March 24, 1964 J. FLORA 3,126,501

MAGNETIC ACTUATORS

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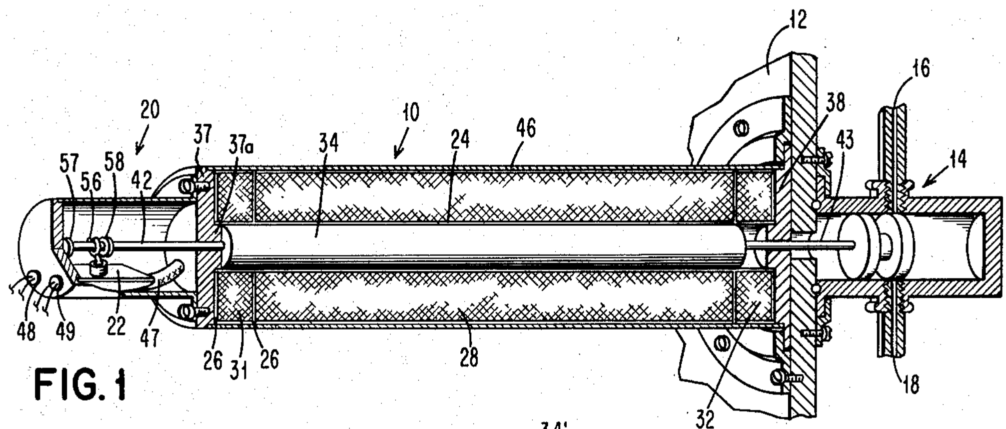

FIG. 1

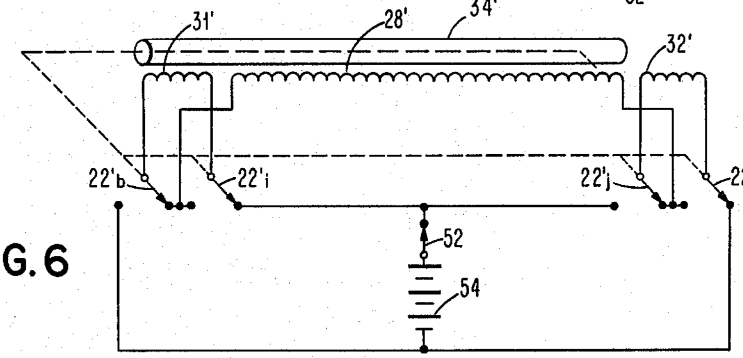

FIG. 6

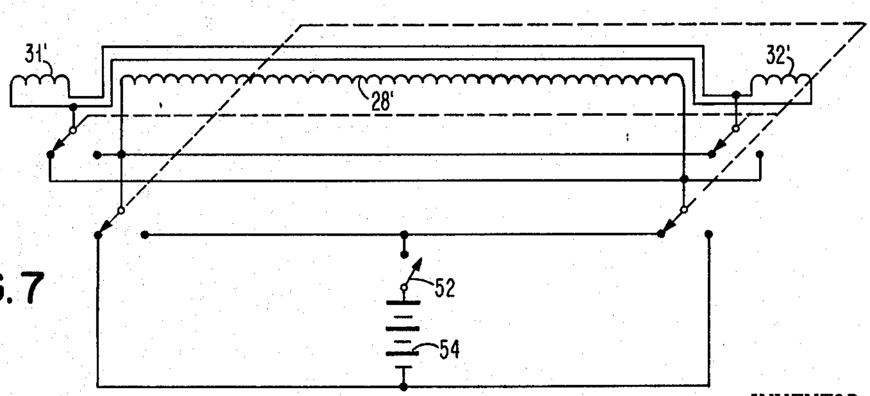

FIG. 7

INVENTOR.
JAMES FLORA

BY [signature]

ATTORNEY

MAGNETIC ACTUATORS

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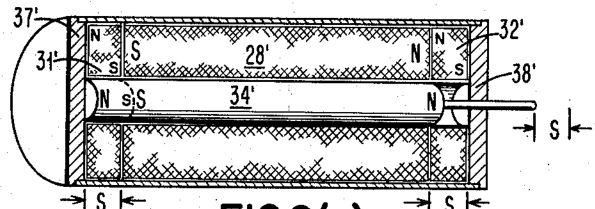

