Jan. 23, 1962 T. H. BONN 3,018,419

REGENERATIVE ACTUATOR DRIVE CURCUITS

Filed Sept. 26, 1955

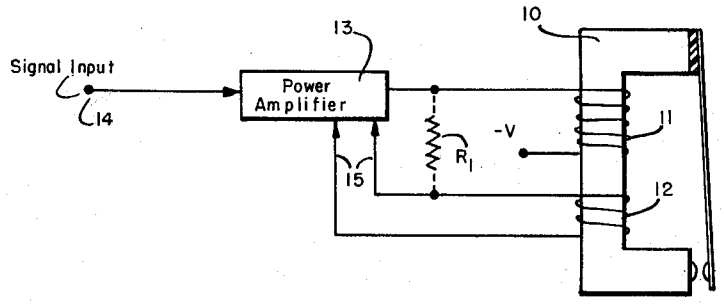


FIG. 1.

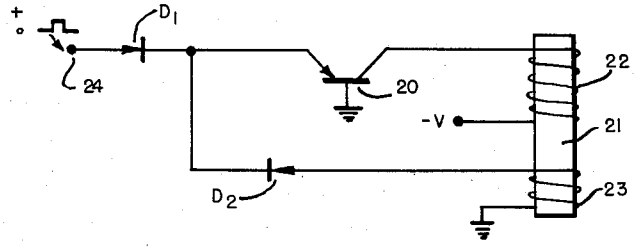


FIG. 2.

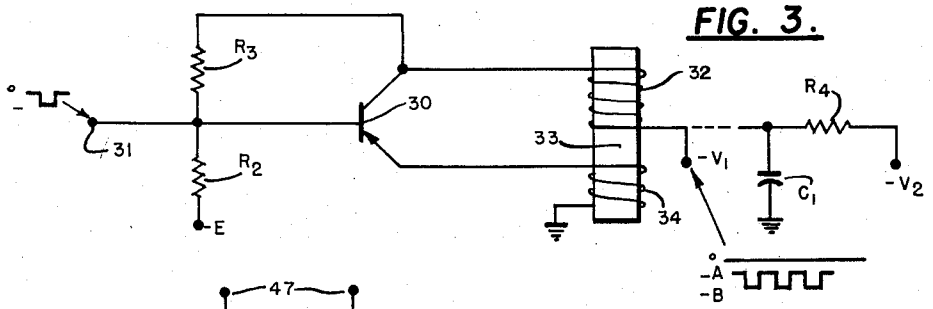


FIG. 3.

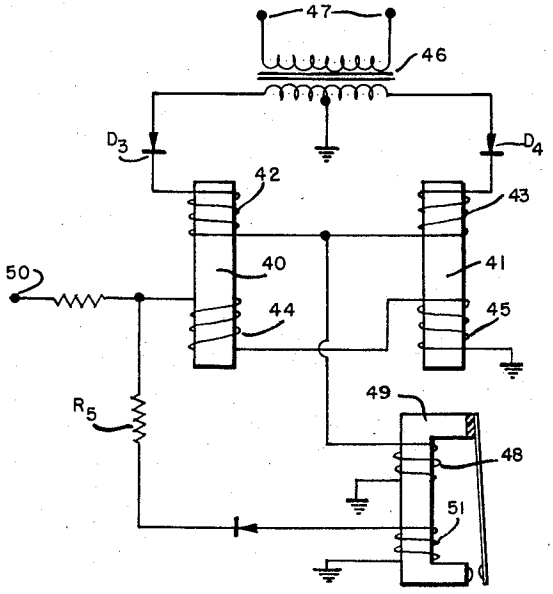


FIG. 4.

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United States Patent Office 3,018,419
Patented Jan. 23, 1962

3,018,419

REGENERATIVE ACTUATOR DRIVE CIRCUITS

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Filed Sept. 26, 1955, Ser. No. 536,386
21 Claims. (Cl. 317—148.5)

The present invention relates to novel electromechanical actuators and to improved drive circuits therefor; and is more particularly concerned with a control structure utilizing an electromechanical actuator wherein feedback is provided between the actuator device and a driving source, thereby to improve the over-all operating characteristics of the combination.

