

Nov. 22, 1949

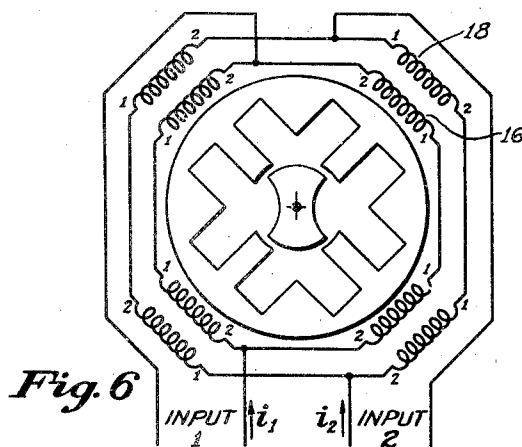
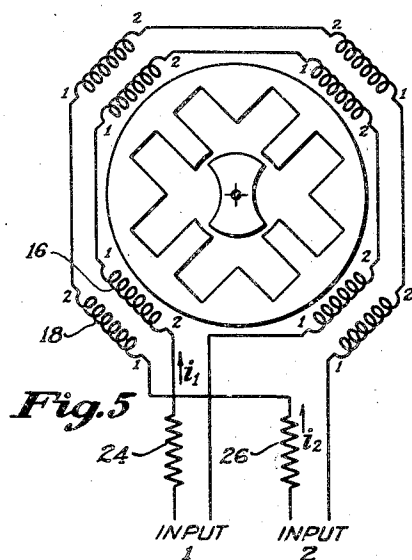
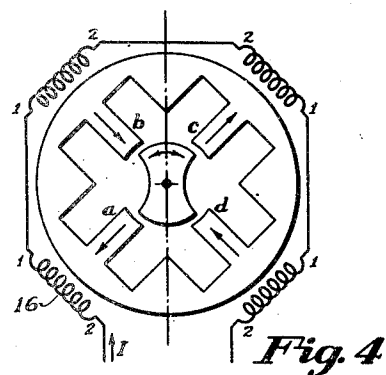
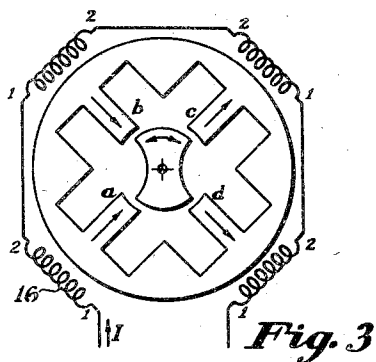
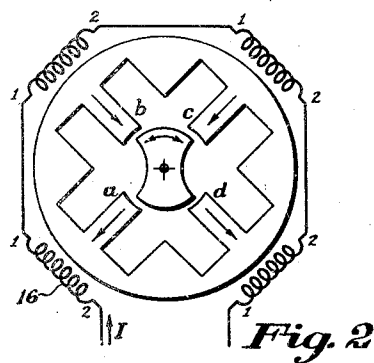
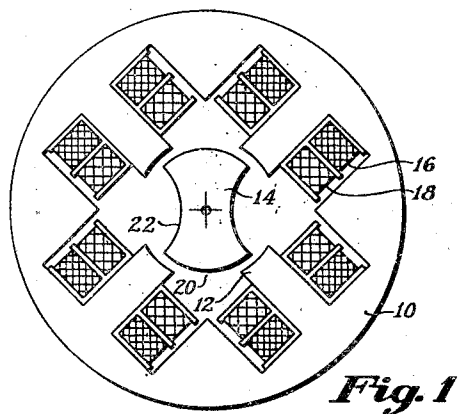
R. K. MUELLER

