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## (54) DC MOTORS

(71) We, SONY CORPORATION, a corporation organised and existing under the laws of Japan, of 7-35 Kitashinagawa-6, Shinagawa-ku, Tokyo, Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

Various types of brushless *dc* motors are known, such as a 2-pole alternate phase motor, a 2-pole 3-phase motor, a bidirectional 2-phase motor and a 4-pole motor. In a 2-pole alternate phase motor, a single pair of magnetic poles is provided, usually formed of permanent magnet north and south pole pieces, and two alternately energized coils also are provided. Either the permanent magnet pole pieces or the coils may constitute the rotor assembly, and the rotor may be disposed either within the stator assembly or in circumscribing relation with respect thereto. Thus, each pole piece extends for an electrical angle of 180°, and each coil likewise subtends an arc of 180 electrical degrees.

In a typical 2-pole alternate phase motor, each coil includes conductor segments for carrying current in directions which are normal to the magnetic flux generated by the permanent magnet pole pieces. In accordance with Fleming's rule, also known as the left-hand rule, torque is produced in a direction perpendicular both to the direction of flux and the direction of current flow. The coils are wound on a cylindrical surface so that the conductor segments include a first current path portion for carrying current in a first direction and a second current path portion for carrying current in a second, opposite direction, these current path portions being separated by 180 electrical degrees. If one coil is energized at the moment that the first current path portion enters the region of magnetic flux having, for example, a north polarity, a rotational torque is produced so as to drive the rotor assembly in a given direction. This coil then is de-energized at the moment that the first current path portion leaves the region of magnetic flux having north polarity, and the other coil then is energized. Thus, each coil is energized only when its first current path portion first enters the region of magnetic flux of given polarity. Consequently, the resultant torque is provided with significant ripple, which may not be desirable. Furthermore, if the motor comes to rest with the first current path portion of each coil disposed in the region of magnetic flux polarity transition, it is necessary to provide auxiliary starting means for subsequently starting motor rotation.

In a typical 2-pole 3-phase motor, magnetic flux is generated by permanent magnet north and south pole pieces. However, the coil structure here is formed of three coils, as opposed to the two coils described in the aforementioned 2-pole alternate phase motor. Each coil is wound on a cylindrical surface and includes first and second current path portions which are separated from each other by 180 electrical degrees. However, the first current path portion of one coil is separated by 120° from the first current path portion of the next adjacent coil. Rotational torque of a given direction is produced when the first current path portion of a coil has advanced by a given electrical angle into the region of magnetic flux of predetermined polarity. This predetermined angle generally is about 30 electrical degrees. After one coil has been energized for a duration corresponding to 120 electrical degrees, the first current path portion of the next coil will have been advanced by an angle of 30 electrical degrees into the region of magnetic flux of predetermined polarity. At that time, the first coil is de-energized and the next coil is energized. Consequently, all three coils are energized in sequence resulting in an overall torque whose ripple is substantially reduced from the ripple attending the aforedescribed 2-pole alternate phase motor. In addition, because of the particular dimensions of each permanent magnet pole piece, the angle subtended by each coil and the phase displacement of the respective coils, the problem of the motor coming to rest at a zero torque location, mentioned above with respect to the 2-pole alternate phase motor, is avoided. That is, auxiliary starting means is not necessary to impart a starting rotation to the motor regardless of the position at which it comes to rest.

However, one undesirable feature of the 2-pole 3-phase motor is the need for three position sensing elements for detecting the relative position of each coil with respect to the permanent magnet pole pieces. These three position sensing elements are needed so as to control the selective energization of each coil. The locations of these position sensing elements must be carefully established during the assembly operation in the construction of the *dc* motor such that each position sensing element is properly aligned with its associated coil. This tends to increase the cost of assembly, and thus the overall cost of such a motor. Furthermore, if the position sensing elements are packaged in module form, such a packaged module can be used only with a 2-pole 3-phase motor of corresponding diameter. A different package module must be used for different diameter motors. Still further, since three coils are provided, three separate switching circuits must be used in order to selectively energize the respective coils. Thus, although the torque characteristics of the 2-pole 3-phase motor are improved over the torque characteristics of the 2-pole alternate phase motor, this improvement is achieved at a significantly increased cost of the motor.

In the 4-pole 2-phase motor, four separate energizations, or current change-over operations, must be carried out over an angle of 360 electrical degrees. This requires two separate position sensing elements and four separate switching circuits. The bi-directional 4-pole motor similarly requires two position sensing elements but also must be provided with four separate switching circuits for each rotational direction of the motor. Hence, this bi-directional motor must be provided with eight separate switching circuits. It is appreciated that such 4-pole motors are significantly more expensive than the relatively simple 2-pole alternate phase motor.

According to the present invention there is provided a *dc* motor comprising:

an armature comprising at least two coils wound on an armature core, each of said coils being curved about the axis of the motor so as to provide an arcuate surface in contact with said armature core and each of said coils having a first current path portion through which current flows in a first direction and a second current path portion through which current flows in a second, opposite direction, one of said first and second current path portions being separated from the other on said armature core by an angle different from 180 electrical degrees;

commutation means for alternately energising said coils; and

a field system comprising at least one pair of magnetic poles for producing a magnetic flux distribution that alternates in magnetic filed polarity in a rotary path about the axis of the motor such that the polarity of the flux changes at two positions spaced 180 electrical degrees apart, the form of said field system in two regions each of 80 electrical degrees extent and respectively centered on said positions differing one from the other in such a way that the flux distributions within said respective regions from each other whereby the flux distribution is asymmetric.

Reference is hereby directed to our copending UK Patent Application No. 13530/78 (Serial No. 1604121), from which the present application was divided out, which includes claims directed to motors disclosed hereinbelow.

The invention will now be described by way of example with reference to the accompanying drawings, in which:

*Figures 1A* to *1C* represent a prior art 2-pole 3-phase *dc* motor;

*Figures 2A* to *2C* represent a prior art 2-pole alternate phase *dc* motor;

*Figures 3* to *5* represent one form of *dc* motor in accordance with our above-mentioned copending Patent Application No. 13530/78; Serial No. 1604121.

*Figures 6A* to *6C* are useful in explaining the operation of the motor of Figures 3 to 5;

*Figures 7A* and *7B* show one example of a coil-energizing circuit, and its manner of operation, useful with the motor of Figures 3 to 5;

*Figures 8A* to *8C* represent a modification of the motor of Figures 3 to 5;

*Figures 9* to *11* represent another modification of the motor of Figures 3 to 5;

*Figures 12* to *13* represent an embodiment of *dc* motor in accordance with the present invention;

*Figures 14A* to *14E* are useful in explaining the operation of this embodiment of a *dc* motor;

*Figure 15* is a waveform diagram useful in explaining the operation of a modification of this embodiment of a *dc* motor;

*Figures 16* to *24* represent various modifications of this embodiment of a *dc* motor;

*Figures 25* to *27* represent another embodiment of *dc* motor in accordance with the present invention; and

*Figures 28* to *30* represent various modifications of this embodiment of a *dc* motor.

Before discussing the embodiments of the present invention, various problems associated with prior art *dc* motors first will be described. Referring initially to Figure 1A, there is illustrated a schematic representation of a 2-pole 3-phase motor. For the purpose of the present invention, it is assumed that the rotor assembly comprises differently magnetized permanent magnet pole pieces. Hence, rotor assembly 101*a* is formed of a north pole piece N, having a circumferential arc of 180°, and an adjacent south pole piece S, also having a circumferential arc of 180°. The magnetic flux generated by the north and south pole pieces alternates in magnetic polarity in a sinusoidal waveform when considered in a rotational path about the motor axis. That is, if a reference point rotates with respect to the north and south pole pieces, the magnetic flux linking that reference point appears as a sinusoid, as shown by the sinusoidal waveform in Figure 1A. Since the north and south pole pieces constitute the rotor assembly 101*a*, the reference point actually is fixed and the north and south pole pieces rotate with respect thereto. Nevertheless, the magnetic flux appears as shown.