FIG.2(a)

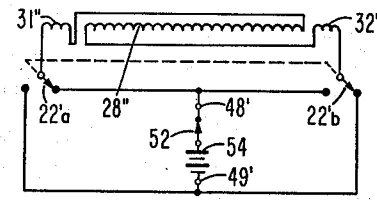

FIG.3(a)

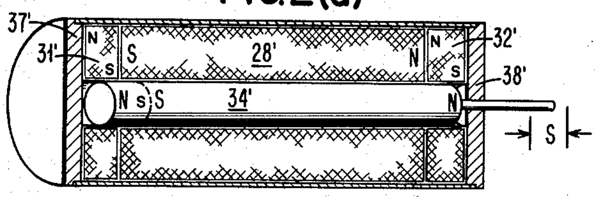

FIG.2(b)

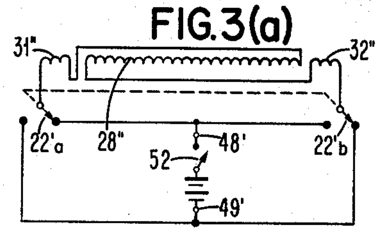

FIG.3(b)

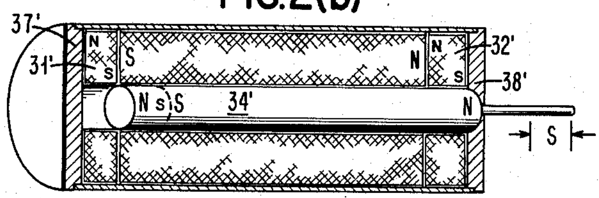

FIG.2(c)

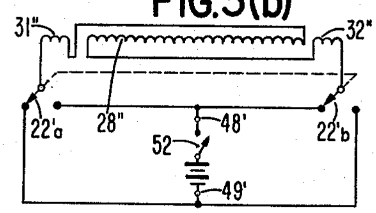

FIG.3(c)

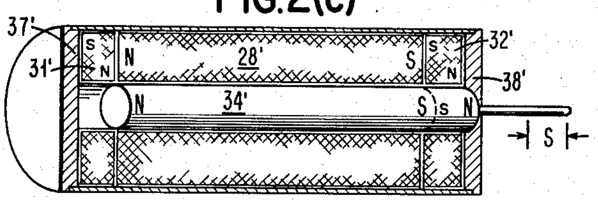

FIG.2(d)

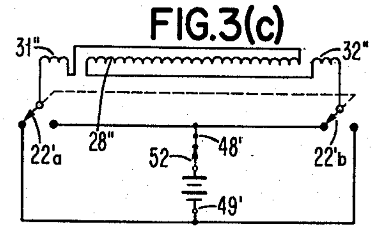

FIG.3(d)

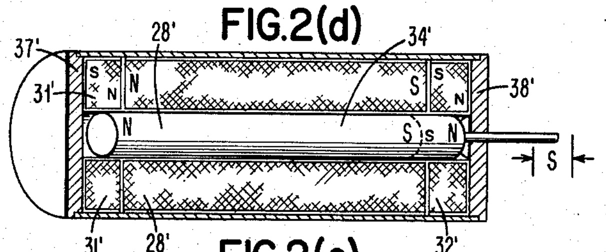

FIG.2(e)

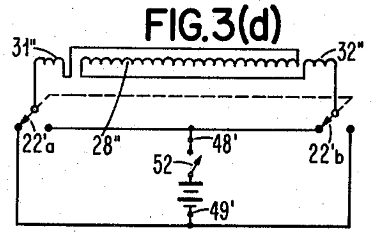

FIG.3(e)

