Aug. 3, 1943. J. RAZEK 2,325,801

RECORDING POTENTIOMETER

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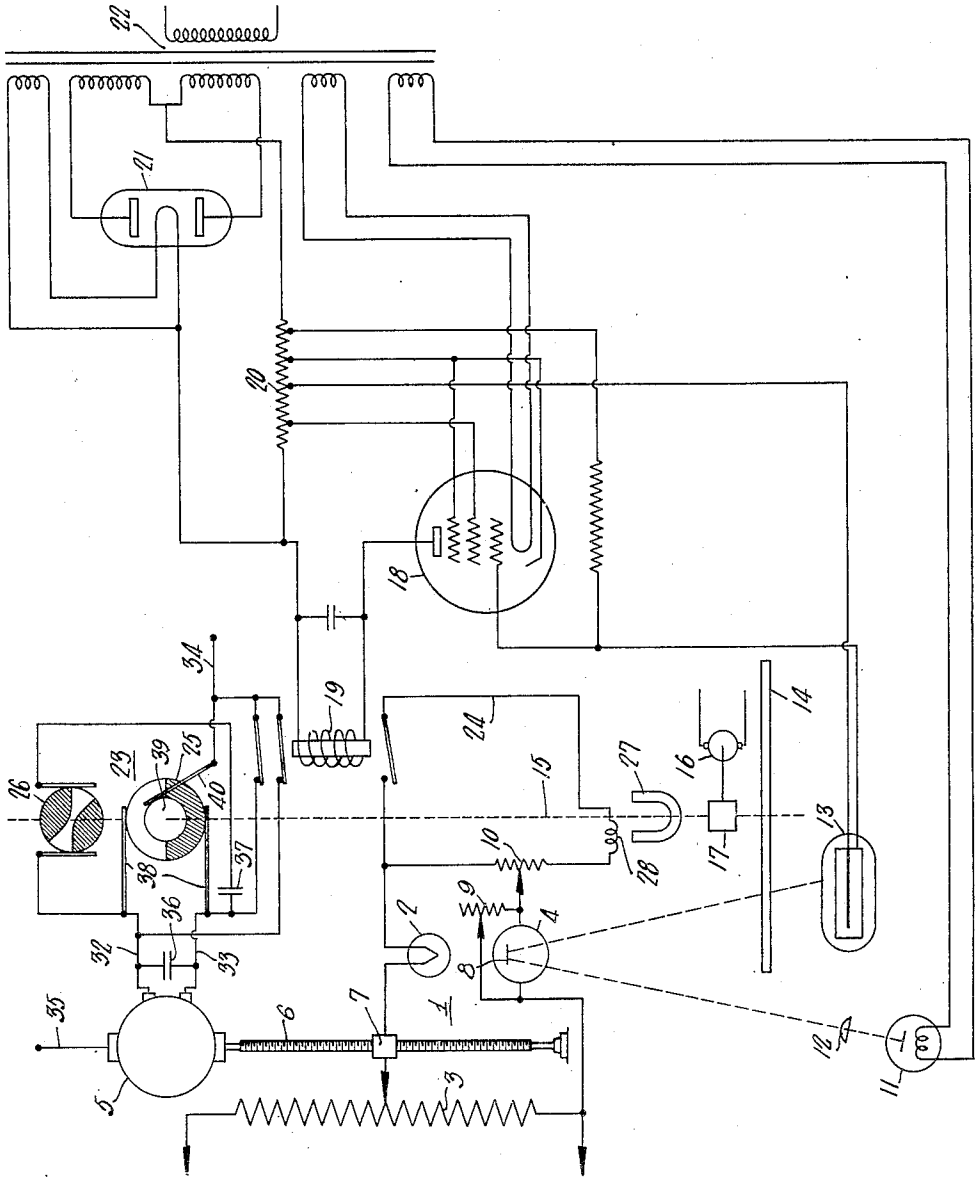


Fig. 1.

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Fig. 2.

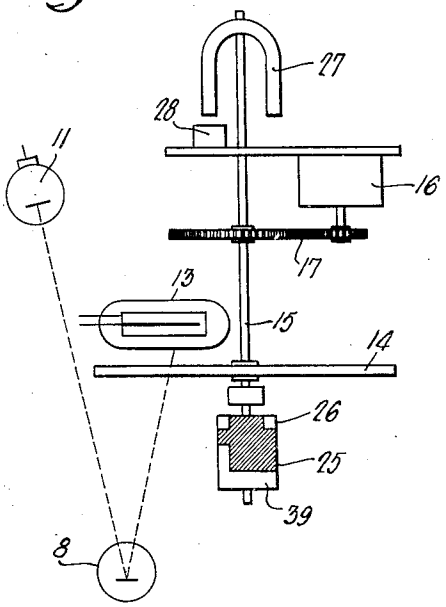


Fig. 3.

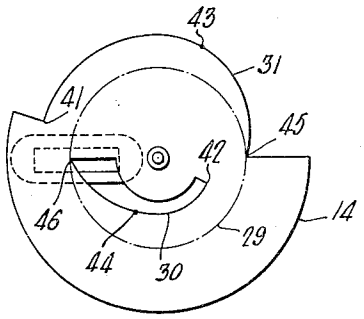


Fig. 6.

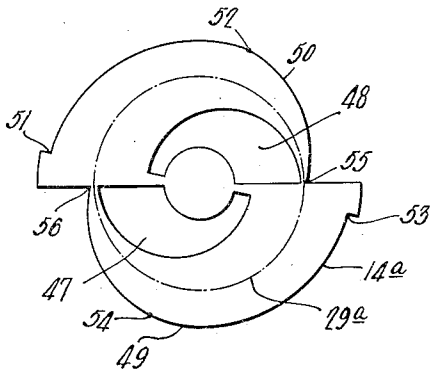
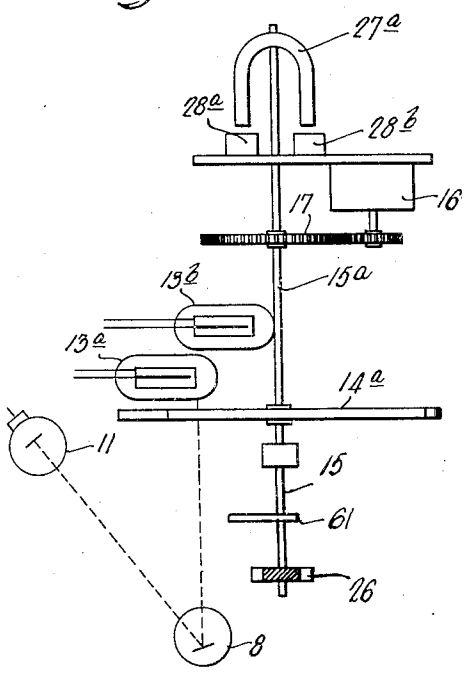


Fig. 5.



