes **38** and **39** are connected to opposite terminals of the secondary winding of the transformer **34**, said tubes will be rendered alternately conductive, and their anodes and the respectively associated conductors **41** and **42** will carry alternate pulses of opposite polarity, causing corresponding potential pulses to be impressed upon the control electrodes of tubes **52** and **53**. According to the phase position, or instantaneous polarity, of said potential pulses with respect to the alternating anode potential impressed upon the tubes **52** and **53** by the secondary winding of transformer **61**, one or the other of said tubes will be rendered conductive to pass a pulsating current of which the unidirectional component will flow through the winding of the relay R_1 or R_2, as the case may be, while the principal part of the alternating component will flow through the capacitor **63** or **64** in parallel therewith.

With either of the tubes **52—53** conducting, as is the case when bridge balance is disturbed, an analysis may be made of current and potential conditions in the circuit affected by said tubes. The unidirectional component of current in the output of the active tube will cause a corresponding potential drop across the resistance of the winding of the associated relay, rendering the conductor **55** or **56**, as the case may be, negative with respect to the conductor **62**, and thus with respect to the conductor **50**. Whereas, with the circuit in a quiescent state corresponding to a condition of bridge balance, the full voltage of the battery **51** is impressed upon the capacitor **60**, the newly introduced potential difference in the circuit through which this potential condition was maintained will now result in a lowering of potential across that capacitor, causing the latter to be discharged to the lesser value. In order for this discharge to take place, current must pass through the circuit, and this current, flowing through the resistor **43** will develop a potential tending to charge the capacitor **44** and to establish upon the secondary winding of transformer **34** a negative potential with respect to the conductor **45**. This negative potential is directly impressed upon the control electrodes of the triodes **38** and **39**, reducing their output currents, and correspondingly lowering the bias potential originally applied to the tubes **52** and **53**. This reduction of bias voltage tends to enhance the conductivity of both tubes; but in so far as the non-conducting tube is concerned, the signal potential applied to its control electrode in phase opposition to the alternating potential on the anode is sufficiently high to maintain the tube in a non-conducting condition. The conducting tube, on the other hand, will pass an increased value of current, thereby rendering cumulative the hereinbefore described effect and tending further to reinforce its own conductivity. With suitably selected circuit component values, this action may be made to produce a very rapid building up of the voltage across the energized relay, resulting in a corresponding trigger, or snap-action, performance.

Neglecting for the moment the effect of the resistor **43** across the capacitor **44**, it will be seen that capacitors **60** and **44** may be considered as being in series to the extent that the charge removed from the former will be imparted to the latter, so that the capacitor **44** will become charged to a voltage which will depend upon the inverse ratio of the respective capacitances. The effect of such resistance as may be in series with the combined capacitors (the principal part of which resistance normally resides in whichever of the resistors **57—58** is carrying current) will be to delay the transfer of charge and the consequent building up of voltage across the capacitor **44**. The magnitude attained by this voltage will be somewhat reduced by the shunting effect of the resistor **43**; and if the value of this resistor is relatively low the charge upon the capacitor **44** may not build up sufficiently to develop an appreciable voltage across its terminals.

The delay in voltage increase across the terminals of the capacitor **44** is an important factor in the timing of the transient effects which characterize a relay-operating event. If the charging transient is of too short duration the relay may not have time to respond. Ordinarily, however, the transient may be made to be effective for a time interval of the order of $\frac{1}{10}$ second, which is quite sufficient to produce the desired effect when use is made of a typical electromechanical relay having an operating time of the order of $\frac{1}{100}$ second.

It will be understood that upon current flowing in the winding of either of the relays R_1 or R_2, as the case may be, and attaining sufficient value to actuate said relay, the motor **25** will be correspondingly operated. By suitable selection of rotation direction with respect to circuit characteristics, the displacement of contact member **16** in response to motor operation may be made such as to tend to correct the electrical unbalance originally responsible for the signal impressed upon the primary winding of the transformer **34**. As is well known in the art, the indication of the pointer **17** on the scale **18** may be calibrated in terms of the temperature to which the thermally sensitive resistor **15** is exposed, or of any other magnitude to whose variations the network may be made directionally and quantitatively responsive.