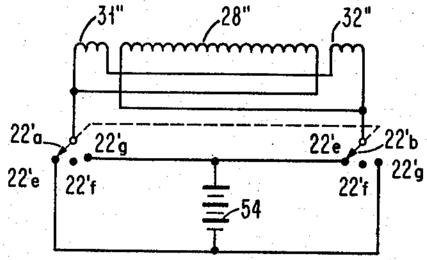

FIG.4

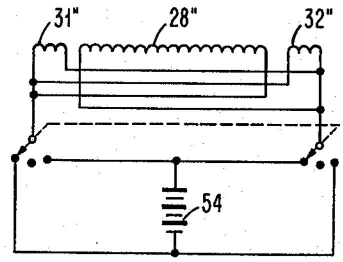

FIG.5

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MAGNETIC ACTUATORS

James Flora, Santa Clara, Calif., assignor to International Business Machines Corporation, New York, N.Y., a corporation of New York

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8 Claims. (Cl. 317—154)

The invention relates to magnetic actuators, and it particularly pertains to magnetic actuators requiring no current for holding the armature in position.

Conventional electromagnetic actuating devices leave something to be desired in the way of size limitations and heat and power dissipation. Frequently the use of a magnetic actuator must be foregone because the space intended for the actuator is either physically too small or insufficiently ventilated. In addition to the effect of excessive heating due to the passage of holding current, the problem of supplying holding current is sometimes a serious consideration in the choice between electromagnetic and other types of actuators.

An object of the invention is to provide an electromagnetic actuator of smaller size and dissipating less heat and power than the conventional devices.

Another object of the invention is to provide a magnetic actuator which requires no holding current, yet provides greater tractive and repelling forces than conventional actuators of similar size.

According to the invention the need for holding current is obviated by the use of an armature of material of high retentivity, such as a permanent magnet, arranged for longitudinal movement between a pair of holding members of material of low retentivity and high permeability to which the permanent magnet armature adheres firmly. An electromagnetic winding is disposed about the armature centrally of the holding members for moving the armature from one holding member to the other. Further electromagnetic windings are disposed about the armature adjacent and between the holding members and armature moving winding. The further winding about the end of the armature in contact with one of the holding members is arranged in electromagnetic opposition to the moving winding. Current flow through the further winding is effective to form a short magnet, preferably of length no greater than the cross-sectional dimension of the armature, and thereby a relatively weak magnet, thus releasing the hold of the permanent magnet armature to the holding member. At the same time current flow through the moving winding is effective to form a longer and stronger magnet, preferably of length ten or more times greater than the cross-sectional dimension of the armature, and to exert sufficient tractive force on the armature to propel it away from the first holding member and into contact with the other holding member. Armature movement in the reverse direction is obtained by reversing the polarity of the applied potential. According to the invention the armature may be of a length such that it is surrounded only by the moving winding and one of the further windings. In this case the current is applied only for a portion of the movement of the armature and is interrupted as the armature moves into the field generated by the other releasing winding. In this there is little or no effect on propulsion of the armature by the releasing winding into the field of which the armature is moved and both releasing windings may be electrically connected in the operating circuit at all times.

Further according to the invention increased speed of operation and other advantages are obtained by switching the connections of the further windings so that one of them is connected in opposing relationship to the moving winding and serves as a releasing winding while the

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other of them is connected in aiding relationship to the moving winding and thereby serves as an auxiliary moving winding. In this case, the armature may underlie all three coils if desired.

Still further according to the invention, the switch mechanism for alternately connecting the windings may be arranged to be actuated directly by the armature in its movement.

In order that the practical aspects of the invention may be more readily put into practice, several embodiments of the invention, given by way of example only, are described hereinafter with reference to the accompanying drawing, forming a part of the specification and in which:

FIG. 1 is a cross-sectional view of an electromagnetic actuator according to the invention;

FIG. 2 (sections *a–e* being taken together) illustrates one theory of operation of a magnetic actuator according to the invention;

FIG. 3 (sections *a–e* being taken together) illustrates the electrical connections of the electromagnetic mechanism as shown in FIG. 2; and

FIGS. 4–7 illustrate the electric connections of alternate embodiments of the electromagnetic actuator according to the invention.