In the driving of electromechanical actuator devices such as relays, solenoids, stepping switches, print hammer actuators and the like, it is ordinarily the practice to provide an actuator comprising a core of magnetic material having a control winding thereon; and to selectively couple current to the said control winding in response to the presence or absence of a signal. This driving of electromechanical actuators has in the past been accomplished by power amplifiers normally exhibiting a substantially constant gain. Inasmuch as electromechanical actuators known to the present time are normally characterized in their operation by the requirement that actuating power be somewhat in excess of holding power, the provision of constant gain drive sources has resulted in inefficient operation due primarily to the fact that, since the drive source must supply sufficient power for actuating the device, there is ordinarily excessive power dissipation in the drive source during a holding operation. Actuator drive circuits, known to the present time, have therefore been characterized by drive circuits which are relatively costly in operation; which ordinarily require a relatively large signal input for actuator operation; and which effect relatively slow operation of the electromechanical actuator employed.

The present invention serves to obviate these disadvantages of known actuator drive circuits by providing a novel electromechanical actuator including a feedback winding thereon. This feedback winding is preferably coupled to the driving source whereby increased power is supplied to the actuator during an initial actuator operation, and decreased power is supplied to the said actuator during a holding operation. In accordance with modifications of the present invention, such as will be described, improved drive circuits are also provided for use in the driving of electromechanical actuators whereby the aforementioned feedback is utilized to automatically turn off the driving source when the drive output has reached a maximum thereby to provide self-timing electromechanical actuators.

It is accordingly an object of the present invention to provide an improved electromechanical actuator.

A further object of the present inveniton resides in the provision of improved actuator drive circuits which are less expensive in operation than those known heretofore.

Another object of the present invention resides in the provision of actuator drive circuits providing greater power amplification during desired operating times than has been the case in the past.

A further object of the present invention resides in the provision of electromechanical actuator circuits having increased sensitivity.

A still further object of the present invention resides in the provision of actuator circuits which are self-timing in operation.

Still another object of the present invention resides in the provision of electromechanical actuator circuits which require less power from a signal source for the driving of an actuator, and which are more reliable in operation than has been the case in the past.

In providing for the foregoing objects and advantages, the present invention provides an improved electromechanical actuator, for instance of the types mentioned previously, which comprises a core of magnetic material carrying a pair of windings inductively coupled to one another. A signal responsive drive circuit is coupled to one of the said windings for selectively producing a flux change in the core thereby to effect operation of the actuator; and the other of the said windings is coupled to the said drive circuit whereby potentials induced in the said other of said windings, in response to flux changes in the core, are fed back in a proper sense to modify the operation of the said drive circuit in a preselected manner.

In accordance with one embodiment of the present invention, this feedback from the second winding to the drive circuit may be positive in nature whereby the driving source supplies maximum power to the actuator during an initial buildup period, and the said driving source thereafter supplies reduced holding power to the said actuator once the flux in the actuator core reaches a desired maximum value. In accordance with another modification of the present invention, which may be employed in combination with the first described modification, the said feedback may change to a negative direction once the flux in the actuator core reaches a maximum and commences to decay. Consequently the drive source is forcibly turned off thereby causing the actuator to revert to an initial operating condition.

The foregoing objects, advantages, construction and operation of the present invention will become more readily apparent from the following description and accompanying drawings, in which:

FIGURE 1 is a generic representation of an actuator drive circuit constructed in accordance with the present invention.

FIGURE 2 is a schematic diagram of an actuator drive circuit employing a transistor for drive purposes.

FIGURE 3 is a modification of the circuit shown in FIGURE 2 illustrating possible variations in the transistor drive as well as in the energization sources and feedback paths which may be provided; and

FIGURE 4 is a still further modification of the present invention illustrating an actuator drive circuit employing a magnetic amplifier for drive purposes.