While the surge of current responsible for the trigger, or snap, action of a relay is only transient in its nature, it may, as has been pointed out, be made of sufficient duration to ensure positive operation of the relay. Since control relays are in general characterized by considerable mechanical hysteresis, in that once actuated they will continue in the energized position even though the exciting current falls materially below the original actuating value, it follows that after decay of the transient, the remaining current steadily flowing so long as the unbalance condition exists may be utilized to maintain the relay actuated as long as necessary. As a condition of balance is approached and the "error signal" becomes of progressively less magnitude, the hereinbefore described phenomena attending the first appearance of the signal will be reversed, and the initial slight decrease of current in the winding of the active relay will be accentuated to an extent sufficient to effect a rapid decrease below the holding value, and the relay released with a snap-action similar to that characterizing its initial operation.

The foregoing discussion having dealt primarily with the performance of the system under conditions of relatively slight unbalance and correspondingly weak "error signals," attention may be given to actions taking place when the unbalance is comparatively great and the corresponding signals of such magnitude as to render the control electrodes of the tubes **38** and **39** alternatively positive with respect to the cathodes. Under such conditions, the control electrodes may act to some degree as anodes, attracting electrons, with a consequent flow of current in the "grid circuit," which current, in turn, will cause a negative potential to build up between the center tap of the secondary winding of the transformer **34** and ground, i. e., across the resistor **43**. The capacitance **44** in parallel with this resistor tends to delay any change in such potential; and the rate of its variation will be determined almost wholly by the relative magnitudes of said capacitor and resistor.

The rate at which balance in the bridge network B is restored is established by the speed of the motor **25**. It is thus possible for the balancing function to be effected so rapidly that the signal voltage may be reduced to a value less than the residual voltage across the resistor **43**. Under this condition, the signal will be insufficient to overcome the bias on the triodes **38** and **39**, so that these tubes will transmit substantially no signal to the tubes **52** and **53**. However, the potential across the resistor **43** tends to reduce the current in the resistors **47** and **48** and correspondingly enhance the conductivity of the tubes **52** and **53**. In the absence of a definite signal, and without a strong bias, both these tubes may become conductive, with a consequent possibility of operation of both the relays R_1 and R_2. With the contacts of these relays connected to the motor control circuit as hereinbefore pointed out their simultaneous operation may be made to result in non-operation, or in dynamic braking, of the motor. Thus, when a large unbalance signal is developed in the bridge circuit the motor tends to become de-energized some time before the balance position is attained. While this characteristic may be advantageously utilized in anticipating balance and preventing hunting, a high value of the resistor **43** may result in a strong signal building up sufficient voltage across the capacitor **44** to inhibit action of the balancing motor and paralyze the system. It will therefore be apparent that the optimum value of the resistor **43** for operation under weak signal conditions may be materially higher than that required to give satisfactory performance with signals which are relatively strong. Thus, in order for the advantages of the system to be realized, it is necessary that the value of the resistor **43**, if of constant magnitude, be a compromise between the values best adapted to operation under the extreme possible conditions.

While it will be appreciated that the herein described circuit is subject to great flexibility in design, with a correspondingly broad selection of circuit component constants, typical values exemplifying a practical system suited to use on a supply of 117 volts at an operating frequency of 400 cycles per second, are shown in the following tabulation:

	Designating numeral	Value
Resistors	43	0.5 to 1 megohm.
	46	680 ohms.
	47	33,000 ohms.
	48	Do.
	57	1.5 megohms.
	58	Do.
Capacitors	44	0.25 microfarad.
	60	0.05 microfarad.
	63	0.25 microfarad.
	64	Do.
Transformers	35	1/6 ratio.
	61	1/1 ratio.
Potential source	51	100 volts.
Relays	R_1 and R_2	"Leach: 237," 6,000 ohm coil.

From the foregoing discussion of resistance values it will be apparent that ideal performance under a wide range of operating conditions would be obtained if the value of the resistor **43** could be varied according to the strength of the signal impressed upon the circuit by the output of the bridge network B. This desirable characteristic may be conferred upon the system by making the resistor **43** non-linear in its characteristic and of such a nature that the resistance value decreases as the applied potential is increased. Among the materials known to have this property are certain ceramic products, of which an example is found in Carborundum units known by the trade name of "Globar, 331 BNR." Substitution of one or more units of this type, rated at a resistance of 50,000 ohms when subjected to a D. C. potential of 150 volts, for the hereinbefore specified constant-value resistor **43** is found greatly to broaden the range of signal values through which the "snap-action" is obtained, while at the same time the desired "anticipatory" performance, minimizing hunting, can be freely utilized without risk of paralyzing the system under conditions of extreme unbalance.