FIG. 1 provides an illustrative example of a magnetic actuator according to the invention. As shown, a magnetic actuating assembly **10** is mounted, by way of example, on a bulkhead **12** by conventional means for operating a device requiring the positioning of an element in two discrete positions. One such device may be a hydraulic valve **14**, as shown, for valving a fluid from an inlet **16** to an outlet **18**. Another such device may be a double-throw electric switch as shown, for example, in a switching assembly **20** containing an electric switch **22** which may be connected for controlling an external electric circuit or, as will be detailed hereinafter, for controlling the internal electric circuit of the magnetic actuating assembly **10** in accordance with more advanced embodiments of the magnetic actuator according to the invention, or for both.

As shown, the magnetic actuating assembly **10** comprises a nonmagnetic tubular element **24**, preferably having a cylindrical bore, in order not to restrain the armature of the device from rotational movement that may be found necessary or desirable. It is contemplated, however, that in some instances it will be desirable to restrain or even control rotational movement of the armature. The tubular element **24** may be separate from or integral with flanges **26** to form bobbins for a centrally disposed moving solenoid winding **28** and a pair of releasing solenoid windings **31** and **32**. Arranged in sliding fit in the tubular element **24** is an armature **34** of material of high magnetic retentivity, such as a permanent magnet made of steel or a known alloy of aluminum, iron, nickel and cobalt, such as the composition known as "Alnico V," comprising eight parts of aluminum, fourteen parts of nickel, twenty parts of cobalt, three parts of copper, and fifty-one parts of iron. The armature has a length ten or more times greater than the diameter and the releasing windings overlie the armature by a distance no greater than the diameter of the armature for reasons that will be more clearly explained hereinafter. The nonmagnetic tubular element **24** is closed by end plates or holding members **37** and **38** made of material of low magnetic retentivity such as soft iron or other known low reluctance materials. The end plates **37** and **38** are provided with apertures through which connecting rods **42** and **43** pass. A tubular shell **46**, which may be of either nonmagnetic or magnetic material, preferably mild steel or iron, connects the holding members **37** and **38** and serves to protect the windings **28**, **31** and **32** as well as to provide a low reluctance return path for the magnetic flux generated by the windings.

Holding members 37 and 38 may be flat plates as shown in FIG. 2 or may have bosses 37*a* as shown in FIG. 1 extending into a nonmagnetic tubular element 24 underlying a portion of the solenoid windings 31 and 32 to concentrate the magnetic flux at the ends of the tube 24. One of the holding members 37 also has an aperture through which a cable 47 is passed to connect the terminals of the windings 28, 31 and 32 through the terminals of the electric switch 22 and to electric terminals 48 and 49 for applying potential for energizing the magnetic actuator.

In a basic and practical embodiment of the invention the three solenoid windings 28, 31 and 32 are connected in series with the current flow therethrough in directions at which the magnetic flux emanating from the releasing windings 31 and 32 are in opposition to the magnetic flux emanating from the moving winding 28. For such connections the armature 34 should be of such length that it underlies one releasing winding; for example, releasing winding 31; the greater part, preferably all, of the moving winding 28; and very little, or none, of the other releasing winding 32. While the releasing and moving windings are shown closely adjacent each other for compactness and optimum results, it should be understood that they may be separated by an appreciable distance if desired.

At the time the magnetic actuator is constructed, the permanent magnet armature 34 will have ends of opposite polarity, conventionally termed north and south poles, and at this time the orientation of the permanent magnet armature 34 is unimportant. For the purpose of explanation it will be assumed that the south pole of the permanent magnet armature 34 is in contact with and adhering to left hand holding member 37.