The stator assembly included in this 2-pole 3-phase motor is formed of three coils $L_1$, $L_2$ and $L_3$. Each coil may be thought of as being wound upon a cylindrical surface concentric with the rotor assembly 101*a*, and each coil having a conductor segment which conducts current in one direction and another conductor segment which conducts current in the opposite direction. As an example, both conductor segments may be parallel to the motor axis, resulting in each coil $L_1$, $L_2$ and $L_3$ extending over an arc of 180°. As shown in Figure 1A, current flowing out of the plane of the drawing is represented as a dot and current flowing into this plane is represented as an "X". Accordingly, current flowing out of the plane of the drawing is assumed, for the purpose of the present discussion, to flow in the positive direction, and thus through a positive path of the coil, while current flowing into the plane of the drawing is assumed to flow in the negative direction, and thus through a negative path of the coil. The positive path of the coil $L_1$ is phase displaced by 120° from the positive path of the coil $L_2$ which, in turn, is phase displaced by 120° from the positive path of the coil $L_3$, which is phase displaced by 120° from the positive path of the coil $L_1$. Hence, the three phases, or the coils $L_1$, $L_2$ and $L_3$ are wound in overlapping relation with respect to each other; yet the positive and negative paths of each coil are separated from each other by 180°.

In operation, when the positive path of the coil $L_1$ advances to a point $\theta_1$ into the region of magnetic flux generated by the north pole piece, the coil $L_1$ is energized. In accordance with Fleming's rule, a rotational torque is generated so as to provide rotation between the rotor and stator assemblies. This rotation continues until the positive path of the coil $L_2$ arrives at the point $\theta_1$. At that time, the coil $L_1$ will have reached the point $\theta_2$, which is displaced from the point $\theta_1$ by 120°. At this time, the coil $L_1$ is de-energized and the coil $L_2$ is energized. Consequently, rotational torque is generated due to the magnetic flux of north polarity and the positive current flowing through the positive path of the coil $L_2$, and also due to the magnetic flux of south polarity and the negative current flowing through the negative path of the coil $L_2$. The coil $L_2$ remains energized until the positive path of the next coil $L_3$ reaches the point $\theta_1$. At that time, the coil $L_2$, whose positive path has reached the point $\theta_2$, is de-energized and the coil $L_3$ is energized. As a consequence thereof, rotational torque is generated due to the magnetic flux of north polarity and the positive current flowing through the coil $L_3$, and also due to the magnetic flux of south polarity and the negative current flowing through the coil $L_3$.

As shown in Figure 1A, the positive path of the coil $L_1$ reaches the point $\theta_1$ at a time $t_1$, while the positive path of the coil $L_2$ reaches the point $\theta_1$ at a time $t_2$, and the positive path of the coil $L_3$ reaches the point $\theta_1$ at the time $t_3$. This means that the coil $L_1$ is energized from the time $t_1$ to the time $t_2$. The coil $L_2$ is energized from the time $t_2$ to a time $t_3$. The coil $L_3$ is energized from the time $t_3$ to a time $t_4$. Figure 1B represents the current energizing waveforms which are associated with the coils $L_1$, $L_2$ and $L_3$, respectively. Since each coil is energized only for a duration that the positive path thereof is within the range of magnetic flux having north polarity, it is appreciated that the rotational torque generated in response to each energization of the respective coils always is greater than zero. Figure 1C is a waveform representation of the generated rotational torque. It is seen that positive torque due to the energization of the coil $L_1$ is generated from the time $t_1$ to the time $t_2$; positive torque due to the energization of the coil $L_2$ is generated from the time $t_2$ to the time $t_3$; and positive torque due to the energization of the coil $L_3$ is generated from the time $t_3$ to the time $t_4$. This sequential energization of the coils, and resultant torque, is then repeated.

Since each coil must be separately energized for a duration of 120°, and since each coil must be energized only when its positive path reaches the point $\theta_1$, an individual position sensing element must be provided for each coil so as to detect when that coil reaches the point $\theta_1$. These three position sensing elements then can be used to generate the energizing currents at the proper times, and as shown in Figure 1B. Furthermore, three separate coil energizing circuits, or switching circuits, are needed to energize the coils $L_1$, $L_2$ and $L_3$, respectively. As mentioned above, the location of each position sensing element with respect to the remaining position sensing elements, and also with respect to the north and south pole pieces must be carefully established. This means that the angular relation of each position sensing element must be individually adjusted during the motor assembly operation. Furthermore, if all three position sensing elements are provided in a single package module, this module can be used only for motors of the same diameters. These problems are disadvantageous in the construction and assembly of a *dc* motor. Referring now to Figure 2A, there is illustrated one example of a 2-pole alternate phase motor wherein a rotor assembly 101*b* comprises adjacent north and south magnetic pole pieces each forming an arc of 180°. The stator assembly is shown as comprising two coils $L_1$ and $L_2$, each of these coils having positive and negative paths, as discussed previously with respect to Figure 1A, the positive and negative paths of each coil being separated from each other by 180°. Here, the coils $L_1$ and $L_2$ do not overlap. Rather, each coil is co-extensive with a magnetic pole piece. Accordingly, each coil may be wound upon the same cylindrical surface concentric with the motor axis. As before, the positive and negative paths may be thought of as conductor segments parallel to the motor axis for conducting currents in opposite directions.

As the rotor assembly 101*b* rotates, the magnetic flux linking a reference point appears as a sinusoidal waveform, as shown in Figure 2A. When the positive path of the coil $L_1$ reaches the point $\theta_1$, that is, when the positive path of the coil reaches the transition between north and south magnetic flux where the effective flux is zero, the coil is energized. The duration of energization of the coil $L_1$ is 180°, that is, until the positive path of this coil reaches the point $\theta_2$ at the next transition between north and south magnetic flux. At that time, the positive path of the coil $L_2$ has reached the point $\theta_1$ and the coil $L_2$ is energized while the coil $L_1$ is de-energized. Then, when the positive path of the coil $L_1$ once again reaches the point $\theta_1$, the coil $L_2$ is de-energized and the coil $L_1$ is energized.

Figure 2B represents the current waveform of the energizing currents flowing through the coils $L_1$ and $L_2$. The coil $L_1$ is energized at the time $t_1$, that is, at the time the positive path of this coil reaches the point $\theta_1$. The coil $L_2$ is energized at the time $t_2$, that is, at the time the positive path of this coil reaches the point $\theta_1$. Hence, a positive torque is generated as a result of the positive current flowing through the positive path of the coil $L_1$ and the magnetic flux of north polarity; and also due to the negative current flowing through the negative path of the coil $L_1$ and the magnetic flux of south polarity which links this negative path. Similarly, when the coil $L_2$ is energized, positive torque is again generated as a result of the positive current flowing through the positive path of the coil $L_2$ and the magnetic flux of north polarity; as well as a result of the negative current flowing through the negative path of the coil $L_2$ and the magnetic flux of south polarity linking that negative path. A waveform representation of this torque is illustrated in Figure 2C.

It is seen that at the times $t_1$, $t_2$, $t_3$, ... the rotational torque which is generated is reduced to zero. This is because, at these times, the positive and negative paths of an energized coil are linked with substantially zero magnetic flux. Because of this zero torque, there is the possibility that if the rotor is stopped at a position wherein the positive (or negative) path of a coil is at the point $\theta_1$ (or $\theta_2$), the subsequent energization of the coil will result in zero torque. This means that an auxiliary starting means may be necessary to impart initial rotation to the rotor. Although the 2-pole alternate phase motor apparently needs only a single position sensing element to detect the rotational poisiton of the rotor with respect to the energizing coils, and only two switching circuits are needed to energize the respective coils, the attendant problem of zero torque at selected angular locations of the rotor is disadvantageous. Furthermore, a substantial ripple is exhibited by the generated torque, as shown in Figure 2C. This also is disadvantageous.

The foregoing problems associated with the motors of Figures 1 and 2 are avoided with the motors described below. Of these, the motors described with reference to Figures 3 to 11 are in accordance with the invention of our abovementioned copending Patent Application No. 13530/78, Serial No. 1604121 while the motors described with reference to Figures 12 to 31 are in accordance with the present invention.