Fig. 3 of the drawings shows an embodiment of the invention especially adapted to improvement of performance in the critical range where the "error signals" from the bridge network may frequently be of such small magnitude as may introduce a stability problem. It will be understood that the arrangement shown in Fig. 3 is to be used in combination with all the elements of Fig. 1, excepting that the relays R_1 and R_2 of Fig. 1 (or Fig. 2) are replaced by relays R_{1a} and R_{2a}, corresponding exactly to the relays R_1 and R_2 in their operation and connections, with the added features that each of the relays of Fig. 3 is provided with an auxiliary set of contacts, shown as the upper contacts in the diagram. Each of said auxiliary sets of contacts has a normally-open and a normally-closed element, between which a common connection is provided whereby each set of contacts will function as a single-pole double-throw switch coincident with normal operation of the relays in controlling the balancing motor.

The common connection of the auxiliary contacts of the relay R_{1a} is connected to one side of a capacitor **70** having a value of the order of 0.02 microfarad, to the other side of which capacitor is connected the common connection of the auxiliary contacts of relay R_{2a}. The normally-closed free contacts of the two relays are interconnected through a resistor **71** having a value of the order of 100,000 ohms. In parallel with the resistor **71** is a pair of series connected resistors **72**, **73** each having a value of the order of 3 megohms and having their common junction connected to the conductor **50**, which is the positive terminal of the D. C. power source **51** in Fig. 1. The normally-open contacts of the relays R_{1a} and R_{2a} are both connected to the point **35**, which is the mid-tap on the secondary winding of the transformer **34**.

Operation of the apparatus shown in Fig. 3 may be described as follows: With both relays R_{1a} and R_{2a} de-energized, corresponding to a condition of repose in the control system, the capacitor **70** will have its terminals connected through the normally-closed auxiliary contacts of said relays to the terminals of resistor **71** in parallel with the series combination of resistors **72** and **73**; and since under this condition there will be no electrical potential difference in the closed loop so formed, the capacitor **70** will be in a discharged condition. Upon energization of either of the relays, its normally-open auxiliary contact will provide a connection between one side of the capacitor **70** and the conductor **35**; and thus said capacitor will be connected between the positive and the negative terminals of the source **51** through a circuit comprising a series combination of the resistor **43** and one or other of the resistors **72**—**73**, whereby charging current will flow in said circuit, producing a potential across the resistor **43** and a corresponding charge upon the ca-

pacitor 44 in parallel therewith, thus temporarily raising the D. C. potential of the secondary winding of the transformer, and incidentally of the control electrodes of the tubes 38 and 39, and correspondingly increasing their output currents. The resultant increase of bias potential impressed upon the tubes 52 and 53 will tend to decrease their conductivity, so that whichever of these tubes is conducting may be cut off, with consequent de-energization of the relay controlled thereby.

Since the foregoing action is initiated upon closing of the contacts of the same relay which operates the motor, and since the resistance in the circuit will delay establishment of the resultant potential across the capacitor 44, the consequent releasing action upon the relay will not be instantaneous; and the motor will have a short time in which to accelerate before its circuit is interrupted. After the relay has dropped out, the capacitor 70 will require an appreciable time to discharge through the normally-closed relay contacts and the series resistors, so that a delay will occur before the effect of the superposed voltage disappears from the capacitor 44, permitting the cycle to be repeated.

There is thus introduced into the performance of the motor a series of pulses, preventing the motor attaining objectionably high speeds with concomitant inertia effects, and tending to bring the balancing mechanism to rest in a series of increments as the balance point is approached. It will be apparent that the constants which have been given as characterizing the values of the resistors and capacitors are only typical, and that without departing from the spirit of the invention they may be varied through considerable ranges consistent with the type of motor employed and with the operating performance desired as characterizing a particular installation.

The terms and expressions which I have employed are used as terms of description and not of limitation, and I have no intention, in the use of such terms and expressions, of excluding any equivalents of the features shown and described or portions thereof, but recognize that various modifications are possible within the scope of the invention claimed.