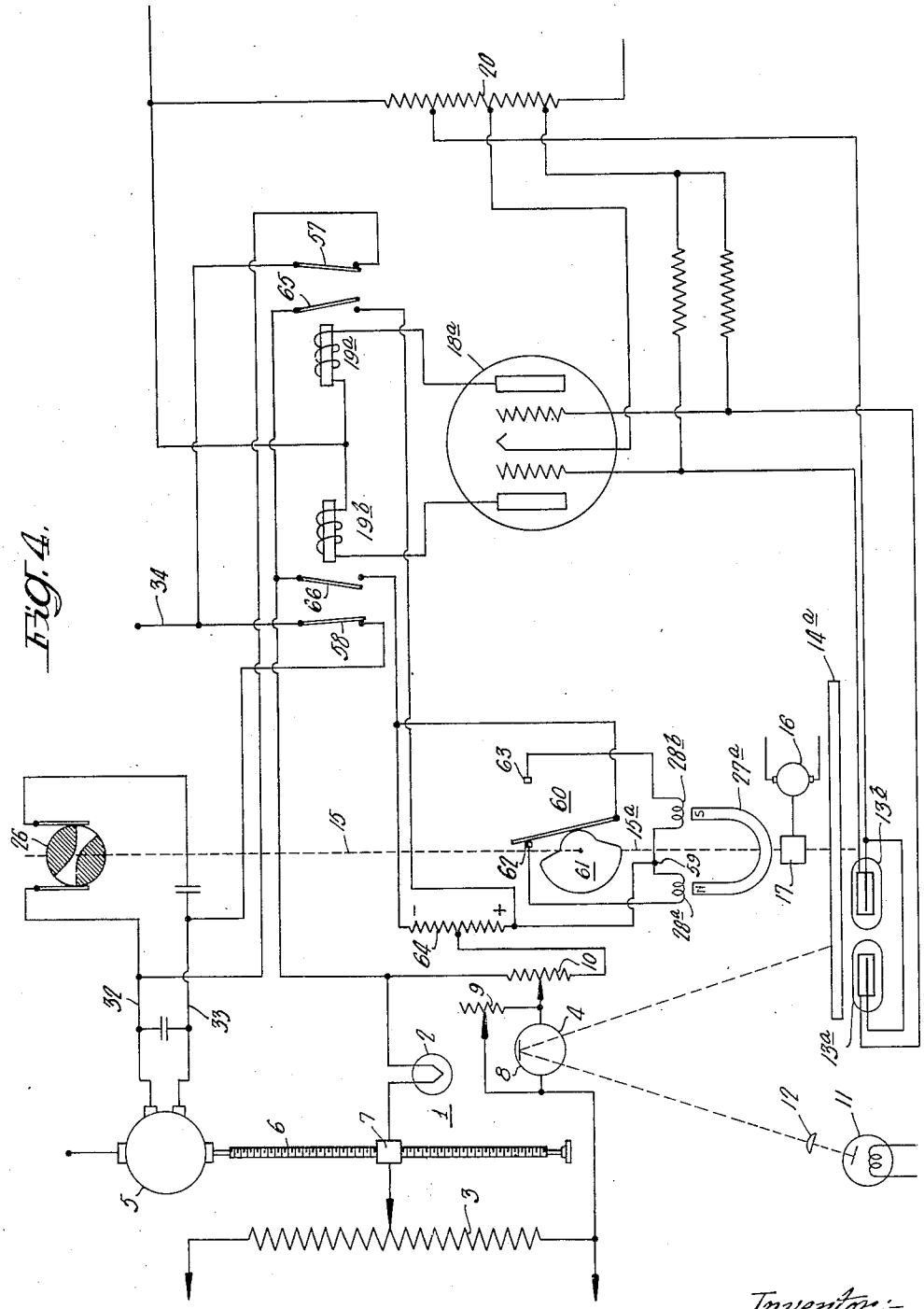
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FIG. 4.



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Fig. 8.

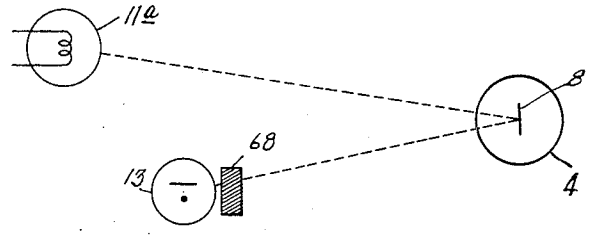
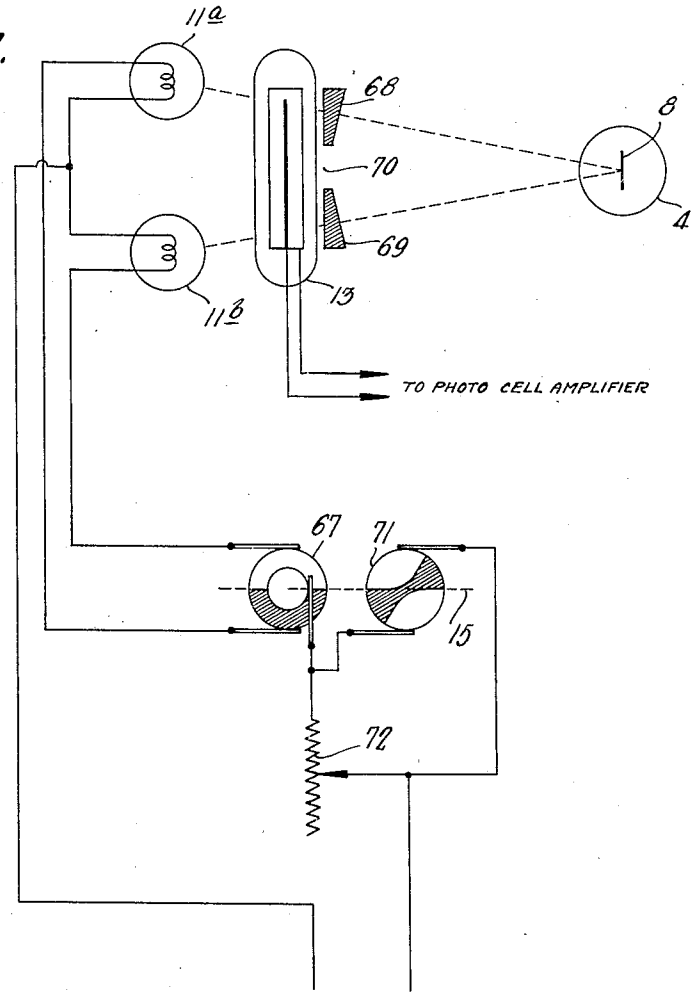


Fig. 7.