Referring now to FIGURE 1, it will be seen that, in accordance with the present invention, an improved electromechanical actuator may comprise a core **10** of magnetic material carrying first and second windings **11** and **12** thereon. In the particular example illustrated in FIGURE 1, the actuator utilizing core **10** has been illustrated as a relay, but it must be understood that this particular representation is for purposes of illustration only and that the actuator may comprise other electromechanical devices having magnetic cores such as solenoids, stepping switches, etc. Winding **11** acts as a main control winding for the actuator and the said winding **11** is coupled at one of its ends to a source of potential —V and is coupled at the other of its ends to the output of a power amplifier **13**. Amplifier **13** may take the form of a vacuum tube, a transistor, a thyratron, a magnetic amplifier, or other amplifier devices known in the art and normally exhibiting a substantially constant power gain; and the said amplifier **13** is responsive to signal inputs appearing at a terminal **14**. The elements **10**, **11**, **13** and **14** thus correspond to a substantially conventional electromechanical actuator; and in operation, signal inputs applied to terminal **14** produce outputs from the amplifier **13** thereby effecting current flow through the wind-

ing 11 and an associated flux change in core 10 for the operation of the actuator employing the said core 10.

In accordance with the improvement of the present invention, the further winding 12 carried by core 10 is inductively coupled to the main control winding 11 whereby flux changes in core 10 induce potentials in the said winding 12, and these induced potentials are returned to power amplifier 13 through a feedback path 15 thereby to modify the normal operation of the amplifier 13. It will be appreciated that the direct connection of winding 12 and feedback channel 15 to the power amplifier 13 may be modified by the inclusion of other feedback paths such as resistor R1.

As modified, the improved actuator circuit shown in FIGURE 1 operates to vary the power input to the actuator utilizing core 10 during preselected portions of the operating cycle. In the illustration of FIGURE 1, winding 12 is such that it provides regenerative feedback to the amplifier 13 whereby during an initial time period when the amplifier 13 is supplying actuating current to winding 11, thereby producing a flux build-up in core 10, the regenerative feedback supplied by winding 12 assures that maximum power is supplied to winding 11. When the actuator utilizing core 10 completes its initial operation, for instance the relay closes, the flux in core 10 tends to stabilize at a predetermined maximum value and this stabilization in flux in turn results in no further potentials being induced in winding 12 whereby the regenerative feedback ceases. Thus, by the provision of regenerative feedback, in the manner discussed, the drive circuit supplies maximum power during initial build-up periods in response to a signal input applied at terminal 14, and thereafter provides reduced power sufficient to hold the actuator, once a desired actuator operation has been completed.

It will be appreciated that in actuators of the type described, the current in winding 11 supplied by power amplifier 13, will decrease in magnitude after a maximum value has been reached; and this decrease in current in turn effects a flux reversal in core 10 once maximum power has been achieved. The flux reversal in turn induces a potential of opposite polarity in feedback winding 12 and this opposite polarity potential may be blocked by an appropriate rectifier circuit in certain modifications of the present invention, or may be employed as feedback in a negative direction to the amplifier 13 for rapidly turning off the said amplifier thereby to produce a self timing electromechanical actuator circuit.

This operation will become more readily apparent from a consideration of the particular circuit shown in FIGURE 2, wherein the power amplifier takes the form of a transistor 20. The actuator once more is represented as a core 21 of magnetic material, having a main control winding 22 and a feedback winding 23 thereon. Winding 22 is coupled at one of its ends to a source of negative potential —V; and is coupled at the other of its ends to the collector of transistor 20. Signal inputs appearing at a terminal 24 may be applied via rectifier D1, poled as shown, to the emitter of transistor 20; and the aforementioned feedback potentials may be coupled from feedback winding 23 via a further rectifier D2 to the said emitter of transistor 20.