I claim:

1. In an electronic control system comprising an initial and a final stage of amplification each having an electron discharge device with a cathode, an anode and a control electrode, together with circuit means whereby the potential upon the control electrode in said final stage is made subject to a condition of the anode in said initial stage, a load circuit including resistance and adapted to carry the output current of said final stage, means including an input circuit for impressing a signal potential of predetermined magnitude upon the control electrode of the device in said initial stage, circuit means responsive to a change in the flow of current in said load circuit for abruptly changing the magnitude of the potential applied to the control electrode of the device in said initial stage solely in a sense to accelerate and augment the change in said load circuit and including a capacitor interconnecting the output circuit of said final stage with the input circuit of said initial stage, a source of unidirectional potential included in said last mentioned circuit means whereby to charge said capacitor and to establish a predetermined voltage across the same when said circuits are in a quiescent state, an auxiliary circuit including a parallel-connected resistor and capacitor, forming a part of said last mentioned circuit means and connected in series with said control electrode and cathode of the device in said initial stage and said signal impressing means, connection means included in said circuits to superpose upon said capacitor voltage the potential drop due to current flow in said load circuit, whereby the charge upon said first-named capacitor is varied to affect the charge upon the capacitor in said auxiliary circuit and correspondingly bias the potential upon the control electrode of the device in said initial stage of amplification.

2. Control means for a balanceable electrical network adapted to produce an output alternating potential representative in intensity and phase position of the degree and sense respectively of unbalance, and including mechanically movable means for effecting a balance thereof, said control means comprising at least an initial and a final stage of amplification, each stage having a pair of electron discharge devices and each of said devices being provided with an anode, a cathode and a control electrode, circuit means whereby the potential upon a control electrode in said final stage is made subject to a condition of an anode in said initial stage, a pair of relay devices for respectively and directionally controlling said mechanically movable means, each having an actuating circuit characterized by electrical resistance and adapted to carry at least a portion of the output of one of said electron discharge devices in said final stage of amplification, means including an input circuit for impressing upon one of the control devices in said initial stage a voltage representative of the output potential of said network to activate said control device, circuit means responsive to a change in the flow of current in one of said relay-actuating circuits for abruptly changing the magnitude of the potential impressed upon said activated control device solely in a sense to accelerate and augment the change in said relay-actuating circuit current and including a capacitor interconnecting the output circuit of said final stage with the input circuit of said initial stage, a source of unidirectional potential included in said last mentioned circuit means whereby to charge said capacitor and to establish a predetermined voltage across the same when said circuits are in a quiescent state, an auxiliary circuit including a parallel-connected resistor and capacitor, forming a part of said last mentioned circuit means and interposed in said input circuit of said initial stage, connection means included in said circuits to superpose upon said predetermined capacitor voltage the potential drop due to current flow in one of said relay-actuating circuits and thereby to vary the charge upon said first-named capacitor and affect the charge of the capacitor in said auxiliary circuit and correspondingly bias the potential upon the control electrode of said activated control device.

3. An electronic control system as in claim 2 and having a supplementary circuit including capacitor means and contact means subject to said relay devices to connect said capacitor means to said source of unidirectional potential to charge the same through said auxiliary circuit, whereby temporarily to superpose upon the potential normally developed across the resistor and capacitor in said auxiliary circuit a supplementary potential in opposition thereto to modify the biasing effect upon the control electrode of the device in the initial stage of amplification to vary the operating current in the active one of said relay devices in a sense opposite to that of the normal operating current, thereby de-activating said relay device and causing said mechanically movable means to be alternately energized and de-energized in a series of successive pulses.

4. Control means for a balanceable electrical network adapted to produce an output error voltage representative of the degree and sense of unbalance and including mechanically movable means for effecting a balance thereof, said control means comprising a multistage amplifier having an output circuit for controlling said mechanically movable means, a control electrode, and an input circuit for applying said error voltage to said control electrode, and bias controlling circuit means responsive to a change in the flow of current in said output circuit for abruptly changing the potential applied to said control electrode solely in a sense to accelerate and augment the change in said output circuit including a non-linear resistor and a capacitor coupling said output circuit to said control electrode, whereby a transient bias voltage is applied to said control electrode in a cumula-

tive sense, in response to voltage changes in said output circuit.