One form of motor is shown in the plan view of Figure 3 and the sectional view taken along lines IV-IV and shown in Figure 4. In this motor, a rotor assembly 101 is an outer rotor which circumscribes and rotates about the stator assembly. The rotor assembly 101, hereinafter, simply a rotor, is a cup-shaped yoke fixed to an end portion of a rotatable shaft 106. The shaft 106 is rotatably supported by a cylindrical support member 103 having a central, axial opening therein, one end of this opening being provided with a bearing 104 and the other, opposite opening being provided with a bearing 105. The cylindrical support member 103, together with the bearings 104 and 105 and the shaft 106, is mounted on a support plate 102. As shown, one end of the shaft 106 extends outwardly from the support plate 102 and is arranged to drive a member secured thereto. As one example, the shaft 106 may be used to drive a rotary drum in a video tape recorder (VTR). Of course, various other examples of apparatus with which the illustrated motor can be used are contemplated, and the particular device to which the shaft 106 is secured is not of present importance.

The other end of the shaft 106 is secured to the rotor 101 by a set screw 106*a*. The rotor 101 includes a permanent magnet north pole piece 107 and a permanent magnet south pole piece 108. The pole pieces 107 and 108 are secured to the inner cylindrical side walls of the cup-shaped yoke and are magnetized in the thickness direction such that the north and south poles face inwardly, that is, towards the shaft 106, as shown more clearly in Figure 4. The in north pole piece 107 subtends an angle of 240° with respect to the motor axis, and the south pole piece 108 subtends and angle of 120°. That is, the north pole piece 107 is an arcuate segment of 240° while the south piece 108 is an arcuate segment of 120°. In the present motor, since only one pair of poles is provided, the "electrical" angle subtended by each pole piece is equal to its "positional" angle. For the purpose of this and the following description, a "positional" angle is a geometric angle between two points on the rotor or on the stator. More sensibly, the "electrical" angle is equal to the "positional" angle divided by the number of pairs of poles.

The stator assembly, hereinafter, simply the stator, is secured to the cylindrical support member 103. The stator is formed of a toroidal core 109 which is concentric with the motor axis, and a pair of coils 110 and 111, each coil being wound toroidally on the core 109. The coils 110 and 111 are spaced apart from each other by 180°. That is, the central portion of the coil 110, as viewed in Figure 4, is 180° from the central portion of the coil 111. Thus, these coils are diametrically opposite to each other. A small gap is provided between the inner circumferential surface of the pole pieces 107 and 108 and the outer circumferential surfaces of the coils 110 and 111.

The cylindrical support member 103 is provided with a flange by which it is mounted upon the side plate 102. An annular mounting plate 113 is provided on the cylindrical support member 103 for supporting a circuit board 112. As one example, the annular mounting plate 113 may be formed of synthetic resin. A drive circuit 114 is attached to the circuit board 112, and leads (not shown) from the coils 110 and 111 also are connected to the circuit board 112. The drive circuit 114 is thus arranged selectively to energize one or the other of the coils 110 and 111 so as to generate a rotational torque whereby the rotor 101 is rotated. In this regard, a position sensing element 115, such as a Hall-effect device, is provided for the purpose of sensing the rotational position of the rotor 101 and to generate suitable signals in response thereto so as to control the drive circuit 114. The hall-effect device 115 may sense the intensity and polarity of the magnetic flux generated by the north and south pole pieces 107 and 108, thereby producing position signals as a function of such detected flux. As another example, the position sensing element 115 may comprise an optical sensor capable of sensing optical indicia provided at discrete locations on the rotor 101. Other forms of position sensing element 115 also can be used if desired.

A developed view of the rotor 101 and the stator coils 110 and 111 is shown in Figure 5A. A magnetic circuit is formed of the north pole piece 107, the core 109, the south pole piece 108 and the cup-shaped yoke of the rotor 101. The magnetic flux which traverses this closed loop is shown by the broken lines in Figure 5A. Current is supplied to the coils 110 and 111 such that current flows out of the plane of the drawing through the conductors of each coil which are closer to the pole pieces, and current flows into the plane of the drawing through those conductors of each coil which are farther away from the pole pieces. Hence, the conductors which face the pole pieces are designated as the positive path while the conductors which are farther from the pole pieces are designated as the negative path. It is appreciated that the flux which links the positive path of an energized coil is greater than the flux which links the negative path because of the particular configuration of the illustrated magnetic circuit. Thus, using Fleming's rule, if the coil 110 is energized when it is juxtaposed to the north pole piece 107, a torque is generated to produce rotation in the direction W, as indicated by the arrow. Of course, an opposite torque is produced as a result of the magnetic flux of north polarity and the negative current flowing through the negative path of the coil 110. However, because of the reduced flux which links this negative path, the opposite, counteracting torque is substantially reduced. The overall torque is thus in the direction W. As will be described below, the coil 110 is energized for only a portion of the angular duration that it is linked with the magnetic flux of north polarity. Hence, the coil 110 is energized only after it is within the vicinity of this magnetic flux, and then it is de-energized prior to the time that it passes out of this vicinity. The coil 111 is similarly energized, following the energization of the coil 110.

It is seen that the positive and negative paths of each of the coils 110 and 111 are separated from each other by the thickness of the core 109. This differs from the separation of 180°, as in the coils $L_1$, $L_2$ and $L_3$ of the prior art motor shown in Figure 1A. This 180° separation is needed in the prior art motor so as to generate torque in a predetermined direction due to the magnetic flux of north polarity which links the positive current and the magnetic flux of south polarity which links the negative current. However, in the embodiment shown in Figure 5A, torque is generated in a predetermined direction primarily due to the magnetic flux of north polarity which links the positive current. Only a very small opposite torque is generated because of the negative current which flows through the negative path of the energized coil. Since the north pole piece 107 is shown in Figure 5A as extending over an angle greater than 180°, if the coils 110 and 111 were wound in the manner shown in Figure 1A, it is possible that both the positive and negative paths of the same coil would concurrently be linked with magnetic flux of the same polarity. This would mean that equal and opposite torques would be generated at that time. This difficulty is avoided by the winding configuration shown in Figures 3, 4 and 5A. Furthermore, if each coil is wound on the same cylindrical surface such that the positive and negative paths likewise are disposed on the same surface, then the number of turns of the coil is a function of the angular separation between the positive and negative paths. That is, and with reference to the coils shown in Figure 1A, the number of turns in each coil is limited by the 180° angular separation between the positive and negative paths thereof. However, by winding the coils 110 and 111 toroidally on core 109, the number of turns of each coil can be increased without this limitation. That is, and as shown more clearly in Figure 5A, the number of turns of a coil is not limited by the angular separation between the positive and negative paths.

A modification of the motor shown in Figures 3 and 4 is illustrated in a developed view in Figure 5B. In this modification, an additional rotor 101′ is provided. This additional rotor 101′ may be disposed interiorally of the core 109 and may be secured to the outer rotor 101 so as to be rotatable therewith. The inner rotor 101′ may be provided with a magnetic north pole piece 107′ and a magnetic south pole piece 108′, these inner pole pieces being aligned with and symmetrical to the outer pole pieces 107 and 108, respectively. The respective magnetic circuits formed between the outer rotor 101 and the core 109, and the inner rotor 101′ and the core 109 are shown by broken lines. Using Fleming's rule, it is seen that the magnetic flux of north polarity generated by the north pole piece 107′ of the inner rotor 101′ links the negative path of the coil 110 so as to generate a torque is the direction W. Thus, torque which is generated as a result of the inner rotor is in the same direction as the torque which is generated as a result of the outer rotor. Consequently, and because of these aiding torques, the *dc* motor is highly efficient.

Although the permanent magnet pole pieces 107′ and 108′ are symmetric with respect to the permanent magnet pole pieces 107 and 108 this symmetry is not an absolute requirement. For example, the permanent magnet pole pieces 107′ and 108′ each may extend for an angle of 180°. Although the torque due to the inner rotor 101′ and the negative path of each energized coil thus may be reduced to zero, as in the prior art 2-pole alternate phase motor shown in Figures 2A to 2C, the net torque is not so reduced because of the asymmetry of the permanent magnet pole pieces 107 and 108 of the outer rotor 101.