In the particular example of FIGURE 2, the transistor 20 comprises a PNP type transistor in a grounded base circuit. It will be apparent to those skilled in the art that NPN type transistors, and transistors of both the point contact and junction types may be employed; and that circuits other than the grounded base connection can be utilized.

When the particular arrangement shown in FIGURE 2 is employed, a positive-going input signal applied at terminal 24 effects current flow to the emitter of transistor 20 whereby drive current passes from the collector of the said transistor 20, via main control winding 22, to the source of negative potential —V. As current commences flowing through winding 22, the flux in core 21 increases in magnitude and this increasing flux induces a potential in winding 23 which may be coupled via rectifier D2 back to the emitter of transistor 20 as regenerative feedback. Thus, upon application of a signal to terminal 24, the power output of transistor 20 rapidly builds to a maximum thereby supplying maximum drive to the actuator utilizing core 21.

After this initial build-up period, and due to saturation of either transistor 20 or core 21, the flux in core 21 achieves a predetermined maximum value; and the lack of further flux change results in no further potential being induced in feedback winding 23. Due to the lack of feedback via rectifier D2, the output of transistor 20 will tend to decrease whereby the power input to winding 22 will fall below its initial maximum value. The actuator employing core 21 may be maintained in its actuated condition, for instance by an auxiliary holding contact; or may be held in its actuated condition by a signal input still appearing at terminal 24. If this latter form of the invention is employed, it will be appreciated that the requirements of the signal source applied to terminal 24 must be sufficient to provide the desired holding current; but such a requirement represents a substantial improvement over circuits known in the past, inasmuch as the signal source alone does not have to supply the increased power necessary for initial actuation of the device.

Due to the decreased output of transistor 20 once maximum power has been achieved, the flux in core 21 will fall below its initial maximum value and this reversal in flux induces a potential of opposite polarity in feedback winding 23. In the particular example shown in FIGURE 2, this reversed potential disconnects rectifiers D2 whereby there is no feedback in the negative direction to transistor 20, and the circuit operates in the manner described, wherein a signal applied to terminal 24 causes transistor 20 to provide sufficient output to hold the actuator in a desired operating state. In many cases, however, it is desirable to open the actuator rapidly once the current in an actuator control winding has reached its peak value; and such operation may be readily achieved by employing a circuit of the type illustrated in FIGURE 2, through the elimination of rectifier D2.

When this modified form of the invention is employed, an initial signal input applied to terminal 24 will once more commence driving current through winding 22 thereby inducing a positive feedback potential in winding 23 so that the power input to the actuator rises rapidly to a desired maximum value. The reversal in flux after this maximum value is achieved, will in turn provide feedback in a negative direction to the transistor 20 (or to whatever other form of power amplifier is employed), thereby forcibly turning off the power amplifier to deenergize the actuator rapidly. When a transistor such as 20 is employed, it should further be noted that this feedback in a negative direction, in addition to forcibly turning off the transistor 20, also tends to absorb minority carriers still existing in the semiconductor material comprising transistor 20, thereby speeding up the decrease of current in the actuator. As a result, the permissible repetition rate of the self-timing actuator circuit provided is considerably increased.

FIGURE 3 illustrates another form of regenerative actuator drive circuit which may be employed in accordance with the present invention. The power amplifier employed once more comprises a transistor 30, but in the particular example illustrated in FIGURE 3, signal inputs appearing at terminal 31 are coupled to the base of transistor 30 rather than to the transistor emitter, as was the case in FIGURE 2. Output current from the transistor once more flows via the collector of the said transistor to a power control winding 32 carried on an actuator core 33; and as before, feedback potentials induced in winding 34 in response to flux changes in the said core 33 are returned to the transistor. In the example of

FIGURE 2, the signal input and regenerative feedback were applied to the same transistor electrode. In accordance with the modification shown in FIGURE 3, however, different electrodes of the transistor may be employed, whereby the signal input may be coupled, as shown, to the transistor base, while the regenerative feedback is injected into the transistor emitter.