5. Control means for a balanceable electrical network adapted to produce an output alternating error voltage representative in intensity and phase position of the degree and sense respectively of unbalance, and including mechanically movable means for effecting a balance thereof, said control means comprising a relay device for controlling said mechanically movable means, said relay device having an actuating circuit and a mechanically movable armature actuated by current through said actuating circuit, an amplifier comprising an electron discharge device having an anode, a cathode and a control electrode, input circuit means for applying between said control electrode and said cathode a bias voltage and said alternating error voltage, an output circuit for said amplifier coupled to said actuating circuit of said relay device, and circuit means including resistance and reactance connecting said output circuit to said input circuit for applying to said control electrode a transient biasing pulse in response to a change in current in said output circuit and in said actuating circuit, for changing the amplification of said amplifier solely in a sense to accelerate and augment said output circuit current change, said resistance and reactance affecting the duration of said biasing pulse and being of such values that said pulse lasts long enough to ensure snap-action operation of said relay.

6. Control means for a balanceable electrical network adapted to produce an output error voltage representative of the degree and sense of unbalance and including mechanically movable means for effecting a balance thereof, said control means comprising an amplifier having an input circuit including voltage-biased input electrodes and an output circuit coupled to and directionally controlling said mechanically movable means, means for applying said error voltage to said input circuit, said amplifier having a variable amplification determined by the bias voltage applied to one of said input electrodes with respect to another of said input electrodes, said input circuit including an auxiliary circuit comprising a non-linear resistor in parallel with a capacitor and connections from said auxiliary circuit to said input electrodes, a capacitor connected from said output circuit to said auxiliary circuit for applying a transient bias voltage to said input electrodes in a sense to provide a temporary change in said amplification in response to a change in the magnitude of said error voltage, said changes being in the same sense and providing a temporary cumulative effect, to ensure positive response of said mechanically movable means.

7. Control means for balanceable apparatus adapted to produce an output error signal representative of the degree and sense of unbalance and including mechanically movable means for effecting a balance thereof, said control means comprising an amplifier having an input circuit including biased input electrodes and an output circuit coupled to and directionally controlling said mechanically movable means, means for applying said error signal to said input circuit, said amplifier having variable amplification determined by the bias applied to one of said input electrodes with respect to another of said input electrodes, said input circuit including an auxiliary circuit comprising a resistor in parallel with a capacitor and connections from common junctions of said parallel resistor and capacitor of said auxiliary circuit to said input electrodes, a capacitor connected from said output circuit to the junction of said parallel capacitor and resistor connected to said one input electrode for applying a transient bias to said input electrodes in a sense to provide a change in said amplification in response to a change in the magnitude of said error signal, said changes being in the same sense and providing a cumulative effect, to ensure positive response of said mechanically movable means.

8. Control means for a balanceable electrical network adapted to produce an output alternating error voltage representative of the degree and sense of unbalance and including mechanically movable means for effecting a balance thereof, comprising, in combination, a multistage direct coupled amplifier, one stage of said amplifier having an anode circuit energized with alternating current so as to give said stage a phase detecting characteristic, a relay device for controlling said mechanically movable means, said relay device having a current-controlled activating circuit, said amplifier having an output circuit for controlling said activating circuit and having an input circuit with input electrodes therein responsive to said alternating error voltage from said network, said input circuit including a parallel-connected resistor and capacitor connected between said input electrodes, and a bias controlling circuit including a resistor and a capacitor coupling said output circuit to said input electrodes for applying thereto in a cumulative sense a transient bias voltage in response to changes in current through said activating circuit of said relay device and said output circuit solely in a sense to accelerate and augment said changes in said current.

9. Control means for a balanceable electrical network adapted to produce an output alternating potential representative in intensity and phase position of the degree and sense respectively of unbalance, and including mechanically movable means for effecting a balance thereof, said control means comprising at least an initial and a final stage of amplification connected in tandem, said initial stage having at least one electron discharge device and said final stage having a pair of electron discharge devices, each of said devices having an anode, a cathode and a control electrode, a pair of relay devices each having an actuating circuit controlled by said final stage, said relay devices respectively and directionally controlling said mechanically movable means, means including an input circuit for impressing upon the control electrode of said discharge device in said initial stage a voltage representative of said output potential of said network, to activate said discharge device, circuit means including a first capacitor and interconnecting said output circuit of said final stage with said input circuit of said initial stage, a source of unidirectional voltage connected to charge said capacitor to a predetermined voltage when said circuits are quiescent, an auxiliary circuit including a parallel-connected resistor and capacitor connected in series with said first capacitor and connected into said input circuit of said first stage, and connections for changing the voltage applied to said first capacitor on the occurrence of a change in the current flow in one of said relay-actuating circuits and solely in a sense to augment said change, thereby applying across said auxiliary circuit a transient biasing voltage for the control electrode of said activated discharge device.