2,488,734

DYNAMO TRANSFORMER

Filed March 7, 1946

4 Sheets-Sheet 1



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DYNAMO TRANSFORMER

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4 Sheets-Sheet 2

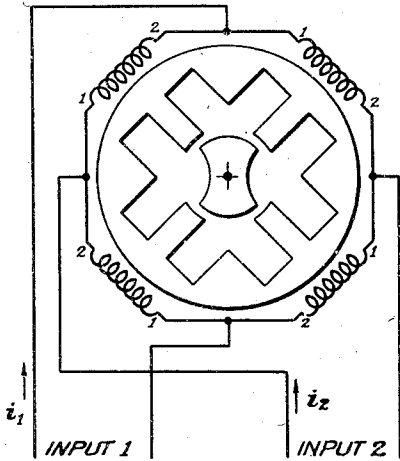


Fig. 7

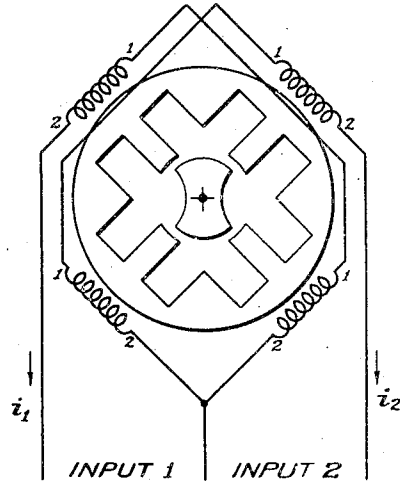


Fig. 8

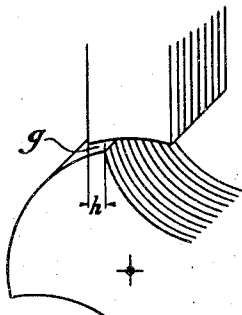


Fig. 9

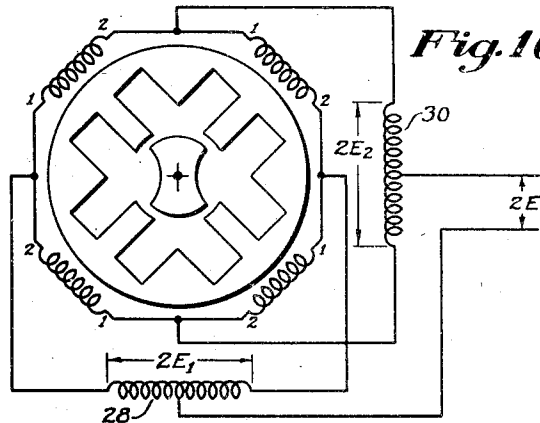


Fig. 10

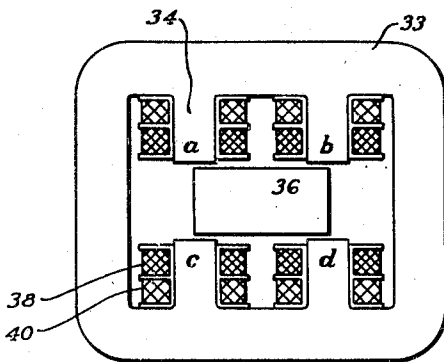


Fig. 12

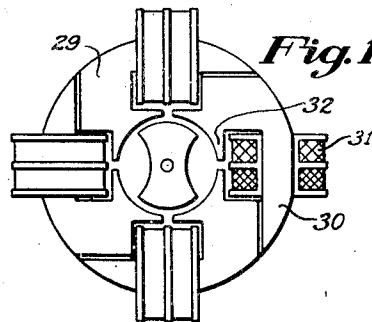


Fig. 11

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DYNAMO TRANSFORMER

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4 Sheets-Sheet 3

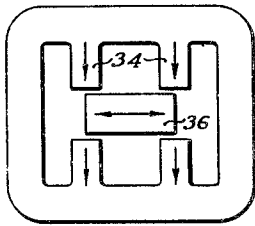


Fig. 13

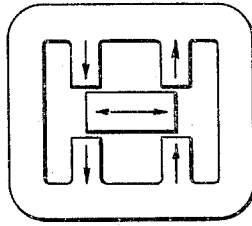


Fig. 14

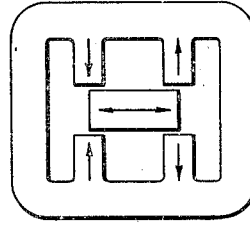


Fig. 15

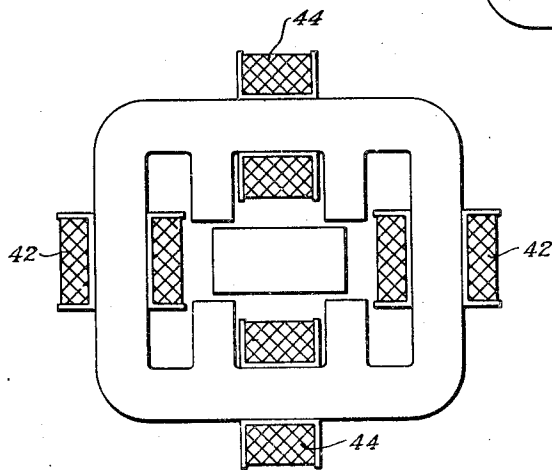


Fig. 16