The actuator drive circuit shown in FIGURE 3 is further characterized by the provision of auxiliary feedback in the transistor **30**; and this auxiliary feedback may be supplied by the voltage divider network comprising resistors R2 and R3 connected as shown between a first source of potential —E and, via the winding **32**, to a second source of potential $-V_1$. The potential sources —E and $-V_1$, as well as the resistors R2 and R3, are so chosen that a desired quiescent potential is maintained on the base of transistor **30**, and a desired auxiliary feedback is effected via resistor R3 once a negative-going signal is applied to terminal **31**.

As has already been discussed, it is often the requirement in actuator circuits that a high current be supplied to the actuator at the beginning of the actuation cycle; and by the same token, it is often required that a high voltage be supplied during this initial actuation period in order to establish the required current in the inductance of the actuator. In the examples thus far described, it has been assumed that one end of the main control winding, such as **11**, **22** and **32**, is returned to a substantially constant potential such as —V. As a matter of practice, however, it has been found that when such a constant potential source is employed, the magnitude of this source must be sufficient to provide the initial high voltage across the actuator control winding; and this initial magnitude of potential, as a result, may be excessive once a holding operation only is desired. If a constant voltage return is employed, therefore, excessive power dissipation may occur in the power amplifier during a holding period; and when the said power amplifier comprises a transistor, the dissipation requirements of such a transistor may well be raised to too high a value.

This difficulty may be overcome, in accordance with the present invention, by causing the potential source coupled to one end of the actuator control winding to exhibit a selectively variable magntude. Thus, in the example of FIGURE 3, the source $-V_1$ may comprise a clock pulse source varying between a first negative potential —A and a second more negative potential —B. The operation of the system in such a case would permit signal inputs during time intervals when the potential source $-V_1$ is at its —B value, whereafter the said potential return source $-V_1$ would decrease to its smaller negative potential —A during a holding period, thereby reducing the power dissipation in transistor **30** during such holding time intervals.

In accordance with a still further modification illustrated in FIGURE 3, the pulse type power supply represented by source $-V_1$, may be replaced by a further variable power source comprising a capacitor C_1 and a resistor R4, returned to a substantially constant negative potential $-V_2$. When this form of variable power supply is provided, the source $-V_2$ charges capacitor C_1 via resistor R4 during time intervals when no signal input is applied to terminal **31**; and the application of a signal input to the said terminal **31** thus permits the initial peak of current desired to be supplied from the capacitor C_1 whereafter a relatively small holding current may be supplied from the source $-V_2$ via the resistor R4. In accordance with this alternative form of the invention, therefore, capacitor C_1 will be charged to substantially V_2 during time periods when the actuator is "off"; and the source $-V_2$, in combination with resistor R4, thereafter supplies the relatively small holding current required once the actuator is actually operated.

The circuits described above relate particularly to transistor drive elements, but other forms of drive elements may be employed, and these may take the forms already mentioned. FIGURE 4 depicts one such alternative form of drive circuit employing a carrier type magnetic amplifier. Such a magnetic amplifier comprises a pair of cores **40** and **41** respectively carrying power or output windings **42** and **43**, and also carrying signal or input windings **44** and **45**. A first end of the output windings **42** and **43** are coupled in conventional manner via rectifiers D3 and D4 to the center tapped secondary of a transformer **46** having its primary winding coupled to a source **47** of carrier potential. The other or lower ends of windings **42** and **43** are coupled to an actuator control winding **48** carried by a core **49** whereby actuator driving current may be selectively supplied by the magnetic amplifier in response to signal inputs appearing at a terminal **50**. As before, the actuator core **49** also carries a feedback winding **51** coupled via a resistance R5 to the magnetic amplifier input whereby the circuit operates in a manner analogous to those already described.

It will be appreciated that in the particular example of FIGURE 4, the regeneration potential appearing across actuator feedback winding **51** is applied to the same input windings, namely **44** and **45**, that are coupled to the source of input signals **50**. In accordance with an alternative construction, a further pair of regeneration windings may be placed upon the amplifier cores **40** and **41**, and the regenerative feedback potentials appearing across winding **51** may be coupled to such auxiliary regeneration windings in the magnetic amplifier.