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UNITED STATES PATENT OFFICE

2,325,801

RECORDING POTENTIOMETER

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Application June 21, 1940, Serial No. 341,776

14 Claims. (Cl. 172—239)

This invention relates to control systems generally, and more particularly to control systems of the normally balanced type which are adapted to produce an effect of magnitude determined by the magnitude of change of a variable condition.

A specific example of such a system is the well known system employing a galvanometer as a detecting means which, in response to unbalance of an electrical network, sets into operation a motor, which in turn operates a rebalancing potentiometer or the like. The rebalancing mechanism, whose actuating is proportionate to the degree of unbalance, may be caused to produce any desired effect or control function, such as actuation of an indicator or recorder, actuation of a corrective mechanism, etc. Various usages of such a system are well known, some examples being control or indication of temperature, fluid level, pressure, etc.

The present invention, while relating generally to control systems of this general type, is particularly directed to a so-called potentiometer recorder employing a moving-coil galvanometer having a mirror or reflector for use in conjunction with electro-optical means, as is generally well known. Therefore, the invention will be described herein with particular reference to such a system or apparatus, it being understood, however, that the invention is not thus limited.

The principal object of the invention is to provide a novel and improved system of the character above mentioned.

A more specific object of the invention is to provide certain novel features in a system of this character by means of which certain inherent defects of prior systems are substantially eliminated, and other desirable results are obtained. A particular feature of the invention resides in the novel method and the several novel means described hereinafter for preventing "hunting" in such a system.

The invention may be clearly understood by reference to the accompanying drawings, wherein:

Figure 1 is a diagrammatic illustration of one embodiment of the invention;

Figure 2 is an elevational view of a physical embodiment of certain elements;

Figure 3 is a face view of the scanning disk employed in this system;

Figure 4 is a diagrammatic illustration of another embodiment of the invention;

Figure 5 is an elevational view of a physical embodiment of certain elements;

Figure 6 is a face view of the scanning disk employed in this embodiment;

Figure 7 is a diagrammatic illustration of a further embodiment; and

Figure 8 is a further view of the same.

In the usual type of potentiometer recorder, when the galvanometer deflects from it normal or equilibrium position in response to unbalance of the system, the deflection sets into operation the motor for moving the potentiometer contact in such a direction as to rebalance the system and bring the galvanometer back to its normal position. If the rebalance is to be attained very quickly, with minimum hunting and minimum "dead" zone, certain difficulties are encountered. By "dead zone" is meant a small range of departure from balance within which the galvanometer does not move, due to some condition such as now to be explained.

In order to prevent hunting, it is customary to provide sufficient damping either in the galvanometer itself or in its circuit. Hunting is caused by the fact that the galvanometer lags a slight amount behind the balancing potential or E. M. F., the lag depending upon the period of the galvanometer. Consequently, when the galvanometer returns to its normal position, the balancing potentiometer will have overshot the true balance position, causing the galvanometer to deflect in the opposite direction. As a result, the potentiometer is operated in the opposite direction. If the damping in the galvanometer is small, this will continue indefinitely, the balancing contact of the potentiometer oscillating about the true balance position. On the other hand, if the damping is sufficiently large to prevent hunting, a large "dead" zone results because the galvanometer is rendered substantially insensitive to small unbalanced effects. In such circumstances, the galvanometer will not move until the departure from balance is greater than the dead zone. This is as objectionable as is the hunting which the damping is intended to cure.

By the present invention, there are provided novel means for preventing, or greatly reducing, the hunting action, while at the same time keeping the resistance in the galvanometer circuit so small that there is no appreciable dead zone. In this manner, the invention effectively solves the problem of minimizing damping without causing the objectionable dead zone.

Referring now to Figure 1, there is illustrated a potentiometer recorder system having the invention applied thereto. This system comprises a normally balanced electrical network 1 which is

unbalanced in response to a change of some condition, and which is rebalanced by the automatic operation of the system. The network 1 may include a thermo-couple 2 which is representative of any device adapted to produce an electrical potential whose magnitude is proportionate to the magnitude of change of some condition. This electrical potential is normally balanced by the potential across the effective portion of the potentiometer 3, which constitutes the adjustable rebalancing mechanism. A moving-coil galvanometer 4 is also included in the normally balanced network, and constitutes a detecting means which responds to unbalancing of the network. As is well understood, whenever the circuit 1 becomes unbalanced, current flows through the galvanometer, causing deflection of the same in a direction corresponding to the direction of unbalance. The galvanometer sets into motion the rebalancing apparatus, which may include a motor 5 arranged to drive a lead screw 6 along which the contact carriage or slide 7 is movable. The operation of the rebalancing motor 5 may effect any desired function, such as the operation of a recorder.

The galvanometer 4 is provided with a mirror or reflector 8 which is moved proportionately to the galvanometer deflection, and serves to control electro-optical means, as described hereinafter. The galvanometer may be shunted by an adjustable resistor 9 by means of which the sensitivity of the galvanometer may be adjusted. Additionally, there is included in the network 1 a potentiometer 10, whose purpose will be described presently.