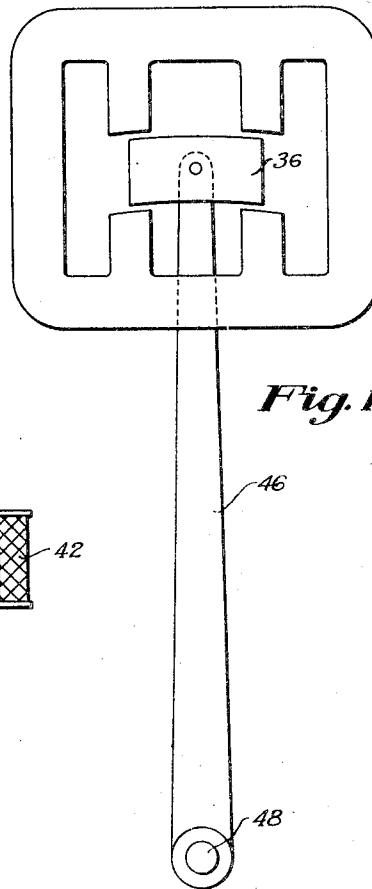


Fig. 17

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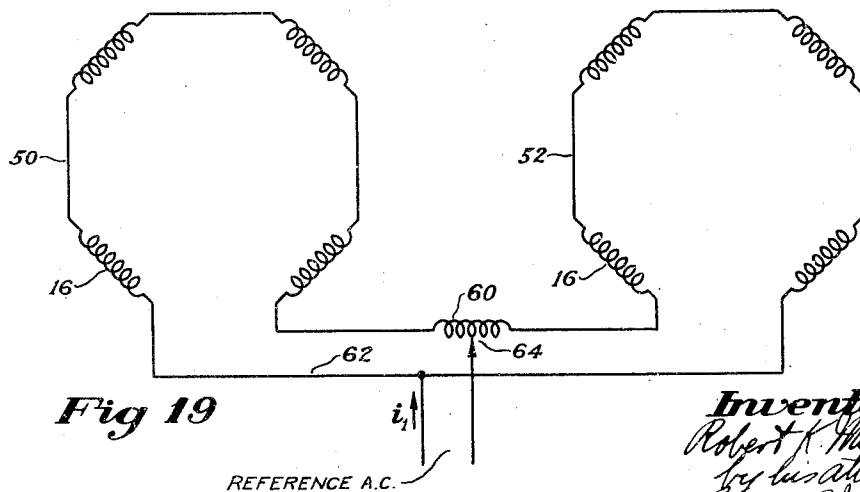
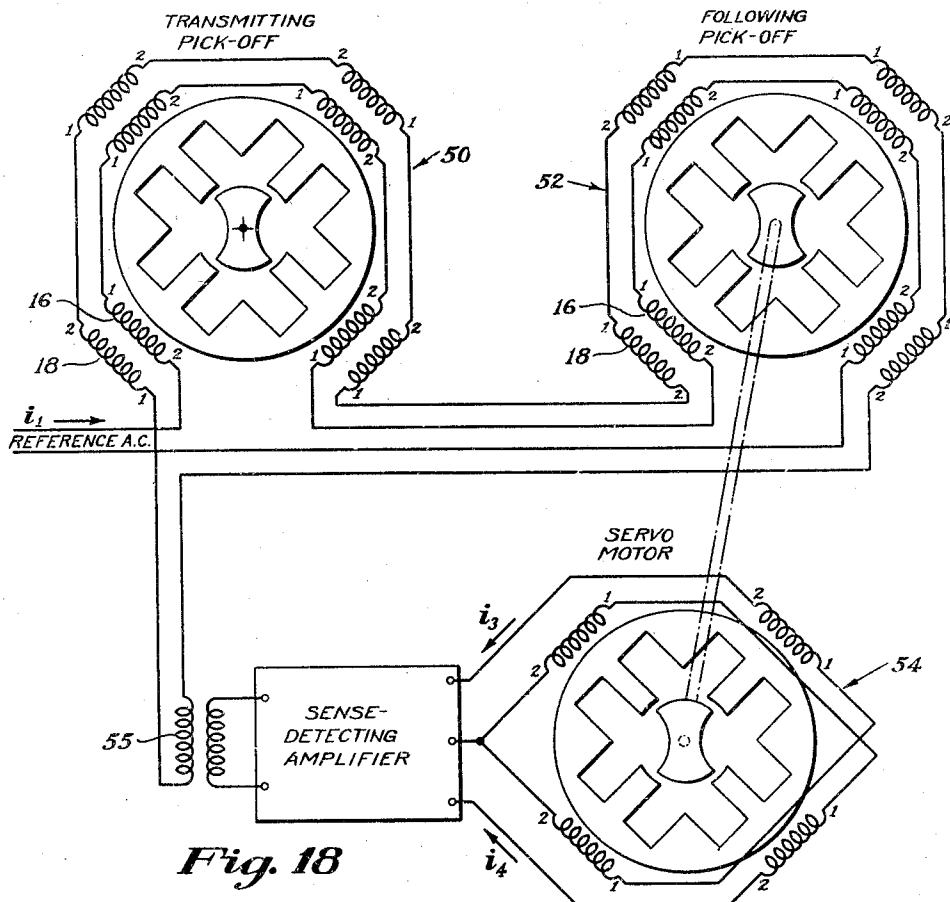
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DYNAMO TRANSFORMER

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4 Sheets-Sheet 4



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UNITED STATES PATENT OFFICE

2,488,734

DYNAMO TRANSFORMER

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New York, N. Y., a corporation of New York

Application March 7, 1946, Serial No. 652,523

2 Claims. (Cl. 171-119)

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The present invention relates to electromagnetic apparatus and more particularly to torque motors and related devices, herein referred to under the general designation of variable dynamo transformers.