10. Control means for a balanceable electric network adapted to produce an output alternating potential representative in intensity and phase position of the degree and sense respectively of unbalance, and including mechanically movable means for effecting a balance thereof; said control means comprising at least an initial and a final stage of amplification connected in tandem, each of said stages having a pair of electron discharge devices, each of said devices having an anode, a cathode and a control electrode; means for energizing the anodes of said final stage with alternating potential; a pair of relay devices each having an actuating circuit controlled by final stage, said actuating circuits including resistance, said relay devices respectively and directionally controlling said mechanically movable means; means including an input circuit for impressing upon the control electrodes of said discharge devices in said initial stage a voltage representative of said output potential of said network, to activate one of said discharge devices; circuit means responsive to a change in the flow of current in

said actuating circuits for abruptly changing the voltage applied to said control electrode of the activated one of said discharge devices of the initial stage solely in a sense to accelerate and augment the change in said actuating circuit current including (1) a series-connected first resistor and a first capacitor and interconnecting said output circuit of said final stage with said input circuit of said initial stage; (2) a source of unidirectional voltage connected to charge said capacitor to a predetermined voltage when said circuits are quiescent; (3) an auxiliary circuit including a parallel-connected second resistor and second capacitor connected in series with said first resistor and first capacitor and connected into said input circuit of said first stage; (4) and connections for applying to said first capacitor a voltage due to current flow in one of said relay-actuating circuits, thereby to vary the charge upon said first capacitor and temporarily affect the charge of said second capacitor so as to apply a transient biasing voltage to the control electrode of said activated discharge device.

11. Control means for a balanceable electrical network adapted to produce an output alternating error voltage representative in intensity and phase position of the degree and sense respectively of unbalance, and including mechanically movable means for effecting a balance thereof; said control means comprising a motor for controlling said mechanically movable means; a relay device for controlling said motor, said relay device having a current-controlled actuating circuit; an amplifier comprising an initial electron discharge device having an anode, a cathode and a control electrode; input circuit means for applying between said control electrode and said cathode a bias voltage and said alternating error voltage; an output circuit for said amplifier coupled to said actuating circuit of said relay device; a first biasing circuit including a capacitor, a source of unidirectional voltage for charging said capacitor, and an auxiliary circuit comprising a parallel-connected resistor and capacitor, said biasing circuit connecting said output circuit to said input circuit for applying to said control electrode a transient biasing voltage in response to a change in current in said output circuit and in said actuating circuit, for changing the amplification of said amplifier in a cumulative sense; and a second biasing circuit including, in series, a supplementary capacitor, resistor means, and contact means controlled by said relay device to connect said supplementary capacitor to said source of unidirectional voltage and to said auxiliary circuit to charge same through said auxiliary circuit and to apply a temporary bias to said control electrode in a sense to actuate said relay in a direction to stop said motor and disconnect said supplementary capacitor from said source, whereby said motor is alternately energized and de-energized.

12. Control means for a balanceable electrical network adapted to produce an output error voltage representative of the degree and sense of unbalance and including mechanically movable means for effecting a balance thereof, said control means comprising an amplifier having an output circuit for controlling said mechanically movable means, a control electrode, and an input circuit for applying said error voltage to said control electrode, and bias controlling circuit means responsive to a change in the flow of current in said output circuit for abruptly superimposing a bias potential on said control electrode solely in a sense to accelerate and augment the change in said output circuit.

13. Control means for a balanceable electrical network adapted to produce an output error voltage representative of the degree and sense of unbalance and including mechanically movable means for effecting a balance thereof in at least a predetermined time, said control means comprising an amplifier having an output circuit for controlling said mechanically movable means, a control electrode, and an input circuit for applying said error voltage to said control electrode, and bias controlling circuit means responsive to a change in the flow of current in said output circuit for abruptly superimposing a bias potential on said control electrode for a time duration which is short as compared to said predetermined time and solely in a sense to accelerate and augment the change in said output circuit.

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