In the motor shown in Figure 5B, it is assumed that the coils 110 and 111 are radially spaced from the outer rotor 101 and inner rotor 101′. As an alternative, the rotors 101 and 101′ may be constructed as discs, and the coils 110 and 111 may be axially spaced from these disc-shaped rotors and disposed intermediate such discs.

Returning to the motor shown in Figure 5A, the magnetic flux generated by the north pole piece 107 and the south pole piece 108 in a rotary path about the axis of the motor is shown by the waveform in Figure 6A. The magnetic flux distribution due to the north pole piece 107 is seen to be substantially trapezoidal and extends over a positional angle greater than 180°. The magnetic flux distribution due to the magnetic south pole piece 108 is substantially sinusoidal and extends for a positional angle substantially less than 180°. In the example wherein it is assumed that the north pole piece 107 extends for 240°, the trapezoidal flux distribution due to the north pole piece likewise is seen to extend for 240°. The magnetic flux of south polarity thus extends for 120°.

Figure 6A also represents the positive path of each of the coils 110 and 111. When the positive path of the coil 110 extends into the magnetic flux of north polarity by an angle of 30°, the coil 110 is energized. This energization extends for a duration of 180°, at which time the positive path of the coil 111, which is 180° displaced from the coil 110, extends into the magnetic flux of north polarity by an angle of 30°. At that time, the coil 110 is de-energized and the coil 111 is energized. Thus, the coil 110 is energized from the point $\theta_1$ to the point $\theta_2$, the latter being displaced from the point $\theta_1$ by 180°. Similarly, the coil 111 is energized from the point $\theta_1$ to the point $\theta_2$. At the point $\theta_1$, the magnetic flux of north polarity is of almost constant magnitude. Thus, the torque which is generated as a result of this substantially constant flux linked with the energized coil exhibits minimal ripple.

Figure 6B illustrates the energizing current waveforms associated with the coils 110 and 111, respectively. Thus, the coil 110 is energized at the time $t_1$ when the positive path thereof reaches the point $\theta_1$. This energization continues for 180° until the time $t_2$. At that time, the coil 110, whose positive path has reached the point $\theta_2$, is de-energized; while the coil 111, whose positive path has reached the point $\theta_1$, is energized. The coil 111 is then energized for a duration of 180°, at which time $t_3$ the coil 111 is de-energized and the coil 110 is energized once again.

Figure 6C represents the waveform of the rotational torque which is produced as a result of the energization of the coils 110 and 111 in the manner shown in Figure 6B. This torque is substantially constant, with minimal ripple, because each coil is energized at a time that it is linked with magnetic flux of substantially constant magnitude, and for a duration during which the magnitude of this flux remains constant. During the duration that a coil is energized, the magnetic flux linked therewith is not reduced to zero. Thus, the problem of zero torque associated with the aforedescribed prior art 2-pole alternate phase motor is avoided. Because of the practically negligible ripple in the generated torque (Figure 6C), the motor can be used as a drive motor for a VTR, a capstan drive motor for a tape recorder, a drive motor for a video disc player and the like, such a drive motor exhibiting substantially constant drive characteristics, thus providing advantageous performance.

It is seen from Figure 6A, that if a coil, for example, the coil 110, is energized throughout the region of magnetic flux having north polarity, the resultant torque which is generated thereby is produced through an angular range having an electrical angle greater than 180°. Accordingly, the position sensing element 115 (Figure 3) is used to detect when the positive path of the coil 110 reaches the point $\theta_1$; that is, the position sensing element 115 senses when the positive path of the coil 110 extends by angle of 30° into the magnetic flux distribution generated by the north pole piece 107. This same position sensing element 115 also may detect when the rotor 101 has been rotated by 180° from the point $\theta_1$. Thus, the position sensing element 115 may also detect when the positive path of the coil 110 extends by an angle of 210° into the magnetic flux distribution generated by the north pole piece 107. These sensed positions of the rotor 101 are used to generate change-over signals for controlling the alternate energization of the coils 110 and 111.

As an example, if the position sensing element 115 is a Hall effect device, it may detect the magnetic flux from the north pole piece 107 which exceeds the magnitude at the point $\theta_1$. Since this magnitude is exceeded throughout the range of points $\theta_1$ to $\theta_2$, the Hall effect device would produce a change-over signal of the type associated with the energizing current of the coil 110, as shown in Figure 6B. Once this change-over signal is produced, the reciprocal thereof can be used to energize the coil 111. As mentioned above, the position sensing element 115 may, in the alternative, comprise an optical position sensor, and suitable detectable indicia may be provided on the rotor 101 so as properly to activate the optical senso As yet another alternative, the position sensing element 115 may be arranged to detect only the positive-going zero crossing of the magnetic flux distribution shown in Figure 6A. Suitable delay circuits then can be used to generate the change-over signals (Figure 6) at the times $t_1$, $t_2$, ... in response to these detected positive-going zero crossings.

One example of the drive circuit 114 which can be used with the position sensing element 115 selectively to energize the coils 110 and 111 is shown schematically in Figure 7A. The position sensing element 115 here is assumed to be a Hall-effect device having output terminals 115*a* and 115*b*. The output terminal 115*a* is coupled to the base electrode of a PNP transistor 116*a* whose emitter electrode is connected through a load resistor to a suitable source of operating potential +V and whose collector electrode is connected to the base electrode of a current switching transistor 117*a*. Similarly, the output terminal 115*b* is connected to the base electrode of a PNP transistor 116*b* whose emitter electrode is connected in common with the emitter electrode of the transistor 116*a* and whose collector electrode is connected to the base electrode of a switching transistor 117*b*. The collector-emitter circuits of the transistors 117*a* and 117*b* are connected in series with the coils 110 and 111, respectively. As the rotor 101 rotates, the magnetic flux generated by the north and south pole pieces 107 and 108 is detected by the Hall-effect device 115 to generate output voltages *a* and *b*, shown in Figure 7B, at the output terminals 115*a* and 115*b*, respectively. It is seen that, although the north and south pole pieces are asymmetrical with respect to each other, and particularly, the north pole piece 107 extends for an arcuate angle of about 240° while the south pole piece 108 extends for an arcuate angle of about 120°, the output voltages *a* and *b* produced by the Hall-effect device 115 are symmetrical with respect to each other. The output voltage *a* is amplified by the transistor 116*a* and inverted so as to render the transistor 117*a* conductive from the $t_1$ to the time $t_2$. Similarly, the output voltage *b* is amplified by the transistor 116*b* and inverted thereby so as to render the transistor 117*b* conductive from the time $t_2$ to the time $t_3$. Consequently, energizing currents flow through the coils 110 and 111, respectively, as shown by the waveforms in Figure 6B. That is, current flows alternately through the coils 110 and 111 for an angular duration of 180° while the energized coil is within the range of magnetic flux having north polarity. The transistor 117*a* is energized when the coil 110 rotates from the position $\theta_1$ to the position $\theta_2$; and the transistor 117*b* is energized when the coil 111 rotates from the position $\theta_1$ to the position $\theta_2$.

Although the arrangement shown in Figure 7A energizes the coils 110 and 111 alternately, each for a duration of 180°, the duration of such alternate energization can be varied. For example, the coil 110 can be energized for a duration greater than 180°, while the coil 111 is energized for a lesser duration. Of course, this duration of energization is dependent upon the arcuate length of the coil, the angular extend of magnetic flux of north polarity and the point within this magnetic flux at which the coil is energized.

If the position sensing element 115 is constructed as a different element, such as an optical position sensing element, the output from this element, such as the voltage *a* (Figure 7B) can be used to energize the coil 110, while a polarity-inverted version, such as the voltage *b* (Figure 7B) can be produced to energize the coil 111.

In the motor of Figures 3, 4 and 6, it is assumed that one magnetic pole piece extends over an arc of 240° while the other magnetic pole piece extends over an arc of 120°. However, this 2:1 ratio is not critical. Rather, it is important simply that the permanent magnet pole pieces 107 and 108 are asymmetrical with respect to each other. For example, one of these pole pieces may extend over an arcuate angle of 270°, while the other pole piece extends over an arcuate angle of 90°. The coils 110 and 111 may then be energized for equal durations of 180° each, or for different durations, for example, 240° and 120°, respectively.