As a specific example of apparatus in this general category the torque motor may be considered. In general any motor can be classed as a torque motor but the term is usually applied to a motor which is not continuously rotatable and in particular cases is capable of movement through only a relatively small angle. Such motors are useful in servomechanisms and in other applications where a definite torque is required which is dependent on an electrical input. One of the objects of the present invention is to provide a torque motor in which the generated torque is substantially independent of displacement over the working range and in which a precise value of torque in accordance with the electrical input may be obtained.

Another form of the invention comprises what may be termed a stiffness motor in which a torque substantially proportional to displacement may be obtained. A device of this type is of great importance as an electrical means to take the place of a mechanical spring. It has the advantage that the "spring constant" may be made practically uniform over the working range and further that the constant may be easily adjusted by electrical means.

Another embodiment of the invention is an electrical transformer or pickoff in which an output voltage may be obtained which is proportional to the mechanical displacement of the rotor. This device is likewise an apparatus of high precision and finds utility in servomechanisms and systems of similar character.

I have devised a simple form of apparatus useful for these and other purposes. The general construction of the apparatus is substantially alike for the various embodiments and only the winding connections need to be varied for different uses.

In the accompanying drawings Fig. 1 is an elevation of one form of apparatus according to the present invention. Figs. 2, 3 and 4 are diagrams of the magnetomotive force patterns for different coil connections; Figs. 5, 6, 7 and 8 are diagrams of winding connections; Fig. 9 is a perspective view illustrating fringing effects; Fig. 10 is a diagram of a combined torque and stiffness motor; Fig. 11 is a diagram of a modified construction; Fig. 12 is an elevation of a device in which the motion is rectilinear; Figs. 13 to 15

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are diagrams of magnetomotive force patterns; Fig. 16 shows a modification of Fig. 12; Fig. 17 is an elevation showing a moving element pivoted on a remote axis; Fig. 18 is a diagram of a simple and precise servomechanism embodying devices of the type described herein; and Fig. 19 is a diagram of a variable-ratio device.

The device shown in Fig. 1 comprises a stator 10 preferably constructed of laminations of magnetic material. The shape is essentially circular with four re-entrant poles 12. A rotor 14 is pivoted or journaled in suitable bearings about an axis at the center of the stator frame. Each pole 12 is provided with either one or two windings indicated as double windings 16 and 18 in Fig. 1. For some purposes which will be hereinafter described a single winding for each pole is sufficient and in other cases the double windings are required.

The rotor is of magnetic material, such as soft iron, and is not permanently magnetized, nor does it carry any windings. It has circular end portions 20, each spanning the distance between centers of two adjacent poles. The pole faces are formed to provide an accurately uniform air gap with relation to the ends of the rotor. The sides 22 of the rotor are not of critical shape and are conveniently formed as circular arcs tangent to the radii drawn to the extreme edges of the circular end portions 20. The normal or neutral position of the rotor is with its edges at the centers of the pole faces as indicated in Fig. 1.

Various uses of the apparatus as torque motors, stiffness motors and transformers depend on the connections of the windings. The different possible connections will be explained in connection with the diagrams of Figs. 2, 3 and 4. In each diagram the four poles are designated consecutively by the letters *a*, *b*, *c* and *d*. In each case a single winding 16 is shown, consisting of all four of its coils connected in series. For simplicity the coils are shown as arranged outside the frame but it will be understood that they are wound on the pole pieces as shown in Fig. 1. A convention designating the directions of the magnetomotive forces is necessary. In these diagrams the ends of each coil are designated 1 and 2. The convention is that when current flows in the coil between points 1 and 2 the magnetomotive force due to the coil is inward toward the rotor, and when the current is from 2 to 1 the magnetomotive force is outward away from the rotor. Thus in Fig. 2 the magnetomotive forces are inward for poles *b* and *c* and outward for poles *a* and *d*.

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The connections shown in Fig. 3 are similar to those in Fig. 2 except that the coils for poles *a* and *c* are reversed. The magnetomotive force patterns of Figs. 2 and 3 are therefore similar in that forces on two of the adjacent poles are directed inwardly, while those of the other two poles are directed outwardly. The connections in Fig. 4 are such that the magnetomotive forces are consecutively directed inwardly and outwardly for the several poles.