FIGS. 2 and 3 illustrate one explanation of the operation of a basic magnetic actuating assembly according to the invention; the former showing the relative positioning of the armature and the polarities of the magnetic armature and the electromagnets formed by the solenoid windings, and the latter showing the interconnections of the solenoid windings and the electrical connections through a control switch 52 to a source of unidirectional potential shown as a battery 54. With the connections given in FIG. 3(*a*) the control switch 52 is closed for energizing the actuating assembly and, hence, moving the utilization device by moving the armature 34′ away from the holding member 37′ into contact with the other holding member 38′. The direct current flowing through the solenoid windings will set up fields of magnetic flux polarity as shown in FIG. 2(*a*). As the magnetic flux builds up the releasing winding 31′ will magnetize a part of the armature 34′ to form a short magnet section with a north pole and a south pole as shown, and the moving winding 28′ will magnetize the remainder of the armature 34′ to form a long magnet section with a south pole and a north pole as shown. Meanwhile the other releasing winding 32′ will be relatively ineffective, since no part of the armature 34′ underlies it, whereby only a very weak magnetic field is generated. With the releasing winding 31′ affecting a portion of the armature 34′ smaller than, or at least not materially greater than, the diameter of the armature 34′, the shorter magnet portion is relatively weak compared with the longer magnet portion which is ten or more times as long as the diameter of the armature. The weak force of the newly formed relatively short magnet section effectively releases the hold of the armature 34′ on the holding member 37′ allowing the tractive force of the moving winding 28′ to move the armature 34′ to the right, with the assistance of the relatively strong north pole of the longer portion of the armature 34′ being attracted to the other holding member 38′. At a position intermediate the stroke *s*, the armature 34′ is magnetized as shown in FIG. 2(*b*) and the control switch 52 is opened, as shown in FIG. 3(*b*), to prevent the field of the other releasing winding 32′, which is building up due to intrusion of the armature 34′ into the core of the other releasing winding 32′, from slowing down the movement of the armature into position and from demagnetizing the strong north pole of the armature 34′ as it now exists and is needed to adhere to the holding member 38′. The armature 34′ is carried by momentum and is attracted to the holding member 38′ by the strong north pole of the longer section.

The armature of the magnetic actuator according to the invention moves very rapidly so that the control switch 52 is preferably constituted by some form of electronic switch incorporating a vacuum tube or transistor. For this reason the circuit of FIG. 3 is suggested, since only one control switching element is required for actuation in both the forward and reverse directions. By action of a collar 57, shown in FIG. 1, on the shaft 42 striking the yoke 56 of the toggle switch 22, as the armature 34′ is driven home as indicated in FIG. 2(*c*), the switch blades 22′*a* and 22′*b*, shown in FIG. 3(*c*), are thrown from the forward contacts 22*e* to the reverse contacts 22*g* in readiness for the reverse actuation of the armature 34′. A similar collar 58 is arranged on the shaft 42 for throwing the switch 22 when the armature is driven in the other direction.

At the beginning of the return stroke the switch 52 is closed, FIG. 3(*d*), and the electromagnets formed by the windings 28′, 31′ and 32′ are reversed in polarity, FIG. 2(*d*). The armature 34′, as shown, is magnetized with both ends of the same polarity as magnetized before on the forward stroke. The consequent south poles, however, are now switched to the end of the magnet nearest the holding member 38′, forming a short, and therefore very weak, magnet portion effective to release the armature 34′ from the holding member 38′. This permits the armature 34′ to be attracted by the moving winding 28′ and the strong north pole of the longer and relatively stronger magnet portion to the holding member 37′. The ends of the armature 34′ after once being magnetized either as south pole or north poles, as shown and described, remain at the same polarity throughout all the operations of the magnetic actuator as connected, only the location of the consequent poles being changed in operation. As the armature 34′ arrives at a point intermediate the strokes, the control switch 52 is opened and momentum plus the magnetic attraction of the strong pole of the armature 34′ carries it into contact with the holding member 37′. As the armature 34′ nears home the switch 22 toggled by the collar 58 striking the yoke 56 and the actuator is then once more in the state shown in FIG. 2(*a*) and connected as shown in FIG. 3(*a*).

While the series connection of the solenoid windings 28, 31 and 32 is believed the most practical, it is also contemplated that the releasing windings may be connected in series, as shown in FIG. 4, and that such series connected windings 31, 32 may then be connected in parallel with the moving winding 28′. FIG. 5 shows a circuit arrangement in which all of the solenoid windings are connected in parallel. Of course separate power sources may be used for each of the separate windings. As shown in FIG. 4 a three position switch with open contacts 22*f* may be employed as both a reversing and as a control switch. Such an arrangement is deemed practical only for manual switching at low speed.