In each of the several embodiments described above, the provision of regeneration causes the actuator drive circuit to supply maximum power to the actuator during an initial buildup period, and thereafter permits decreased holding power to be supplied by the drive circuit with the attendant advantages achieved by such operation. While preferred drive circuits operating in this manner have been described, many variations are possible, and certain of these variations have already been discussed in respect to the possible forms of electromechanical actuator and the various froms of power amplifier which may be employed, as well as in respect to the various feedback connections and potential sources which may be utilized.

Other variations are also possible, and in particular, reference is made to the copending application of John Presper Eckert, Jr., Serial No. 524,844, filed July 28, 1955, now Patent No. 2,831,985, for: "Amplifier With Feedback"; which copending application is assigned to the assignee of the instant application. The aforementioned Eckert copending application, while not concerned with the driving of electromechanical actuators of the type here involved, does teach a novel amplifier feedback system employing a plurality of gates in combination with selectively timed pulsing sources; and such an improved amplifier circuit may be employed in achieving the advantages of the present invention by utilizing the said amplifier circuit for the driving of actuators including feedback windings, as discussed above.

Other modifications will be suggested to those skilled in the art, and it must therefore be understood that the foregoing description is meant to be illustrative only and should not be considered limitative of my invention; and all such modifications as are in accord with the principles discussed, are meant to fall within the scope of the appended claims.

Having thus described my invention, I claim:

1. In a control circuit, an electromechanical actuator device comprising a core of magnetic material having a mechanical element adjacent thereto and movably responsive to predetermined flux changes in said core, an actuator control winding on said core, an auxiliary winding on said core, an amplifier coupled to said control winding for selectively driving current therethrough, and means coupling said auxiliary winding to said amplifier thereby to provide regenerative feedback to said ampli-

fier as the current in said control winding changes in magnitude thereby to increase the driving output of said amplifier as the magnitude of flux changes in a predetermined sense.

2. The circuit of claim 1 wherein said actuator device comprises a relay.

3. The circuit of claim 1 wherein said amplifier comprises a transistor.

4. The circuit of claim 1 wherein said actuator control winding is coupled at one of its ends to said amplifier, said control winding being coupled at the other of its ends to a source of variable D.C. potential.

5. The control circuit of claim 1 wherein said means coupling said auxiliary winding to said amplifier includes a rectifier, said rectifier being so poled that it is rendered conductive by potentials induced in said auxiliary winding as the flux in said core increases in magnitude.

6. In a control circuit, an actuator device comprising a core of magnetic material having first and second windings inductively coupled to one another, a mechanically movable element adjacent said core and movable between first and second positions in response to variations in the amount of flux in said core, an amplifier having its output coupled to said first winding, signal means coupled to the input of said amplifier whereby said amplifier selectively drives actuator control current through said first winding thereby to tend to move said element from one to another of said first and second positions, and means coupling potentials induced in said second winding to said amplifier thereby to provide feedback to said amplifier to vary the magnitude of said actuator control current whereby the amount of flux in said core rapidly changes when said element tends to move from one to the other of said first and second positions.

7. The circuit of claim 6 wherein said last named means comprises a rectifier coupling said second winding to said amplifier whereby feedback to said amplifier is effected only as said actuator control current is changing in a predetermined sense.

8. The circuit of claim 7 wherein said rectifier is poled to provide positive feedback to said amplifier as said actuator control current increases in magnitude.

9. The circuit of claim 6 wherein said amplifier comprises a transistor.

10. The circuit of claim 6 wherein said amplifier comprises a magnetic amplifier.

11. In a control circuit, an electromechanical actuator device comprising a core of magnetic material having first and second windings thereon, signal responsive drive means coupled to said first winding for selectively passing current therethrough thereby to effect a flux change of predetermined sense in said core for actuating said electromechanical device, said flux change inducing a potential in said second winding, and means coupling the potential induced in said second winding to said drive means for providing regenerative feedback to said drive means whereby the output of said drive means increases thereby to accelerate said flux change in said predetermined sense.