For a torque motor a combination of the connections of Figs. 2 and 3 may be used. These connections are shown in Fig. 5 wherein one of the windings 16 is connected as in Fig. 2 and the other winding 18 is connected as in Fig. 3. The two windings are connected to separate inputs indicated as input 1 and input 2, each of which may include a resistor 24 for a purpose to be presently described. One winding carries a current *i*₁; the other winding carries a current *i*₂. The currents may be either direct current or alternating current of the same frequency.

The torque tending to move the rotor from neutral position is proportional to *i*₁*i*₂. The torque is substantially constant over the range of motion for which fringing effects are negligible, as will be explained later. In general only a few degrees of motion are required, say ten or twenty degrees, at the most, and within that range a remarkably uniform torque is obtained. It will be understood that if the torque is unresisted the rotor will move until it is centered with respect to one opposite pair of poles. In most applications, however, the torque is resisted by other torques and only a small range of motion is permitted.

In most instances it is desirable that the torque should be proportional to voltages, rather than currents, and to this end resistors 24, 26 are connected in series with the inputs, the resistors being of sufficiently high resistance that the currents, and hence the magnetomotive forces, are substantially proportional to the input voltages, notwithstanding changes in mutual inductance, as will be explained later. Then if the input voltages are *e*₁ and *e*₂, the torque is proportional to *e*₁*e*₂. If there is a time phase difference between the inputs this product must be multiplied by the cosine of the phase angle. In any event a torque is obtained which is proportional to the two quantities *e*₁ and *e*₂. If one of the inputs is a constant reference voltage, the torque will be proportional to the other input voltage.

For practical applications simpler winding connections may be used than are shown in Fig. 5. Before describing such connections the principles on which the device operates will be explained. The operation depends on two fundamental principles; first that the self-inductance for each input is constant for all angular positions within the working range; and second that the mutual inductance increases linearly with the displacement from neutral.

That the self-inductance for each input remains constant may be seen by considering Fig. 2. With the rotor in neutral position the inductance has a certain value which depends primarily on the length of the air gaps between the rotor and the pole pieces. In the succeeding description the entire magnetic reluctance is considered to be concentrated in the air gaps. The reluctance of the paths through the rotor and frame will be neglected since it has been found in practical experience to be negligible. If the rotor is turned slightly from neutral, say in a clockwise direc-

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tion, the reluctance decreases at poles *a* and *c* and increases at poles *b* and *d*. More flux will pass into the rotor through poles *a* and *c* and less through poles *b* and *d* but it can be readily seen that the total flux through the four gaps remains constant. Since the coils are all in series the inductance of the entire winding 16 is a constant regardless of the angular position of the rotor. This is true if fringing effects are neglected which is proper within the limited range of motion for which the motor is particularly useful. From similar considerations the total self-inductance of each winding 16 and 18 in Fig. 5 is likewise constant regardless of the angular position of the rotor.

It can also be readily seen that the mutual inductance between the windings 16 and 18 changes with displacement from neutral position. For in neutral position the net mutual flux is zero, but with a change in position, flux due to the magnetomotive forces of one winding will link the coils of the other winding. The mutual flux linkages, and hence the mutual inductance, are proportional to the angle of displacement. The energy output upon motion from neutral to any angular position is the mutual inductance times the product of the currents in the two sets of windings. The torque is proportional to the derivative of energy with respect to displacement, and since the mutual inductance is proportional to displacement the torque is constant for all displacements.

The magnetomotive force pattern of Fig. 4 in which the magnetomotive forces are alternately toward and away from the rotor produces a different operation. The motor is one in which the torque is proportional to displacement of the rotor from neutral. It is the equivalent of a spring and is useful for many purposes. Only one winding 16 is required and its four coils are connected in series according to the convention of Fig. 4. For this connection the total self-inductance does not remain constant for different positions of the rotor. For purposes of explanation the rotor can be considered as divided along its axis as indicated by the dot-and-dash line in Fig. 4. No flux crosses that line and each half of the rotor may be considered separately. The flux passing through one half of the rotor crosses two air gaps in series. Upon any movement from neutral position one of the gaps is increased in area while the other is reduced. The total reluctance of the flux path is not maintained constant.