If one magnetic pole piece extends over an arcuate angle which is too large with respect to the arcuate angle of the other pole piece, the magnetic flux is so densely concentrated into the smaller pole piece as to saturate it. Hence, the magnetic flux which links the coils 110 and 111 exhibits a reduced magnetic flux density. This means that in the graphical representation of magnetic flux density as shown in Figure 6A, the magnitude over the range of $\theta_1$ to $\theta_2$ is reduced. As a result thereof, the rotational torque due to this magnetic flux likewise is reduced. Hence, it is preferred that the arcuate extent of the north and south pole pieces be sufficient that the magnitude of the magnetic flux density generated by one of these pole pieces is at least equal to some predetermined value which is substantially constant over as wide an angular range as possible. For example, the arcuate extent, or circumferential dimension, of one magnetic pole piece may be between 220° to 280°, while the angular extent, or circumferential dimension, of the other magnetic pole piece is in the range of 80° to 140°. As a still further limitation, the larger magnetic pole piece may exhibit a circumferential dimension of from 240° to 260°, while the smaller magnetic pole piece may exhibit a circumferential dimension of from 100° to 120°.

In the foregoing example, it has been assumed that the arcuate extent, or circumferential dimension, of the north pole piece is greater than that of the south pole piece. If desired, this can be reversed, and the south pole piece can be larger than the north pole piece. Furthermore, it has been assumed that the motor is a simple 2-pole motor. However, the foregoing principles are equally applicable to a 4-pole or 2n-pole motor, as desired. In that event, the foregoing description of angular extent, angular duration and angular position should be understood as referring to "electrical" angle.

Furthermore, the arcuate extent, or circumferential dimension, of the coils 110 and 111 has not been specified. However, it should be appreciated that these coils are diametrically opposed with respect to each other and each is angularly (circumferentially) smaller than at least the larger pole piece.

With the construction of the *dc* motor, as described above with respect to Figures 3 to 7, the rotational torque is not reduced to zero at any point of the rotation of the rotor through an angle of 360 electrical degrees. Since the magnetic flux density which is linked with the energized coil throughout substantially the entire duration of such energization is constant, the rotational torque exhibits only negligible ripple. Because only the positive (or negative) path of each coil is linked with magnetic flux of substantial magnitude, opposite rotational torques are not generated by reason of the positive and negative currents flowing through the energized coil.

A comparison of the torque waveform shown in Figure 6C with the torque waveform shown in Figure 1C indicates a substantial improvement over prior art 2-pole 3-phase motors. This improvement is attained with a concomitant reduction in the number of position sensing elements which must be used, and the complexity of the coil energizing circuit. Hence, the cost of manufacturing is advantageously reduced. Furthermore, the coil drive circuit can easily be formed as an integrated circuit. Since only a single position sensing element is used, any positional adjustment of that element with respect to the coils is relatively simple. Also, the same single position sensing element can be used for motors of different diameters. This means that standardized parts for motors of different dimensions can be achieved. This adds to a further reduction in the overall cost of manufacturing and assembling such motors.

The rotor 101, shown in Figures 3 and 4, can be modified as illustrated in Figures 8A to 8C, wherein Figure 8B is a top view of the modified rotor 101, Figure 8A is a sectional view taken along lines VIIIA-VIIIA of Figure 8B, and Figure 8C is an exploded view. A disc-type permanent magnet 120, magnetized in its thickness direction, is interposed between yokes 121 and 122 formed of magnetic path forming members. In particular, the yoke 121 is in magnetic contact with the north pole of the disc-magnet 120 and the yoke 122 is in magnetic contact with the south pole of the disc-magnet 120. The yoke 121 is provided with a semi-cylindrical side wall 121*b* which extends over an arcuate range, or circumferential dimension, of about 240°. A centrally disposed opening 125 is provided in a base or bottom wall 121a of the yoke 121 and receives the motor shaft 106.

The yoke 122 is provided with a similar semi-cylindrical wall 122*b* which extends over an arcuate range, or circumferential dimension, of about 120°. The yoke 122 is provided with a cup-like base 122*a* in which a centrally disposed opening 126 is provided, the opening 126 being aligned with the opening 125 so as to receive the shaft 106 therethrough. A set screw 127 mounted on a collar of the yoke 122 is provided to secure the yokes 121 and 122 to the shaft 106. The disc-magnet 120, which is also provided with a centrally-disposed opening 124, is secured to the bottom wall 121a of the yoke 121 and the cup-like base 122*a* of the yoke 122, as shown in Figure 8A.

It is appreciated that the yoke 121 and 122 generate magnetic flux having the distribution shown in Figure 6A. Hence, the yokes 121 and 122 are analogous to the pole pieces 107 and 108, respectively. The stator coils 110 and 111 (not shown) are arranged to be mounted within the yoke 121 and 122, analogous to the mounting of the stator structure shown in Figures 3 and 4. Accordingly, further description of the operation of and advantages derived from the motor shown in Figures 8A to 8C is not provided.

The motors shown in Figures 3 to 8 are of the so-called radial air gap type of *dc* motor. That is, in these motors the rotor 101 is radially spaced from the stator assembly. Although the rotor is shown as the outer-rotor type, the radial air gap type of motor nevertheless can be constructed as an inner-rotor type. As yet another modification, the *dc* motor may be of the so-called axial air gap type wherein the rotor and stator assemblies are axially spaced apart from each other. An example of an axial air gap type of *dc* motor is shown in the plan view of Figure 9 and sectional views of Figures 10 and 11 taken along lines X-X and XI-XI of Figure 9. In Figures 9 to 11, the same reference numerals are used to identify those components which have been described previously.

In the illustrated axial air gap type of motor, the motor is provided with four poles, such as north pole pieces 107*a* and 107*b* and south pole pieces 108a and 108b, which are circumferentially arranged alternately within the cup-shaped yoke of the rotor 101, as shown in Figures 9 and 11. One pair of pole pieces is formed of the north pole piece 107*a* and the adjacent south pole piece 108*a*; and the other pair of poles is formed of the north pole piece 107*b* and the adjacent south pole piece 108*b*. In each pair, the north and south pole pieces are asymmetric with respect to each other, and the north pole piece in one pair is diametrically opposed to the north pole piece in the other pair, while the south pole piece in one pair is diametrically opposed to the south pole piece in the other pair. The circumferential dimension of the north pole piece 107*a* is equal to about 240 electrical degrees, which corresponds to a positional angle of 120°, while the south pole piece 108*a* has a circumferential dimension of 120°, which corresponds to a positional angle of 60°. The north pole piece 107*b* and the south pole piece 108*b* exhibit similar circumferential dimensions.

The annular core 109 is provided with four coils 110*a*, 110*b*, 111*a* and 111*b* wound toroidally thereon. Adjacent coils are spaced apart from each other by a positional angle of 90°. The coils 110*a* and 110*b* are diametrically opposed to each other and are connected in series; as are the coils 111*a* and 111*b*. As clearly shown in Figure 9 the respective coils are spaced axially from the pole pieces. Hence, the pole pieces are magnetized in the axial direction so as to provide suitable north and south poles in facing relation to the coils 110a to 111b.

As can be seen from Figure 9, the coil 111*a* is provided with a positive (or negative) path which is formed of a conductor that extends in the radial direction. Thus, the positive (or negative) path of the coil 111*a* is closer to the north pole piece 107*b* than is the negative (or positive) path thereof. A similar relation is provided between the coil 111*b* and the north pole piece 107*a*, the coil 110*a* and the south pole piece 108*a* and the coil 110*b* and the south pole piece 108*b*. The magnetic flux distribution attributed to the north and south pole pieces is as shown in Figure 6A, with the understanding that the angular positions are electrical angles rather than positional angles. Hence, rotational torque is generated by, for example, the interaction of the coil 111*a* and the pole piece 107*b* which generates a magnetic flux of north polarity linked with the coil 111*a*, and a similarly directed torque generated by the magnetic flux of the pole piece 107*a* linking with the coil 111*b*. The coils 111*a* and 111*b* are energized for an angular duration of 180°, and then the coils 110*a* and 110*b* are energized for an angular duration of 180°.