The electro-optical means employed in Figure 1 comprises a light source 11, a suitable focusing lens 12, and a single light-sensitive cell or phototube 13, arranged as illustrated. The incidence of the reflected light beam upon the cell 13 is controlled by means of a continuously rotating scanning disk 14 which constitutes a feature of the invention and which will be described in greater detail later. In the normal or balance position of the galvanometer mirror 8, the disk 14 interrupts the light beam and prevents it from impinging on the cell 13. However, when the galvanometer mirror is deflected in one direction or the other, causing the reflected light beam to move to the right or to the left, as viewed in Figure 1, the disk 14 permits the light beam to impinge on cell 13, which is thereby activated. The disk 14 is mounted on a rotatable shaft 15, as represented in Figure 1 by the broken line representation, and this shaft is continuously driven by a motor 16 through reduction gearing represented schematically at 17. The shaft is rotated at a substantially constant speed, which may be about 75 R. P. M.

The phototube 13 operates through an electron discharge tube 18 to energize a relay 19, whose functions will be described presently. While any suitable electron discharge tube may be employed, it is preferred to employ a pentode tube, as illustrated, the operation of which is well understood. The operating voltages for the tube 18 may be derived from the voltage divider 20 connected to a full wave rectifier 21 fed from a supply transformer 22, as well understood. As illustrated, the filament heating current for tube 18 and the energizing current for lamp 11 may also be derived from this transformer. It will be understood, of course, that any other suitable arrangement may be employed.

The relay 19 is connected in the plate circuit of tube 18, and is adapted to perform two functions. It controls the motor controlling device designated generally by reference character 23, and it also controls an energizing circuit 24 for potentiometer 10. The device 23, in conjunction with the scanning disk 14, controls the direction of operation of the motor 5, causing the motor to operate in the proper direction to effect rebalancing. Additionally, the device 23 performs a speed reducing function as described later. To these ends, the device 23 comprises commutators 25 and 26 mounted on the shaft 15 and coordinated with one another and with the disk 14.

There is also mounted on shaft 15 a magnet 27 having associated therewith a stationary coil 28 whereby an electrical potential is generated in the coil and is applied to potentiometer 10 under control of relay 19, as described hereinafter.

Referring to Figure 3, along the dot and dash circle 29, the disk 14 is solid; and when the galvanometer mirror 8 is in its normal position, the reflected light spot impinges on the disk at the said circle, and the light is intercepted. On the inner side of the said circle, the disk has cut therein a slot 30; and on the outer side of the circle, the disk is cut away to provide the spiral edge 31. When the galvanometer mirror is deflected toward the right, as viewed in Figure 1, the light beam is admitted to the photocell 13 through slot 30. When the galvanometer mirror is deflected in the opposite direction, causing the light beam to impinge on the outer portion of the disk, the light beam is admitted to the photocell along the cut-away outer portion of the disk. As constructed, however, the disk controls the light spot in a particular manner to be described later.

Referring again to Figure 1, the motor 5 is a capacitor-controlled split phase type motor, arranged to be dynamically braked. The direction of rotation of the motor is determined by which of the two leads 32 and 33 is connected to the input lead 34, the other input lead being shown at 35. The speed of the motor is determined to a large degree by the magnitude of the capacitor 36 connected across the leads 32 and 33. Preferably, the capacitor 36 should have a capacitance equal to about one microfarad, but this depends on the type of motor used. In accordance with the present invention, the speed of the motor is reduced during a portion of the rebalancing cycle by connecting an auxiliary capacitor 37 in parallel with the capacitor 36. As explained hereinafter, it is desired to reduce the motor speed to about one-quarter of its normal value, and to this end the capacitor 37 should have a capacitance of about three microfarads. The connection of the auxiliary capacitor 37 is controlled by the commutator 26.

Normally, the relay 19 is in the condition illustrated, and the motor 5 is dynamically braked because both of the leads 32 and 33 are connected to the supply lead 34 through the upper normally closed relay contacts. Consequently, the motor is normally at standstill. The commutator device 25 serves to connect the supply lead 34 alternately to the leads 32 and 33. As illustrated diagrammatically in Figure 1, the device 25 comprises a disk or drum, the shaded area of which represents an insulating portion, while the unshaded area represents a conductive portion. The contact fingers or brushes 38 engage the disk at diametrically opposite points. A cylindrical conductive extension 39 is engaged by the

brush 40. Were it not for the normally closed relay contacts, the motor 5 would operate, first, in one direction, and then in the other, making as many alternations per minute as the speed of the shaft 15. However, with the relay contacts closed, the motor is normally dynamically braked, as above mentioned.

The commutator device 26 may comprise a disk or drum having insulating and conductive sections as illustrated, the insulating sections being represented by the shaded area, while the conductive sections are represented by the unshaded areas. When the brushes engage the conductive portions, the capacitance 37 is rendered effective to reduce the motor speed. The commutator 26 is so designed and so coordinated or phased with commutator 25 that the motor slow-down occurs only during the latter part of each rebalancing cycle.

In the actual physical embodiment of the apparatus, the commutators 25 and 26 may be combined in a single drum, as shown in Figure 2. This drum may be formed of insulating material with metallic inserts. As illustrated, the upper portion of this composite device constitutes the commutator 26, while the lower portion constitutes the commutator 25. Suitable brushes (not shown) will be arranged cooperatively with the device according to the illustration of Figure 1.

Considering the operation of the system through a complete cycle, assume that the network 1 becomes unbalanced, causing current to flow therein in one direction or the other, with resultant deflection of the galvanometer mirror 8. As the scanning disk 14 rotates past the photocell 13, the spot of light will be admitted to the photocell when the controlling portion 30 or 31 of the disk passes in front of the photocell. As a result, the photocell will be activated, and will operate through the electron tube 18 to energize relay 19. The opening of the upper relay contacts places the motor 5 under control of the commutator 25. This commutator is so oriented on shaft 15 with respect to the disk 14 that it causes the motor 5 to operate in the proper direction to effect rebalancing. Accordingly, the potentiometer 3 is actuated in the proper direction to rebalance the system. Usually, the rebalancing action will comprise successive and intermittent cycles which are initiated during successive revolutions of the disk. Each cycle terminates when the light beam is intercepted and relay 19 is deenergized. This intermittent action continues until the system is completely rebalanced.

For high speed operation, the time of travel of the potentiometer contact from one end of the slide wire to the other must be quite small, i. e., about three or four seconds. Therefore, if the movable contact is near the balance position, even a small impulse would move the contact so rapidly that it would overrun the equilibrium position, in spite of the dynamic braking. This is due to the fact that there is an inevitable lag in the galvanometer and in the relay system.