The reluctance of one gap is

$$\frac{1}{a+b\theta}$$

(where *a* and *b* are constants and *θ* is the angle of displacement from neutral) and the reluctance of the other gap is

$$\frac{1}{a-b\theta}$$

The total reluctance of the flux path is the sum of these expressions which is equal to

$$\frac{2a}{a^2-b^2\theta^2}$$

The total magnetic energy is the square of the magnetomotive force divided by the total reluctance, and hence is proportional to *a*²−*b*²*θ*². The torque, which is proportional to the derivative of the energy with respect to *θ*, is therefore proportional to *θ* itself. Thus the device acts in the manner of a spring. The strength of the spring

is proportional to the magnetomotive force squared, which, in turn, is proportional to the current squared in the winding. The strength of the spring is easily varied by the series resistor 28 or any suitable means for varying the current. The device thus offers an opportunity for accurate spring adjustment.

Referring to the torque motor exemplified by the magnetomotive force patterns of Figs. 2 and 3, these patterns may be obtained by various winding connections, some of which may be preferred to the connections of Fig. 5 because of their simplicity or their better adaptation to associated equipment. A simple modification of Fig. 5 is shown in Fig. 6 wherein the windings 16 and 18 have their coils connected in series-parallel fashion (but with necessary reversal of some coil connections in order to duplicate the magnetomotive force patterns of Figs. 2 and 3); the same results are obtained as in Fig. 5 and the same theoretical considerations are applicable.

In Fig. 7 only a single set of four coils is used, the coils being connected in the form of a square with inputs 1 and 2 connected to diagonally opposite corners. It will be seen that the coils may be connected in such a manner that the winding convention of the coils for input 1 is the same as for Fig. 2 and the winding convention for input 2 is the same as for Fig. 3. Current i_1 if impressed alone would produce the magnetomotive force pattern of Fig. 2, and current i_2 alone would produce the pattern of Fig. 3. In combination the same results are obtained as in the double winding construction of Fig. 5. The arrangement of Fig. 7 cannot be used, however, if the input circuits have to be isolated.

Fig. 8 represents a further simplification in that only two coils are used for each input. Input 1 is connected to the coils on poles a and c in series and input 2 is connected to the coils on poles b and d in series. It will be observed that if the two currents are equal in magnitude, the same magnetomotive force pattern is obtained as in Fig. 2. When the currents are unequal, the pattern is a composite of Figs. 2 and 3; hence the connection is proper for a torque motor. The torque is constant for all angular positions but is proportional to $(i_1 + i_2)(i_1 - i_2)$. The fact that the torque is dependent on sum and difference terms makes the arrangement convenient for application in some electronic circuits and particularly for the servomechanism to be described later.

Mention has been made of fringing effects. These are explained by reference to Fig. 9 which is a perspective view of a portion of the rotor opposite one of the pole faces, the rotor being shown as displaced counterclockwise from neutral. At this position a certain portion of the width of the rotor is directly opposed to the pole face according to the dimension indicated at h . The length of the air gap is indicated by g . In general it has been found that the range of movement of the rotor should be limited so that h is always somewhat larger than g and preferably not less than twice as large. This is the requirement for high precision since variable fringing effects may disturb the linear relationships heretofore described if the rotor is allowed to turn farther toward the edge of the pole face. In cases where extreme precision is not essential an increased motion of the rotor may be permitted. It will be noted from Fig. 9 that the rotor and pole faces are of considerable thickness so that the thickness is always large in

comparison to the other dimensions of the air gap.

Connections for a combined torque and stiffness motor are shown in Fig. 10. Here a single coil per pole may be used. A source of potential $2E_1$ is connected to two diagonal corners of the bridge and another source $2E_2$ is connected to the other two corners. These potentials may be supplied by transformers, the secondaries of which are indicated at 28 and 30. Another source of potential indicated as of magnitude $2E$ is connected at its ends to the mid-points of the transformer secondaries 28 and 30. The point of zero potential for the system may be taken as the mid-point of the source designated $2E$. The currents due to these separate voltages produce a magnetomotive force pattern which is equivalent to the superposition of the three patterns of Figs. 2, 3 and 4.

Assuming that the currents in the coils are proportional to the potential differences across them an expression for torque in terms of the voltages can be obtained. The derivation of this expression would serve no useful purpose here but the final expression is that the torque is equal to $k_1 E_1 E_2 + k_2 E^2$ where k_1 and k_2 are constants determined by the characteristics of the motor.

It will be noted that the total torque is made up of a constant term proportional to the product of the voltages E_1 and E_2 and a stiffness torque proportional to E^2 and also proportional to the displacement angle from a neutral position. The neutral position is not necessarily that shown in Fig. 10 but depends upon the solution of the above expression for zero torque. It is to be noted that the three voltages E , E_1 and E_2 need not all be of the same frequency. The voltage E which is the only one appearing in the stiffness term may conveniently be direct current. The voltages E_1 and E_2 may be direct or alternating currents and if alternating require at least one frequency component in common. If there is a time phase between E_1 and E_2 the constant torque component is proportional to the cosine of the phase angle.