Only one position sensing element 115 need be provided to detect the angular position of the rotor 101 for selectively energizing the respective coils. When one coil reaches the angular position $\theta_1$ (Figure 6A), it is energized together with the diametrically opposed series-connected coil. This energization continues until the energized coils reach the angular position $\theta_2$, at which time the series-connected coils are de-energized and the other diametrically opposed series-connected coils are energized. The position sensing element 115 detects when the angular position $\theta_1$ and $\theta_2$ are reached so as selectively to control, or change over, the energization of the coils 110*a* and 110*b* and the coils 111*a* and 111*b*. The drive circuit shown in Figure 7A can be used as the drive circuit 14. Hence, rotational torque having the waveform shown in Figure 6C is generated by the motor shown in Figures 9 to 11.

In the motor described above with respect to Figures 3 to 11, and claimed in our abovementioned copending UK Patent Application No. 13530/78, Serial No. 1604121, the coils are wound toroidally on a toroidal core. A description will now be given, with reference to Figures 12 and 13, wherein the same reference numerals are as used previously are used to identify like component parts, of a motor in which the coils are wound on a cylindrical surface concentric with the axis of the motor. More particularly, Figure 12 is a plan view of a motor constituting an embodiment of the present invention, and Figure 13 is a sectional view taken along lines XIII-XIII in Figure 12. The north pole piece 107 here is shown as a north pole piece 107*a* and the south pole piece 108 here is shown as a south pole piece 108*a*. The pole pieces 107*a* and 108*a* have equal circumferential dimensions, each being shown herein as about 140°. An auxiliary north pole piece 107*b* and an auxiliary south pole piece 108*b* are interposed between the north and south pole pieces 107*a* and 108*a* so as to complete the 360° circumference of pole pieces. The auxiliary north pole piece 107*b* and the auxiliary south pole piece 108*b* are each seen to have circumferential dimensions of about 40°. Furthermore, the north and south auxiliary pole pieces are seen to alternate in polarity with the main north and south pole pieces 107*a* and 108*a* so as to provide north, south, north, south magnetic flux in a rotary path about the motor axis.

The coils 110 and 111 are provided on a cylindrical surface and are mounted on the toroidal core 109. It is seen that the coils 110 and 111 are not toroidally wound about the core 109. Rather, these coils are wound in a manner similar to the coils of the prior art motors shown in Figures 1 and 2. The coil 110 is provided with a positive path 110*a* and a negative path 110*b* through which current flows in positive and negative directions, respectively, along conductors which are aligned in the axial direction. The embodiment of Figures 12 and 13 differs from the motors of Figures 3 to 11 in that the positive and negative paths of the coil 110 are equally spaced from the magnetic pole pieces. The coil 111 is similar to the coil 110 and includes a positive path 111*a* and a negative 111*b*, these positive and negative paths extending in the axial direction.

The positive and negative path portions of the coil 110 are separated from each other by a circumferential dimension equal to about 120°. Similarly, the positive and negative paths of the coil 111 are separated from each other by a circumferential dimension equal to 120°. That is, the angle defined by the positive and negative paths of a respective coil is equal to 120°. The coils 110 and 111 are diametrically opposed to each other, or separated by 180°.

The position sensing element 115 and the coil drive circuit 114 are provided on a circuit board 112, similar to the construction shown in Figure 3. In one embodiment, the position sensing element 115 is a Hall effect device, and an annular magnetic member 118 is provided on the rotor 101 in facing relation to this Hall effect device. The annular magnet 118 preferably is magnetized in its thickness direction so as to provide north and south poles each extending over a positional angle of 180°. Thus, the rotation of the annular magnet 118 past the Hall effect device 115 results in the generation of positional signals by the Hall effect device corresponding to the angular position of the rotor 101; these angular position signals being used by the drive circuit 114 selectively to energize the coils 110 and 111, in a manner soon to be described.

The motor shown in Figures 12 and 13 is redrawn in Figures 14A and the coils 110 and 111 are each represented by a single turn. A magnetic circuit is provided from the north pole piece 107*a* to the core 109, and then to the south pole piece 108*a* and the cup-shaped yoke of the rotor 101. Another magnetic circuit, or path, extends from the north pole piece 107*a* to the core 109 and then to the auxiliary south pole piece 108*b* to the cup-shaped yoke. Yet another magnetic circuit extends from the auxiliary north pole piece 107*b* to the core 109 and then to the south pole piece 108*a* and the cup-shaped yoke. Finally, a further magnetic circuit extends from the auxiliary north pole piece 107*b* to the core 109 and then to the auxiliary south pole piece 108*b* and the cup-shaped yoke. These magnetic circuits are represented by the broken lines shown in Figure 14A. The magnetic flux distribution in a rotary path about the axis of the motor is as shown in Figure 14B. The magnetic flux of south polarity extending from 0° to 140° is due to the south pole piece 108*a*; the magnetic flux of north polarity extending from 140° to 180° is due to the auxiliary north pole piece 107*b*; the magnetic flux of south polarity extending from 180° to 220° is due to the auxiliary south pole piece 108*b*; and the magnetic flux of north polarity extending from 220° to 360° is due to the north pole piece 107*a*. Hence, the magnetic flux is seen to exhibit a sinusoidal distribution from 0° to 140°, another sinusoidal distribution from 140° to 220°, and the first-mentioned sinusoidal distribution from 220° to 360°.

If it is assumed that the coil 110 is energized for a complete 360° rotation, then the rotational torque generated by the magnetic flux distribution shown in Figure 14B linking positive path the 110*a* appears as shown by a curve *a* in Figure 14C. This rotational torque is seen to have substantially the same waveform as the magnetic flux distribution shown in Figure 14B. Now, when positive current flows through the positive path 110*a*, negative current flows through the negative path 110*b* of the coil 110. If the negative path 110*b* is assumed to occupy the same position which is illustratively occupied by the positive path 110*a*, then the rotational torque generated by the magnetic flux which links this negative path portion would be as shown by a curve *b'* in Figure 14C. It is appreciated that the curve *b'* is the negative, or inverted version of the curve *a*, as is expected from the negative current flowing through the negative path 110*b*. However, actuality, the negative path 110*b* is angularly displaced, or phase delayed, by 120° from the postive path 110*a*. Thus, the curve *b'* in Figure 14C should be phase delayed by 120°. Such a phase delayed curve is shown as a curve *b*, which represents the torque which is generated as a result of the magnetic flux linking with the negative path 110*b*. Of course, the total torque which is generated is equal to the sum of the curves *a* and *b*. That is, the total torque is equal to the sum of the component which is due to the linking of the magnetic flux with the positive path 110*a* and the component due to the linking of the flux with the negative path 110*b*. When the curves *a* and *b* are added, the resultant, overall torque is as shown by the solid curve A in Figure 14C.

It is seen that the overall torque, represented by the curve A is positive over a rotational angle greater than 180°. In particular, this positive torque extends from about 132° to about 352°, for an angle of about 220°. It is appreciated that if the coil 110 is energized within this 220° range of positive torque, then the rotor 101 will be rotated in the direction W (Figure 14A). In this embodiment, the coil 110 is energized for a duration equal to 180 electrical degress within this range of 220°, and then the coil 111 is energized for a duration equal to 180 electrical degrees. For example, if the coil 110 is energized from the angular position $\theta_1$ to the angular position $\theta_2$, then when the positive path 110*a* reaches the angular position $\theta_2$, the positive path 111*a* of the coil 111 reaches the angular position $\theta_1$. At that time, the coil 110 should be de-energized and the coil 111 should be energized. As a typical example, the angular position $\theta_1$ is equal to a rotational angle of 150° which, it is seen from Figure 14A, extends by 10° into the magnetic flux of north polarity generated by the auxiliary north pole piece 107*b*. Of course, the period of energization of the coil 110 and then the coil 111 extends from 150° to 330°, the latter angular position corresponding to $\theta_2$. Accordingly, if the coil 110 is energized from the time that the positive path 110*a* reaches the angular position of 150° with the angular position of 0° being referenced at the boundary between the main north and south pole pieces 107*a* and 108*a*, then the coil 110 is de-energized when the positive path 110*a* reaches the angular position 330° and the positive path 111*a* of the coil 111 reaches the angular position 150°. The coil 111 is then energized from the time that its positive path 111*a* reaches the angular position 150° until the positive path 111*a* reaches the angular position 330°. At that time, the coil 111 is de-energized and the coil 110 is energised once again. The resultant overall torque which is generated in accordance with this selective energization of the coils 110 and 111 is shown in Figure 14D. The angular positions indicated in Figure 14D are the angular positions occupied by the coil 110. Hence, the coil 111, designated as the "B-phase", is energized for a duration of 180° from the time that the positive path 110*a* of the coil 110 is at 330° until this positive path of the coil 110 is at 150°. At that time, the coil 111 is de-energized, and the coil 110, shown as the "A-phase" is energized for a duration of 180 electrical degrees. It is appreciated that the overall rotational torque is not reduced to zero at any point during the rotation of the rotor 101.