Higher speed actuation can be obtained by the use of the switching arrangements shown in FIGS. 6 and 7; showing series and series-parallel connections, respectively, in the arrangement of FIG. 6, the reversing switch 22 is a four pole-two position switch connected to the solenoid windings as shown whereby the releasing winding 31′ is opposing the moving winding 28′ and the other solenoid winding 32′ is aiding the moving winding 28′ thereby increasing its size and effect and obviating the repulsion effect that it would exhibit were it connected as a releasing winding as shown in FIG. 3. The toggle switch **22** reverses the connection of the windings as well as the direction of polarity of the potential applied to the winding for the return stroke. In such arrangements as shown in FIGS. 6 and 7, if found desirable, the armature **34** may be long enough to underlie both the releasing winding **32'** (or **31'** when so switched) and a position of the other (releasing) winding **31'** (or **32'**) connected as an auxiliary moving winding.

In an embodiment of an actuator constructed according to the arrangement in FIGS. 2 and 3 with a stroke of 0.080 inch, an armature force of six pounds was developed at a current of 60 milliamperes. An armature force of four pounds was obtained at a current of 40 milliamperes, and the subsequent holding force of the permanent magnet armature **34** on the holding members **37** and **38** was eight pounds. At a current of 30 milliamperes an armature force of two and one-half pounds was developed with a subsequent holding force of five pounds.

Larger forces can be developed by increasing the size of the permanent magnet armature, or by increasing the current flow in the windings. The theoretical limit to the motive force obtainable is dependent on the current that can flow before the magnetic structure is fully saturated.

While the invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in the form and details may be made therein without departing from the spirit and scope of the invention.

The invention claimed is:

1. A magnetic actuator including an elongated armature of material of high magnetic retentivity arranged for movement in two directions,
   holding members of material of low magnetic retentivity arranged at either end of said armature in the path of movement thereof,
   an electromagnetic winding disposed about said armature and centrally of said holding members for moving said armature into contact alternately with said holding members,
   said armature having residual magnetism attracting it to the one of said holding members with which it is in contact,
   further electromagnetic windings disposed about said armature adjacent said holding members,
   means connecting said moving winding and said further windings for current flows at which the magnetic flux emanating from the one of said further windings adjacent the holding member with which the armature is in contact is in opposition to the magnetic flux emanating from said moving winding and the other of said further windings is connected for current flow at which the magnetic flux emanating therefrom is aiding the magnetic flux emanating from said moving winding, and
   means to apply unidirectional potential to said windings to release said armature from the holding member with which it is in contact and move it into contact with the other holding member.

2. A magnetic actuator as defined in claim 1 and wherein said means connecting said windings comprises reversing switch means for inverting the current flow relationship of said windings for reversing the directions of movement of said armature.

3. A magnetic actuator including a sleeve of nonmagnetic material, a primary solenoid wound about said sleeve and arranged centrally thereof, secondary solenoids wound about said sleeve and arranged on either side of said primary solenoid, means interconnecting said solenoids for current flow at which the direction of magnetic flux produced by said secondary solenoids extends in a direction opposite to that produced by said primary solenoid, end plates of magnetizable material arranged at each end of said sleeve, a bar of permanent magnet material arranged in said sleeve for longitudinal movement between said end plates and having a length substantially equal to the length of said primary solenoid and one of said secondary solenoids, and means to apply unidirectional potential to said interconnecting solenoids to move said bar from end-to-end within said sleeve.

4. A magnetic actuator including a tubular sleeve of nonmagnetic material, a primary solenoid wound about said sleeve and arranged centrally thereof, secondary solenoids wound about said sleeve and arranged on either side of said primary solenoid, means interconnecting said solenoids for current flow with the direction of magnetic flux produced by said secondary solenoids in a direction opposite to that produced by said primary solenoid, end plates of magnetizable material arranged at each end of said sleeve, a shell of magnetizable material surrounding said solenoids and interconnecting said end plates, a bar of permanent magnet material arranged in said sleeve for longitudinal movement between said end plates and having a length substantially equal to the length of said primary solenoid and one of said secondary solenoids, means coupling said bar to a utilization device, and means to apply unidirectional potential to said interconnected solenoids to move said bar from end-to-end within said sleeve.