The devices heretofore described are useful as motors. Apparatus of similar form may be used as a "pick-off" or variable transformer to give a variable voltage or current in accordance with the position of the rotor. For a pick-off in which the output voltage is proportional to rotor displacement, the connections of any of Figs. 5, 6, 7 and 8 may be used except that one of the inputs, say input 2, becomes an output. For a constant excitation voltage applied to input 1 an output voltage appears at the terminals of the output, and the magnitude of the voltage is varied by displacing the rotor. When the rotor is in neutral position the output voltage is zero. As the rotor is moved the output voltage increases. The phase of the output voltage differs 180 degrees for motions in opposite directions from neutral. The operation of the device as a pick-off depends upon principles heretofore explained, namely, the constancy of self-inductance and the fact that the mutual inductance is a linear function of displacement. The magnitude of the output voltage will be proportional to the displacement. As in any transformer, alternating current must be used. This type of device is useful as a means of measuring angular displacements and is particularly applicable to servomechanisms and similar equipment.

A pick-off having an output voltage proportional to the square of the rotor displacement is useful in some measuring applications and is

provided by connecting each winding (18 and 19) in the same coil sequence as shown for the single winding of Fig. 4. As heretofore noted in connection with the description of Fig. 4, the self-inductance of each winding is variable and is in fact represented by an expression of the form $a^2 - b^2\theta^2$. Upon passage of a current through the input winding, the back electromotive force involves a term proportional to θ^2 , that is, proportional to the square of the displacement. The mutual inductance is constant, regardless of rotor position, hence, a voltage proportional to the square of the displacement appears at the output terminals.

A modified construction of the apparatus is shown in Fig. 11 wherein the coils are wound on the portions of the stator between the pole faces. The stator is conveniently built up of identical laminations of the shape indicated at 29, the laminations of alternate layers being inverted and having their long end portions 30 inserted through the coils 31. This construction permits the use of wide angle pole-faces as indicated at 32, although the device may be constructed with narrow pole faces if desired. The wide poles allow a greater range of movement of the rotor, but with some slight loss of linear characteristics at the ends of the range. Magnetomotive force patterns identical to those shown in Figs. 2 to 4 may be obtained with this construction by appropriate coil connections which need not be described in detail. This embodiment of the invention may be used in any of the ways described for the construction of Fig. 1.

The principles of the present invention may also be applied to motors and pick-offs in which the motion of the moving part is in translation or about an axis remote from the center of the stator. In this type of device, one form of which is shown in Fig. 12, the stator 33 is provided with four re-entrant poles 34 lettered *a*, *b*, *c* and *d*. Poles *a* and *b* are at one side of the frame and are respectively opposed to poles *c* and *d* at the other side. A rectangular movable member 35 is used in place of the rotor. Each pole is provided with suitable coils 36 and 40. The apparatus may be used either as a force motor or as a pick-off. The term "force motor" is used in contradistinction to a torque motor because the member 35 is constrained to move sidewise instead of rotating.

The magnetomotive force patterns for different coil connections are indicated by Figs. 13, 14 and 15, in which the same notation for indicating the magnetomotive forces is used as in Figs. 2, 3 and 4, but for convenience the coils are omitted. The double arrows on the member 35 indicate that the member is mounted for sidewise movement. Fig. 13 corresponds exactly to Fig. 2 in principle, Fig. 14 to Fig. 3, and Fig. 15 to Fig. 4. Thus for a force motor the coils are connected to give a magnetomotive force pattern which is a combination of the patterns of Figs. 13 and 14. A constant force will be exerted on the member 35 independently of its position (so far as fringing effects are negligible) and the force is proportional to the product of the currents in the two sets of coils. For a pick-off, the same connections are used and with a current of constant amplitude in one set of coils, the voltage induced in the other set of coils will be proportional to the sidewise displacement of the element 35 from neutral. Fig. 15 represents a stiffness motor, in which the force on the element 35 is proportional to the displacement from neutral position.

The theoretical considerations for the translational device are identical with those for the rotary device, namely, that for Figs. 13 and 14, the self-inductance of each winding is constant and the mutual inductance is proportional to displacement, and that for Fig. 15 the reluctance involves a term dependent on the square of the displacement. In actual construction and arrangement the translational form differs from the rotary form. Thus in the rotary form the rotor always presents the same aspect to diametrically opposite poles, *a*, *c* and *b*, *d*, while in the translational form the member 35 presents the same aspect to directly opposite poles which are likewise indicated as *a*, *c* and *b*, *d*. Various simplified coil connections for the translational device may be used in exactly the same manner as for the rotary form. Moreover, instead of using coils wound on the pole-pieces, as in Fig. 16, the coils may be wound on the legs between the coils, as indicated at 42 and 44. It will be apparent to those skilled in the art that the windings may be connected to give any desired magnetomotive force pattern represented by Figs. 13 to 15.