The drive circuit 114, which may be similar to the drive circuit shown in Figure 7A, selectively energizes the coil 110 and the coil 111 with energizing current having the waveforms shown in Figure 14E. Preferably, each coil is energized for a duration of 180°. However satisfactory operation of the illustrated motor does not require that the coils be energized only for these equal angular durations. For example, the coil 110, that is, the A-phase, may be energized over an angular range of 190°, and the coil 111, the B-phase, may be energized over the angular range of 170°.

The annular magnet 118, which is used in conjunction with the position sensing element 115 to detect when the rotor 101 rotates to the angular position $\theta_1=150°$ is shown by the broken lines in Figure 13. As illustrated therein, a north-south boundary of the annular magnet 118 is positioned at 150° with respect to the 0° reference formed by the boundary between the main north and south pole pieces 107*a* and 108*a*. Hence, when this boundary in the annular magnet 118 is detected by the position sensing element 115, a suitable change-over signal is supplied to the coil driving circuits so as to change over or switch, the energization of these coils, whereby the coil 111 is de-energized and the coil 110 is energized. The annular magnet 118 is provided with another north-south boundary at 180° from the first-mentioned north-south boundary. This other north-south boundary is seen to be provided at 330° with respect to the 0° reference position of the main north and south pole pieces. Hence, when the position sensing element 115 senses this other north-south boundary, another change-over signal is produced so as to switch the energization of the coils, whereby the coil 110 is now de-energized and the coil 111 is energized. Thus, the cooperation of the annular magnet 118 and the position sensing element 115 results in the current change-over signals shown in Figure 14E, whereby the coils 110 and 111 are alternately energized.

The circumferential dimension of each of the main north and south pole pieces is less than 180°, and shown in Figures 12 to 14 as 140°. The angular spacing between the positive and negative paths of each of the coils 110 and 111 is less than the circumferential dimension of each main pole piece, and has been described herein as being equal to about 120°. However, as is apparent from the torque derivation curves *a* and *b*, the positive and negative paths of each coil may be separated from each other by less than 120°. Furthermore, although the magnetic flux distribution generated by the main and auxiliary pole pieces exhibits sinusoidal waveform components, as shown in Figure 14B, the flux distribution attributed to the main north pole piece 107*a* (or to the main south pole piece 108*a*) may be of a trapezoidal form, such as shown previously in Figure 6A. Similarly, the magnetic flux distribution due to the auxiliary pole pieces 107*a* and 108 may be of reduced magnitude. If the magnetic flux density over the angular range from 140° to 220° is thus reduced, such as shown by a curve a in Figure 15, then the resultant, overall rotational torque appears as shown by a curve A in Figure 15. In this figure, the curve A is derived by summing the components of torque due to the magnetic flux linking the positive path of the energized coil (this component being shown as the curve *a*) and the component produced by the magnetic flux linking the negative path of the coil (this component being shown by a curve b). The curve A of Figure 15 is seen to resemble the curve A of Figure 14C, except that the ripple of Figure 14C is substantially reduced. Here again, the coils 110 and 111 are alternately energized such that the torque generated as a result of the energization of each coil is substantially the same. This torque is represented as the section S of the curve A between the angular positions $\theta_1$ and $\theta_2$. That is, when the positive path 110*a* of the coil 110 reaches the angular position $\theta_1=150°$, the coil 110 is energized and remains energized until the positive path 110*a* reaches the angular position $\theta_2=330°$. At that time, the coil 110 is de-energized and the coil 111 is energized for an angular duration of about 180°. Thus, with the energization of the coil 111, a torque substantially similar to section S of curve A in Figure 15 is generated.

In view of the distribution of magnetic flux generated by the main and auxiliary pole pieces, as shown in Figure 14B, it is appreciated that the auxiliary pole pieces are not considered in calculating the number of pairs of poles. Thus, in the embodiments shown in Figures 12 to 14, even although four separate magnetic pole pieces are provided, the motor is a 2-pole motor consisting of only two main poles.

Another embodiment of this invention is shown in Figure 16A wherein a north pole piece 107 and a south pole piece 108 define one boundary therebetween and wherein an air gap 130 is provided between the other ends of these pole pieces. As before, each of the north and south sole pieces has a circumferential dimension of 140°. Hence, the air gap 130 is provided for a circumferential dimension of 80°. The total circumferential dimension of the north pole piece 107, the south pole piece 108 and the air gap 130 is equal to 360°. Thus, it is seen that the auxiliary pole pieces 107*b* and 108*b*, shown in Figures 13 and 14, are omitted. In addition, the positive and negative paths of each coil 110 and 111 are separated from each other by 100°. This differs from the embodiment of Figures 13 and 14 wherein the positive and negative paths of a coil are separated by 120°.

Referring to Figure 16B, it is seen that the magnetic flux density linking the coils 110 and 111 in the vicinity of the air gap 130 is substantially reduced relative to the remaining flux density. This, of course, is because no flux is generated by the air gap. The component of rotational torque due to the magnetic flux distribution shown in Figure 16B linking the positive path 110*a* of the coil 110 appears as shown by a curve *a* in Figure 16C. The component of rotational torque due to the magnetic flux distribution linking the negative path 110*b*, which is phase delayed by 100° from the positive path 110*a*, is as shown by a curve *b* in Figure 16C. The resultant, overall torque generated by the magnetic flux linking the coil 110 is as shown by a curve A. As is recognized, a similar rotational torque is generated as a result of the magnetic flux distribution linking the coil 111.

It is appreciated that the rotational torque which would be generated if a coil is energized for 360° is positive for an angular range which is greater than 180°. Thus, if the coils 110 and 111 are energized alternately, and each for a duration of about 180°, then positive torque that does not return to zero is generated for a rotational angle of 360°. Figure 16D is a waveform representation of this positive torque -- the curve identified as the A-phase curve is the torque generated by energizing the coil 110 for a duration of 180°, and the curve identified as the B-phase curve is the torque which is generated when the coil 111 is energized for a duration of 180°.

By providing the air gap 130, it is seen that the overall torque shown in Figure 16D exhibits even less ripple than the overall torque which is shown in Figures 14D and 15.

The coils 110 and 111 may be energized with a circuit of the type shown in Figure 7A using a position sensing element and annular magnet, such as an element 115 and a magnet 118 shown in Figures 12 and 13. In Figure 15C, the coil 110 may be energized from the time that its positive path reaches the angular position of 150° until its positive path reaches the angular position of 330°. A similar, alternate energization of the coil 111 then ensues.