In accordance with the present invention, this tendency to overrun and cause hunting, is substantially prevented, or at least reduced to a minimum, by causing the motor 5 to move much slower in the latter part of each operating cycle, as mentioned above. This reduction in motor speed is effected by the insertion of the auxiliary capacitor 37 during the latter part of the cycle through the action of the commutator 26, which is so oriented on the shaft 15 with respect to the commutator 25 that the circuit through capacitor 37 is completed during a predetermined portion of the motor cycle. Preferably, the commutator 26 is designed to insert the capacitor 37 for about sixty degrees of the cycle.

As stated above, the capacitor 37 is preferably designed to reduce the motor speed to about one-quarter of its normal speed. This reduces the motor torque, but sufficient torque remains to properly actuate the contact slide 7 along the lead screw 6. Obviously, it would be possible to design the commutator 26 so as to reduce the motor speed during several portions of the operating cycle, but in general reduction of the speed during a single portion of the cycle will be sufficient, particularly in view of the further feature now to be described.

In order to further reduce the tendency of overshooting, and consequent hunting, and to obtain additional desirable results as mentioned hereinafter, the invention provides a novel means for introducing into the galvanometer circuit a periodicity different from the natural periodicity of the galvanometer circuit, the effect of which is to damp the action of the galvanometer. This result is accomplished by interposing an E. M. F. in the galvanometer circuit in such sense as to compensate for the above-mentioned galvanometer lag. A desirable method of doing this is illustrated in Figure 1, wherein an E. M. F. of proper sense is generated in the coil 28. It will be apparent that rotation of the magnet 27 through a complete revolution will generate an E. M. F. in coil 28, first, in one direction, and then in the other, as the magnet prongs are alternately moved in proximity to the coil. The magnet is so oriented on shaft 15 with respect to disk 14 and commutator 25 that the E. M. F. induced in coil 28 is of proper sense in relation to the direction of unbalance of the system. Of course, when the system is balanced, and the lower relay contact is open, the induced E. M. F. has no effect; but when the relay is energized, in response to unbalancing of the system, the induced E. M. F. is applied to potentiometer 10 so as to include an adjustable portion of the generated voltage in circuit with the galvanometer.

As mentioned above, the principal cause of overshooting and hunting is the time lag of the galvanometer with respect to the balancing E. M. F. of the potentiometer 3. The effect of the E. M. F. introduced by way of potentiometer 10 is to accelerate or push the galvanometer forward toward the balance position, thus compensating for its inherent time lag. In other words, the galvanometer spot is pushed toward the equilibrium or balance position so as to compensate for the inherent lag. As soon as the galvanometer reaches the balance point, the relay 19 is deenergized, and the compensating E. M. F. is removed from the circuit.

Furthermore, as mentioned above, an effect of introducing the E. M. F. is the introduction of a periodicity different from that of the galvanometer circuit, which effectively damps the circuit during the rebalancing cycle without affecting the normal sensitivity of the galvanometer.

Since the compensating E. M. F. "anticipates" reverse deflection of the galvanometer due to overshooting, and since it functions in anticipation of the overshooting action, this feature of the invention may be aptly termed the "anticipator."

As a result of the motor slow-down and anticipator features above described, the balance point is generally approached very quickly with only

one or two overshoots of rapidly diminishing amplitude. Since high speed recording is generally used with printing devices, this small amount of overshooting is of little significance. However, it is possible by careful adjustment of the phase and amount of the anticipator action to eliminate even this small amount of overshooting.

A further desirable result obtained by the use of the anticipator feature is its tendency to prevent sticking of the galvanometer. As is well known, a moving coil galvanometer is provided with end stops to limit the amount of deflection thereof. In a system of this character, when the amplitude of unbalance is large, the galvanometer current is proportionately large and the force pushing the galvanometer coil against the stops is frequently many times the normal force to which the coil is subjected. This results in a tendency of the coil to remain at the stops, even after the current has reduced and the balance point is approached. The result of this sticking of the galvanometer is to cause the balancing motor to badly overshoot until the galvanometer current reverses its direction, causing the coil to leave one stop and strike the other stop with considerable violence.

With the anticipator included, however, the galvanometer current is really composed of two parts, one due to the slide wire unbalance and the other due to the anticipator E. M. F. Since the latter component is always in a direction to move the galvanometer toward its equilibrium position and away from the stops, it tends to prevent sticking of the galvanometer. Moreover, during the rebalancing action, the current component due to the slide wire unbalance is decreasing, and the resultant force due to the anticipator current increases and tends to pry the galvanometer coil loose from its stops in the event that the sticking action occurs.

Obviously, the source of the anticipator E. M. F. may take forms other than that employed in Figure 1. For example, instead of employing the magnet and coil, an external source of E. M. F. may be employed utilizing a commutator on shaft **15** to insert the E. M. F. into the galvanometer circuit in proper sense. Other possible arrangements will be apparent to those skilled in the art.

A further feature of the invention resides in the particular construction of the scanning disk and the results obtained thereby. Referring to Figure 3, it will be convenient to refer to the circle **29** as the zero circle, since as mentioned above, this circle corresponds to the equilibrium position of the galvanometer, or, in other words, the position of zero deflection. The scanning disk should preferably be so constructed that the distance from the zero circle **29** to the point **41**, as well as the distance from the zero circle to the point **42**, is such as to allow the galvanometer spot to strike the edge of the photocell cathode about one-eighth inch inside the edges thereof. The end stops of the galvanometer should be set so that the spot of light will never leave the cathode no matter how large the galvanometer current. The edge portion of the disk between points **41** and **43** is a circular arc, with the center of the disk constituting the center of such arc. Likewise, the portion of the slot edge between points **42** and **44** is circular arc about the center of the disk. The edge portion of the disk between points **43** and **45** spirals uniformly inward to the zero circle **29**. The edge of slot **30** between points **44** and **46** spirals uniformly outward to the zero circle **29**. Since the various paths along the scanning disk traversed by the light spot are concentric circles, it will be seen that the action of the disk varies for different amplitudes of deflection of the light spot. Thus, for small deflections to the right, as viewed in Figure 3, only a portion of the slot **30** will be effective; while for small deflections to the left, only a portion of the edge **31** will be effective. The angle subtended by points **43** and **45**, as well as the angle subtended by points **44** and **46**, should preferably be approximately equal to and coordinated with the angle of each of the conducting segments of the commutator device **26**. Consequently, when the galvanometer unbalance is so small that the spot of light strikes either of the spirals **44—46** or **43—45**, the motor **5** will only operate in the slow-speed part of its cycle. This further minimizes any tendency to overshoot.