In actual construction, to avoid the use of a mounting for sliding movement of the member 35, it is preferably mounted on an arm 46 for rotation about a remote axis 48, as shown in Fig. 17. The element 35 and pole faces are formed on arcs about the axis 48. The motion of the movable element is in effect a translation with respect to the poles.

An extremely precise servomechanism for following small angular displacements and embodying several of the variable dynamo-transformers heretofore described is shown in Fig. 18. The preferred units are a transmitting pick-off 50, a following pick-off 52 and a servomotor 54. The motor 54 may be of the type shown in Fig. 8. The following pick-off 52 and the motor 54 are mounted on the same shaft. The winding connections of the units 50 and 52 are the same as illustrated in Fig. 5. The coils 16 of one set of the unit 50 are connected in series and in the same sense with the corresponding coils of the unit 52 whereby these coils carry the current i_1 supplied from any suitable reference source. The output coils 18 are connected in series opposition and to a transformer 55 forming the input of a sense-detecting rectifier and amplifier 56. The voltage applied to the amplifier is proportional to the "error," that is, to the difference between the angular positions of the rotors of the units 50 and 52. The amplifier output feeds direct current to the motor 54 for which the connections are as in Fig. 8. Thus the coils on two opposite poles carry a current i_3 and the coils on the other two opposite poles carry a current i_4 . The construction of the sense detecting rectifier is well known in the art and is not described in detail here. It is sufficient to note that with zero input to the amplifier the currents i_3 and i_4 are the same, but with an input other than zero to the amplifier one of the currents increases and the other decreases. As heretofore shown the motor torque is proportional to $(i_3 + i_4)(i_3 - i_4)$.

When the rotors of the pick-offs 50 and 52 are in the same angular position the voltages induced in their output coils will be equal and opposite, and zero voltage will be applied to the amplifier input with the result that no torque is applied to the rotor of the output motor 54. If there is any difference in angular positions a voltage will be impressed on the amplifier input which depends on the amount and sense of the angular differ-

ence. The currents i_3 and i_4 will then assume such values as to bring the motor 54 into correspondence with the pick-off 50. Thus the motor follows the motions of the transmitting pick-off 50 with high precision. It will be understood that the accuracy of the system depends upon the precision with which the induced voltages in the pick-offs 50 and 52 can be brought into balance. The transformers herein described have been found especially suitable for this type of system.

If desired the motor may be made to follow the transmitting pick-off with a displacement ratio different from unity. This is accomplished by relatively varying the magnetomotive forces of the two windings 16. By using a turns ratio different from unity in either or both sets of coils of the units 50 and 52, the magnetomotive force ratio may be made different from unity. Thus if the winding 16 of the pick-off 52 has twice as many turns as the corresponding winding of the pick-off 50, the output will have only one-half the angular motion of the input.

Another connection for obtaining a desired displacement ratio is shown in Fig. 19. Here the windings 16 of the pick-offs 50 and 52 are connected to the ends of a current divider, consisting of a large inductive impedance 60. One side of the source of reference voltage is connected to a line 62 joining the ends of the windings, and the other side of the source is connected to the impedance 60 through a variable tap 64. The current will divide between the two windings in a ratio dependent on the position of the tap. The ratio of rotor displacements of the two pick-offs is inversely proportional to the ratio of currents. The impedance is preferably a large inductance, in order that the currents in the two windings will remain in substantially the same phase.

Although the invention has been illustrated and described as embodied in several particular modifications it will be understood that the invention is not limited to these constructions but may be embodied in other forms.

Having thus described the invention, I claim:

1. A dynamo transformer comprising a stator having four symmetrically disposed poles, a movable element of magnetic material mounted within the stator and having a neutral position with respect to the poles, the movable element being capable of limited movement from said neutral

position, two sets of stator windings, one set of windings being associated with all four poles and connected to produce a magnetomotive force pattern in which the forces are directed inwardly in two adjacent poles and outwardly in the other two poles, and the other set of windings being associated with all four poles and connected to produce a similar pattern but displaced from that of the first set.

2. A dynamo transformer comprising a stator having four symmetrically disposed poles, a movable element of magnetic material mounted within the stator and having a neutral position symmetrical with respect to the poles, the movable element being capable of limited movement from said neutral position, two sets of stator windings, one set of windings being associated with all four poles and connected to produce a magnetomotive force pattern in which the forces are directed inwardly in two adjacent poles and outwardly in the other two poles, said set of windings having a substantially constant self inductance, and the other set of windings being associated with all four poles and connected to produce a similar pattern but displaced from that of the first set, said other set of windings being also of substantially constant self-inductance, the mutual inductance of the windings being substantially proportional to the displacement of the movable element from neutral position.

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