5. A magnetic actuator including a tubular sleeve of nonmagnetic material, a primary solenoid wound about said sleeve and arranged centrally thereof, secondary solenoids wound about said sleeve and arranged on either side of said primary solenoid, means connecting said solenoids in series with the direction of magnetic flux produced by said secondary solenoids being in a direction opposite to that produced by said primary solenoid, end plates of magnetizable material arranged at each end of said sleeve, a shell surrounding said solenoids and interconnecting said end plates, a bar of permanent magnet material arranged in said sleeve for longitudinal movement therein from one of said end plates to the other and having a length substantially equal to the length of said primary solenoid and one of said secondary solenoids, means for coupling said bar to a utilization device, and means to apply unidirectional potential across said series connected solenoids to move said bar from end-to-end within said sleeve.

6. A magnetic actuator including a tubular member of nonmagnetic material, an actuating solenoid arranged about said tubular member centrally of the length thereof and having a predetermined width, releasing solenoids arranged about said tubular member on either side of said actuating solenoid and having widths less than the width of said actuating solenoid by a ratio greater than 1:9, holding members arranged in said tubular member and spaced apart substantially by the sum of the widths of said solenoids, at least one of said holding members having an aperture therein, an armature of material of high magnetic retentivity arranged in said tubular member between said holding members for reciprocating movement, said armature having a length substantially equal to the sum of the widths of said actuating solenoid and one of said releasing solenoids and a mean cross-sectional dimension to length ratio greater than 1:9, a shell surrounding said solenoids and joining said holding members to form a completely enclosed structure, a member of nonmagnetic material arranged for reciprocating movement in said aperture of said holding member and coupled to said armature for actuating a utilization device in accordance with the axial movement of said armature, means interconnecting said solenoids electrically with the lines of magnetic flux generated by said releasing solenoids in a direction opposite to those of said actuating solenoid, and means to apply a pulse of unidirectional potential across said interconnected solenoids to move said armature longitudinally of said tubular member from one holding member to the other.

7. A magnetic actuator including a tubular member of nonmagnetic material, an actuating solenoid arranged about said tubular member centrally of the length thereof and having a predetermined width, releasing solenoids arranged about said tubular member on either side of said actuating solenoid and having widths less than the width of said actuating solenoid, by a ratio greater than 1:9, holding members arranged in said tubular member and spaced apart substantially by the sum of the widths of said solenoids, at least one of said holding members having an aperture therein, an armature of material of high magnetic retentivity arranged in said tubular member between said holding members for reciprocating movement, said armature having a length substantially equal to the sum of the widths of said actuating solenoid and one of said releasing solenoids and a mean cross-sectional dimension to length ratio greater than 1:9, a shell surrounding said solenoids and joining said holding members to form a completely enclosed structure, a member of nonmagnetic material arranged for reciprocating movement in said aperture of said holding member and coupled to said armature for actuating a utilization device in accordance with the axial movement of said armature, means including switching means controlled by the movement of said armature interconnecting said solenoids electrically with the lines of magnetic flux generated by one of said releasing solenoids opposing those of said actuating solenoid, and the lines of magnetic flux of the other of said releasing solenoids aiding those of said actuating solenoid, and means to apply a pulse of unidirectional potential across said interconnected solenoids to move said armature longitudinally of said tubular member between said holding members.

8. A magnetic actuator including an armature of material of high magnetic retentivity having a length at

least ten times the mean cross-sectional dimension and having identical magnetic polarity at both ends, holding members of material of low magnetic retentivity arranged one at an end of said armature in magnetic contact therewith and the other spaced from the other end of said armature at a distance substantially no greater than said mean cross-sectional dimension, a solenoid arranged about said armature and adjacent said holding member in contact with said armature for establishing a concentration of magnetic polarity opposite to that at the ends of said armature at a distance no greater than said mean cross-sectional dimension from said holding member in contact with said armature thereby effectively to demagnetize that end of said armature and release it from the holding member, and a further solenoid arranged about said armature centrally of said holding members for attracting said armature away from the holding member with which it is in contact and permitting it to travel into contact with the other holding member.

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