It is possible also to vary the operation of the system by adjusting the speed of rotation of the scanning disk. For example, in some instances a slow speed operation may be desirable. One such instance is the case where the system is employed as a recorder and a single curve is being drawn, in which case the reading can, of necessity, change only slowly. In this case the speed of the scanning disk may be reduced so that the time of travel of the disk between points **41** and **43**, and between points **42** and **44**, is about the same as the total crossing time for the contact carriage **7** over the screw **6**. The slow speed of the motor **5** may be arranged so that the galvanometer spot will travel from the point **43** to the zero circle **29** in about the time that the disk rotates through the angle subtended by points **43** and **45** (or the corresponding points on the inner spiral). In this way the galvanometer spot is led or guided to its equilibrium position at the zero circle **29**. Exact adjustment is unnecessary, since if the spot overruns its equilibrium position, due to the fact that the scanning disk is rotating too slowly, the relay **19** will open, thus stopping the motor **5** until the scanning disk catches up. Should the scanning disk rotate too fast, it will overrun the spot and pick it up on the next rotation. When the system is operated in this manner for slow-speed operation, it may be unnecessary to utilize the anticipator device above described.

A further advantage of the rotating scanning disk employed according to the invention is that it introduces a periodicity into the motion of the galvanometer spot different from its own period. The relative aperiodicity of the disk and galvanometer will tend to damp out the sustained oscillations to which the simple back-coupled system, including the galvanometer, photocell and balancing motor, would inevitably be subjected.

Referring to the system generally, it will be noted that nowhere in this system is any damping resistance introduced into the galvanometer circuit other than the unavoidable damping of the essential circuit elements, such as the slide wire resistance. The result of this is that the full galvanometer sensitivity is always utilized and the "dead" zone is minimized substantially to a vanishing point. Moreover, there are no critical adjustments which might change during operation. Even the galvanometer zero point, which should be at or near the zero circle **29**, is not critical, since with automatic standardizing at frequent intervals, a slow shift in this point is balanced out.

The adjustment of the photocell relay system

is likewise not critical, it being required only that the relay 19 drop out when the light is cut off from the photocell, and that the relay cut in when the light strikes the cell. For example, if the relay closes at 4 milliamperes and cuts out at 3 milliamperes, the certainty of operation is assured for a large change in line voltage and tube condition by causing the current through the relay to change from 1 milliampere, or less to about 8 milliamperes. Should the line voltage fluctuate, causing the intensity of light 11 to vary, there will be no significant change in the operation of the relay. It follows, of course, that there is no necessity for employing any voltage regulating means to compensate for variations in line voltage.

Referring now to Figure 4, there is illustrated a different embodiment of the invention in which reversing of the motor 5 is not under direct control of the scanning disk as in the case of Figure 1. In Figure 4 those elements corresponding to the elements of Figure 1 have been designated similarly, in this instance, two photocells 13a and 13b are employed in conjunction with the scanning disk 14a shown in Figure 6. The zero circle corresponding to the zero position of the galvanometer spot is shown at 29a. The scanning disk 14a has two spiral slots 47 and 48 cut therein within the zero circle 29a, and the disk is cut so as to provide outer spiral edges 49 and 50 outside the zero circle. When the light beam or galvanometer spot is deflected from its zero position to the left, as viewed in Figure 4, the photocell 13a is activated under control of the outer spiral edge of the disk 14a. On the other hand, when the light spot is deflected to the right, the photocell 13b is activated under control of the spiral edges of the slots or windows in the disk. The direction of operation of the motor 5 depends upon which photocell is activated.

In Figure 6, the scanning disk is shown with uniformly spiral edges, but as described above in connection with the first embodiment, it may be desirable to arrange these edges so that they have a circular and spiral portion. Thus, the outer edge portions between points 51 and 52 and between points 53 and 54 may be circular with respect to the disk center, while the portions between points 52 and 55 and between points 54 and 56 may be spiraled uniformly toward the zero circle. Likewise, the corresponding inner edge portions may be similarly constructed. Here again the spiral portions of the disk may correspond to the conducting segments of commutator 26, as previously described.

The photocells 13a and 13b operate their respective relays 19a and 19b through the two triode sections of the double triode tube 18a. It will be understood, of course, that two separate tubes may be employed if desired. The normally-closed contacts 57 and 58 of the respective relays are connected, respectively, to the motor input leads 32 and 33. Due to the normally-closed condition of these contacts, the motor is dynamically braked and is normally at standstill, as described above in connection with Figure 1. When one or the other of the relays is energized, however, the opening of the associated contact 57 or 58 causes energization of the motor through the contact which remains closed. For example, if relay 19a is energized, thereby opening contact 57, the motor is energized by way of input lead 33 through the closed contact 58. Thus, the relays 19a and 19b determine the direction of operation of the motor, the arrangement being such that the motor is operated in the proper direction for rebalancing. It will be seen, therefore, that the scanning disk 14a in this instance simply controls the activation of the photocells 13a and 13b, and the photocells select the appropriate relay, which in turn effects actuation of the motor 5 in the proper direction to rebalance the system. In this instance the commutator 25 employed in Figure 1 is dispensed with.

In the system of Figure 4, the anticipator feature is also modified. In this instance the rotatable magnet 27a has associated with it two diametrically-opposed coils 28a and 28b so arranged that when one of the magnet poles, say the north pole, is near the left coil 28a the current generated in that coil flows toward the junction point 59. The other coil 28b is wound in such direction that when the north pole of the magnet moves in its vicinity the current generated in the said coil flows toward the left, that is, toward the junction point 59. A double throw single pole switch 60 is actuated by a cam 61 which is mounted on shaft 15 with magnet 27a and is designed and arranged to alternately close circuits for the coils 28a and 28b. As illustrated, when the north pole of the magnet is at the left, contact is made at 62 and current flows in the closed circuit in the direction above mentioned. When the north pole moves to the right, the switch 60 closes at its other contact 63, thereby completing the circuit of coil 28b and causing current to flow in the direction above mentioned. This arrangement of the magnet and coils in association with the cam-operated switch is simply an elementary direct current generator.