12. The circuit of claim 11 wherein said drive means comprises a transistor having first and second electrodes, a signal source coupled to said first electrode, and means coupling said second electrode to one end of said first winding.

13. The circuit of claim 12 wherein the potential induced in said second winding is coupled to said first electrode.

14. The circuit of claim 12 wherein said transistor includes a third electrode, the potential induced in said second winding being coupled to said third electrode.

15. The circuit of claim 14 including further feedback means between said first and second electrodes.

16. The circuit of claim 11 wherein signals are coupled to said drive means during selected ones of a plurality of spaced time intervals, said drive means being coupled to one end of said first winding, and a source of variable potential coupled to the other end of said first winding, said source having a first magnitude during said spaced time intervals and having a different magnitude intermediate said spaced time intervals.

17. In a control circuit, an electromechanical actuator device having a core of magnetic material, a mechanical element movable between first and second predetermined positions in response respectively to flux changes of first and second opposite senses in said core, signal responsive drive means coupled to said actuator device for effecting a flux change of predetermined sense in said core thereby to operate said actuator device so that said mechanical element tends to move from a selected one to the other of said predetermined positions, and means coupling said core to said drive means for applying feedback to said drive means in response to changes in flux in said core thereby to increase the power output of said drive means as said element moves from said selected one to the other of said predetermined positions.

18. In a control circuit, an electromechanical actuator device having a core of magnetic material, a mechanical element movable between first and second predetermined positions in response to flux changes in said core, first and second windings on said core inductively coupled to one another, drive means coupled to said first winding, signal means coupled to said drive means for selectively causing said drive means to produce an output thereby to effect a flux change in said core, the power output produced by said drive means in response to operation of said signal means normally being insufficient to move said element from said first to said second position when said element is in said first position, but being sufficient to hold said element in said second position when said element is in said second position, and means coupling potentials induced in said second winding, in response to flux changes in said core, to said drive means thereby to increase the power output of said drive means when said flux change in said core is of a sense tending to move said element from said first to said second position whereby said signal means and said potentials in said second winding cooperate to effect a power output from said drive means of sufficient magnitude to move said element from said first to said second position.

19. An electromechanical actuator comprising a core of magnetic material, a mechanical element adjacent to said core and movable in response to predetermined changes in flux density in said core, an actuator winding linking said core, signal input receiving means, amplifier means coupled to said signal input receiving means and to said actuator winding to produce changes in the flux density in said core in response to signal inputs, a feedback winding linking said core, means coupling said feedback winding regeneratively to said amplifier means, whereby the potentials induced in said feedback winding by said changes in the flux density in said core produce further changes of said flux density to move said mechanical element.

20. An electromechanical actuator comprising input signal receiving means, amplifier means, an actuator winding, a movable mechanical element positioned in a flux responsive orientation with said actuator winding, means coupling said amplifier means to said input signal receiving means and to said actuator winding in manner to produce a change in the amount of flux linking said actuator winding in response to input signals impressed on said input signal receiving means, and a feedback winding inductively coupled to said actuator winding and connected to said amplifier means in a regenerative sense, whereby said change in the flux linking said actuator winding initiates a regenerative action to modify the flux in the same sense to effect movement of said mechanical element.

21. A relay device comprising a transistor amplifier, the input of which is connected to the input of the relay device, and an electro-magnetic relay, characterized by the electro-magnetic relay being provided with a main winding which is connected to the output of the amplifier and with an auxiliary winding which is connected to the input of the transistor, the auxiliary winding being arranged in such a way that a positive feed back is obtained from the output to the input of the amplifier, and by a rectifier being connected in series with the auxiliary winding and the input circuit of the transistor in such a way that the input impedance of the device is high for control signals at the same time as a low impedance is obtained for the feed back current.

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