A resistance 64 is connected as illustrated so as to be common to the circuits of the coils 28a and 28b. From the above discussion it will be seen that the current flow in resistance 64 will be in the same direction regardless of which coil is effective. The center point of resistance 64 is connected to the lower end of the potentiometer 10, while the ends of the resistance 64 are connected respectively to the normally-open contacts of relays 19a and 19b. The upper end of the potentiometer 10 is connected to both of the relay contacts 65 and 66.

By this arrangement, an anticipator E. M. F. is introduced into the galvanometer circuit by way of potentiometer 10 and the polarity of this E. M. F. will depend upon which of the relays 19a and 19b is energized which, in turn, is dependent upon which of the photocells 13a and 13b is activated. For example, assume that the voltage across resistance 64 is polarized as indicated. If relay 19a is energized by activation of photocell 13a, the relay contact 65 will close, thereby connecting the positive end of resistance 64 to the upper end of potentiometer 10. On the other hand, if relay 19b is energized by the action of photocell 13b, the relay contact 66 will close, thereby connecting the negative end of resistance 64 to the upper end of potentiometer 10. Thus the polarity of the anticipator E. M. F. is dependent upon the direction of unbalance of the normally-balanced network 1, and the E. M. F. is always in a proper direction to move the galvanometer 8 toward its equilibrium position.

It will be obvious that the unidirectional current in resistance 64 could be provided by means of a battery permanently connected across the resistance, instead of employing the generator arrangement. However, a battery would maintain the potential across resistance 64 constant, whereas in the arrangement illustrated this po-

tential pulsates according to the proximity of the coils 28a and 28b to the magnet poles. This pulsating effect is advantageous in that the phase relation of the magnet on the shaft 15 may be so adjusted that the potential across resistance 64 is zero when the scanning disk is in such position that the light beam near the zero position is passing to one or the other of the photocells. In other words, with the magnet and coil arrangement the anticipator E. M. F. can be caused to be a maximum when the galvanometer is far from its balance position, and the E. M. F. will approach zero when the galvanometer deflection approaches zero. Thus the magnitude and effect of the anticipator E. M. F. will vary automatically in accordance with the amplitude of the galvanometer deflection. Obviously this is of great advantage.

As will be apparent from Figure 6, the scanning disk 14a is adapted to initiate a rebalancing cycle twice during each revolution. Aside from this and the differences above described, the operation of the system is essentially the same as in the system of Figure 1. In this instance the motor slowdown feature is the same as in Figure 1, the commutator 26 being properly coordinated with the scanning disk and functioning in the same manner as described in connection with Figure 1.

In Figure 5 the rotating assembly is shown in mechanical form and will be understood from the foregoing discussion.

In Figures 7 and 8 there is illustrated an alternative form of electro-optical means which may be employed in the system of Figure 1, eliminating the scanning disk 14. In this instance, there are provided two light sources or lamps 11a and 11b which are alternately energized by means of the commutator 67. The energizing circuits for the lamps are readily traceable. The commutator 67 is continuously rotated by virtue of its being mounted on the shaft 15. The single photocell 13 is adapted to be activated by the light beam from one or the other lamps whenever the galvanometer deflects from its normal position. In the normal position of the galvanometer mirror 8, the light beams from the lamps strike the barriers 68 and 69. When the mirror is deflected a substantial amount in one direction or the other, the light beam from one or the other lamp impinges on the unscreened portion of the photocell, thereby activating the same. The photocell is connected to the amplifier tube as in Figure 1. Since the commutator 67 is mounted on the same shaft with the commutator 25, and the two are properly coordinated, the reversal of the lamps is coordinated with the action of commutator 25. Consequently, the direction of rotation of the balancing motor 5 will depend upon which light beam is effective in any instance, which in turn depends on the direction of deflection of the galvanometer. If the galvanometer is deflected far from its balance position, causing the effective light beam to fall in the space 70 between the barriers 68 and 69, the balancing motor should run throughout its cycle. However, if the galvanometer deflection is small, the starting of the balancing motor should preferably be delayed until the half revolution of the commutator 25 has almost terminated. This will bring the motor 5 into the slow-speed portion of its cycle, and will minimize overshooting. This desirable result is accomplished by causing the barriers 68 and 69 to have progressively decreasing density or opacity toward the intermediate space 70 and also by providing a second commutator 71 mounted on shaft 15 and so arranged that during the early part of the cycle, the resistance 72 is cut into one or the other of the lamp circuits, causing the lamp to glow feebly. As the commutator 71 rotates, the resistance 72 is short-circuited, thus causing the energized lamp to glow with full brilliancy. As an alternative, the commutator 71 and resistance 72 could be replaced by a continuously varying rheostat driven by the same shaft. The natural lag in the filament brightness of a lamp, however, makes the simple arrangement shown more satisfactory.

The photocell sensitivity and the lamp brightness, as well as the opacity of the barriers 68 and 69, are so arranged that when the energized lamp is glowing faintly, i. e., during the early part of the cycle, the relay 19 will close only if the galvanometer beam falls upon the middle exposed section of the photocell adjacent space 70. This corresponds to a large galvanometer deflection. If the galvanometer deflection is less however, the relay will close to start the balancing motor only in the latter part of the cycle when the resistance 72 has been short-circuited by the commutator 71 and the lamps are at full brilliancy.

The particular time of the cycle at which the motor will start, will, therefore, depend upon the degree of unbalance. For a small amount of unbalance, the motor will start late in its cycle, whereas for a large amount of unbalance, the motor will run during the complete cycle.

Since the commutator 25 rotates fairly rapidly, the barriers 68 and 69 can be replaced by a single barrier or uniform light transmission characteristic, instead of varying the light transmission, without noticeable change in the operation, provided that corresponding adjustments are made in the photocell sensitivity and in the brightness of the lamps. In such case, the light barrier may have a transmission characteristic of about sixty-five per cent of full light transmission.

It will be understood that the system of Figure 1 when modified according to Figure 7, will be the same as in Figure 1 except for the elimination of the scanning disk and the employment of the elements shown in Figure 7.

While various embodiments of the invention have been illustrated and described, it will be understood that further embodiments and modifications are possible without departing from the scope of the invention.

I claim:

1. A normally balanced control system, comprising a normally balanced electrical network, means in said network for producing a variable electrical potential to unbalance said network, adjustable means for producing in said network a balancing electrical potential, current-operated means in said network responsive to unbalance of said potentials, a motor for actuating said adjustable means, cyclically operative means for controlling said motor, means actuated by said current-operated means for governing the action of said motor-controlling means, means coordinated with said motor-controlling means for generating an electrical potential, and means operable by said governing means for applying said last-mentioned potential to said network.

2. A normally balanced control system, comprising variable means for unbalancing the system, adjustable means for rebalancing the system, a motor for adjusting said rebalancing means, detecting means responsive to unbalance of the system, means operable by said detecting

means for actuating said motor, cyclically operative means for controlling the operation of said motor-actuating means in dependence upon unbalance of the system, and means coordinated with said cyclically-operative means for reducing the speed of said motor during a predetermined portion of the operating cycle.

3. A normally balanced control system, comprising variable means for unbalancing the system, adjustable means for rebalancing the system, a motor for adjusting said rebalancing means, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for activation thereby, a continuously operable scanning disk constructed and arranged to variably control the activation of said electro-optical means by said detecting means according to the extent of unbalance of the system, and means coordinated with said scanning disk for controlling the operation of said motor according to the position of the scanning disk at the time of unbalance of the system.

4. A normally balanced control system, comprising variable means for unbalancing the system, adjustable means for rebalancing the system, a motor for adjusting said rebalancing means, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for activation thereby, said electro-optical means including a single light-responsive device and a pair of light sources whose effects are varied by said detecting means, cyclically-operable means for alternately energizing said light sources, means for causing the light from one or the other of said sources to activate said device in dependence upon the direction of unbalance of the system, means controlled by said device and coordinated with said cyclically-operable means for operating said motor in a direction dependent upon which light source is effective, and means for varying the light received by said device according to the degree of unbalance of the system so as to vary the operation of said motor in dependence upon the degree of unbalance.

5. A normally balanced control system, comprising variable means for unbalancing the system, adjustable means for rebalancing the system, a motor for adjusting said rebalancing means, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for activation thereby, a rotatable shaft, means for operating said shaft at a substantially constant speed, means operable by said shaft for controlling the activation of said electro-optical means, means operable by said electro-optical means for controlling said motor, means operable by said shaft for generating an electrical potential, and means for applying said potential to the system so as to reduce hunting thereof.

6. A normally balanced control system, comprising variable means for unbalancing the system, adjustable means for rebalancing the system, a motor for adjusting said rebalancing means, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for activation thereby, said electro-optical means including a single light-responsive device and a pair of light sources whose effects are varied by said detecting means, means for alternately energizing said light sources, means for causing the light from one or the other of said sources to activate said device in dependence upon the direction of unbalance of the system, means controlled by said device for operating said motor in a direction dependent upon which light source is effective, and means for varying the light received by said device according to the degree of unbalance of the system so as to vary the operation of said motor in dependence upon the degree of unbalance.

7. A normally balanced control system, comprising variable means for unbalancing the system, means for rebalancing the system, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for controlling said rebalancing means, scanning means for controlling said electro-optical means, means for applying an electrical potential to the system to reduce hunting, and common driving means for operating said scanning means and said last-named means in predetermined positional relation with one another.

8. A normally balanced control system, comprising variable means for unbalancing the system, means for rebalancing the system, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for controlling said rebalancing means, a scanning disk for controlling said electro-optical means, means including an electrical generator for applying an electrical potential to the system to reduce hunting, and common drive means for operating said scanning disk and said generator in predetermined positional relation with one another.

9. A normally balanced control system, comprising variable means for unbalancing the system, means for rebalancing the system, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for controlling said rebalancing means, a scanning disk for controlling said electro-optical means, said disk being solid along a circle corresponding to the equilibrium condition of the system, and having eccentric control areas inside and outside said circle which vary the control of said electro-optical means according to the extent of unbalance of the system at any time, and means for rotating said disk continuously during the operation of the system.

10. A normally balanced control system, comprising variable means for unbalancing the system, means for rebalancing the system, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for controlling said rebalancing means, a scanning disk for controlling said electro-optical means, said disk being solid along a circle corresponding to the equilibrium condition of the system, and having eccentric control areas inside and outside said circle which vary the control of said electro-optical means according to the extent of unbalance of the system at any time, means for rotating said disk continuously during the operation of the system, and means operable by said last means in coordination with said scanning disk for controlling the direction of rebalancing according to whether the inside or outside area of the disk is effective.

11. A normally balanced control system, comprising variable means for unbalancing the system, means for rebalancing the system, detecting means responsive to unbalance of the system,

electro-optical means arranged cooperatively with said detecting means for controlling said rebalancing means, said electro-optical means including a pair of light-responsive devices and a light source, a scanning disk for controlling said electro-optical means, said disk being solid along a circle corresponding to the equilibrium condition of the system, and having eccentric control areas inside and outside said circle which vary the light impinging on the respective light-responsive devices according to the extent of unbalance of the system at any time, and means for rotating said disk continuously during the operation of the system.

12. A normally balanced control system, comprising variable means for unbalancing the system, adjustable means for rebalancing the system, a motor for adjusting said rebalancing means, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for activation thereby, means operable by said electro-optical means for controlling said motor, a rotatable shaft, means for operating said shaft at a substantially constant speed, a scanning disk on said shaft for controlling the activation of said electro-optical means, said disk having different areas of control for different directions of unbalance of the system, and means operable by said shaft for controlling the direction of operation of said motor according to which of said disk areas is effective.

13. A normally balanced control system, comprising variable means for unbalancing the system, adjustable means for rebalancing the system, a motor for adjusting said rebalancing means, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for activation thereby, a rotatable shaft, means for operating said shaft at a substantially constant speed, means operable by said shaft for controlling the activation of said electro-optical means, means operable by said electro-optical means for controlling said motor, and means operable by said shaft for reducing the speed of said motor during a predetermined portion of the rebalancing cycle.

14. A normally balanced control system, comprising variable means for unbalancing the system, adjustable means for rebalancing the system, a motor for adjusting said rebalancing means, detecting means responsive to unbalance of the system, electro-optical means arranged cooperatively with said detecting means for activation thereby, a rotatable shaft, means for operating said shaft at a substantially constant speed, means operable by said shaft for controlling the activation of said electro-optical means, means operable by said electro-optical means for controlling said motor, means operable by said shaft for reducing the speed of said motor during a predetermined portion of the rebalancing cycle, means operable by said shaft for generating an electrical potential, and means for applying said potential to the system so as to reduce hunting thereof.

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