Another modification of this embodiment is shown in Figure 17A wherein a north pole piece 107 and a south pole piece 108 each exhibit a circumferential dimension of 180°. However, a cut-out portion 131 is provided in the surface of the pole pieces facing coils 110 and 111. The cut-out portion 131 may have an arcuate extent of about 80°, and is comparable to the air gap 130 shown in Figure 16A. As a result of the cut-out portion 131, the magnetic flux density linking the coils 110 and 111 in the vicinity thereof is relatively low. The resultant magnetic flux distribution in a rotary path extending about the axis of the motor is shown in Figure 17B. It is seen that the cut-out portion 131 has the same effect upon the magnetic flux distribution (shown in Figure 17B) as does the air gap 130 (having the magnetic flux distribution shown in Figure 16B). Accordingly, in the embodiment shown in Figure 17A, the resultant, overall torque is positive over a range which is greater than 180°, as shown in Figure 16C. Therefore, by alternately energizing the coils 110 and 111 for approximately 180° durations, a torque having the waveform shown in Figure 16D is imparted to a rotor 101. That is, the torque which is generated by the embodiment shown in Figure 17A is quite similar to the torque which is generated by the embodiment shown in Figure 16A.

In the embodiment of Figure 16A, and in the embodiment of Figure 17A, the air gap 130 and the cut-out portion 131, respectively, may be filled with non-magnetic material having relatively low magnetic susceptibility. Nevertheless, this will not materially disturb the magnetic flux distribution shown in Figures 16B and 17B, respectively.

Yet another modification is shown in Figure 18A wherein a 4-pole brushless motor is illustrated. One pair of pole pieces is constituted by a north pole piece 107*a* and a south pole piece 108a, separated by an air gap 130*a* therebetween. The other pair of poles is constituted by a north pole piece 107*b* and a south pole piece 108*b* separated by an air gap 130*b* therebetween. The respective pairs of poles are symmetrical with respect to each other and extend about positional angles each equal to 180°. The coils are constituted by coils $110_A$ and $110_B$ forming one phase, and coils $111_A$ and $111_B$ forming the other phase. The coils $110_A$ and $110_B$ are diametrically opposed with respect to each other, as are the coils $111_A$ and $111_B$.

The circumferential dimensions and angular separations of the respective elements shown in Figure 18A are electrically equal to the circumferential dimensions and angular separations shown in Figure 16A. Since two pairs of poles are provided in the embodiment of Figure 18A, it is seen that the electrical angle is equal to twice the positional angle therein. Because of the two symmetrical air gaps 130*a* and 130*b*, the rotation of the rotor 101 in the embodiment of Figure 18A is more uniform than the rotation of the rotor 101 in the embodiment of Figure 16A.

A modification of the embodiment shown in Figure 18A is illustrated in Figure 18B. In this modified embodiment, three pairs of poles are provided, and two phases of coils also are provided. Thus, one pair of poles is constituted by a north pole piece 107*a* and a south pole piece 108*a* separated by an air gap 130*a*. Another pair of poles is constituted by a north pole piece 107*b* and a south pole piece 108*b* separated by an air gap 130*b*. The third pair of poles is constituted by a north pole piece 107*c* and a south pole piece 108*c* separated by an air gap 130*c*. The pairs are symmetrical with respect to the axis of the motor, and north and south pole pieces are seen to alternate circumferentially. One phase is constituted by the coils $110_A$, $110_B$ and $110_C$, and the other phase is constituted by the coils $111_A$, $111_B$ and $111_C$. These coils are seen to be arranged symmetrically with respect to the motor axis and a coil of one phase alternates with a similar coil of the other phase. Because of the symmetry provided by the three pairs of poles, the respective air gaps and the phases of coils, the rotation of a rotor 101 in the embodiment of Figure 18B is more uniform than the rotation of the rotor in the embodiment of Figure 16A.

Referring now to Figure 19A, yet another embodiment of the present invention is illustrated. In this embodiment, a north pole piece 107 and a south pole piece 108 each exhibit a circumferential dimension of 180°. However, the cup-shaped yoke of a rotor 101 is provided with a cut-out portion 132 which extends over an angle of about 80°. Whereas the cup-shaped yoke is included as part of the magnetic circuit whereby magnetic flux links coils 110 and 111 the cut-out portion 132 removes a portion of this magnetic circuit. Hence, the magnetic flux which links the coils in the vicinity of this cut-out portion is of reduced density. Thus, the magnetic flux distribution in a rotary path about the motor axis has the waveform shown in Figure 19B. It is appreciated that this waveform is quite similar to the waveform shown in Figure 16B. Hence, the overall torque which is generated by the magnetic flux linking the coils 110 and 111 is as shown in Figures 16C and 16D. In the embodiment of Figure 19A, it is contemplated that the coils 110 and 111 are alternately energized for substantially equal durations of about 180°. If desired, the cut-out portion 132 of the cup-shaped yoke may be filled with non-magnetic material.

Yet another embodiment of this invention is illustrated in Figure 20A wherein a north pole piece 107 and a south pole piece 108 each exhibits a circumferential dimension of 180°. However, in this embodiment, a cut-out portion is provided in the north and south pole pieces, and a magnetic shield plate 133 is fixed in this cut-out portion. The arcuate extent of this ferromagnetic shield plate is an angle equal to the arcuate extent of the cut-out portion 131 shown in Figure 17A. The shield plate 133 may extend over a larger arc.

As shown by the broken lines in Figures 20A, the shield plate 133 functions as a magnetic short circuit to prevent a portion of the magnetic flux generated by the north and south pole pieces in the vicinity of this shield plate from reaching coils 110 and 111. Consequently, in the air gap between the shield plate 133 and a core 109, the magnetic flux density is substantially reduced. That is, the coils 110 and 111, in the vicinity of the shield plate 133, are shielded from magnetic flux. As a consequence thereof, the magnetic flux density in a rotational path about the motor axis has the waveform shown in Figure 20B. It is seen that the magnetic flux is reduced to about zero in the angular range defined by the shield plate 133. This magnetic flux distribution is similar to the magnetic flux distribution shown in Figure 16B. Hence, the overall torque imparted to a rotor 101 in the embodiment shown in Figure 20A has the waveform shown in Figure 16D.

Figure 21A illustrates yet another embodiment of this invention wherein a north pole piece 107 and a south pole piece 108 extend for less than 180°. These pole pieces define a boundary at, for example, a 0° reference position, and a yoke 134 formed of ferromagnetic material is positioned in the gap between the other ends of the pole pieces. The yoke 134 is seen to fill an air gap 130 described previously with respect to Figure 16A. Hence the north pole piece 107 and the south pole piece 108 each have a circumferential dimension of 140°, and the yoke 134 has an arcuate angle of about 80°.

The magnetic path through the yoke 134 from the north and south pole pieces is shown by the broken lines in Figure 21A. Hence, this yoke modifies the magnetic flux distribution linking coils 110 and 111 in the vicinity thereof. This flux distribution along a rotary path of the motor axis has a waveform of the type shown in Figure 21B. This magnetic flux distribution is similar to that shown in Figure 14B, and is even more similar to the embodiment described with respect to Figure 15. Hence, the overall torque which is imparted to a rotor 101 in the embodiment of Figure 21A is as shown by curves A in Figures 14C and 15. Thus, if the coils 110 and 111 are alternately energized, the overall torque is not reduced to zero at any point along a rotation of 360°, and the ripple exhibited by this torque is relatively small.

A still further embodiment is shown in Figure 22A. This embodiment is similar to the embodiment described with respect to Figures 12 to 14, except that the auxiliary north pole piece 107*b* in the earlier-described embodiment is now formed of a pair of auxiliary north pole pieces 107*b* and 107*c*, and the auxiliary south pole piece 108*b* in the earlier-described embodiment now is replaced by a pair of auxiliary south pole pieces 108*b* and 108*c*. The remainder of the motor construction shown in Figure 22A is substantially similar to the previously described embodiment. However, the positive and negative paths of each coil 110 and 111 in Figure 22A may be spaced apart by less than 120°, for example, by 100°.

As a result of the alternately arranged auxiliary pole pieces 107*b*, 108*c*, 107*c* and 108*b*, the magnetic flux distribution in a rotary path about the axis of the motor appears as shown in Figure 22B. It is seen that magnetic flux of south polarity is separated from magnetic flux of north polarity by north and south polarity ripples which are attributed to the respective auxiliary pole pieces which are disposed between the main pole pieces. Of course, in the embodiment of Figure 22A, as in the embodiment of Figures 12 to 14, the main north pole is adjacent to an auxiliary south pole and the main south pole is adjacent to an auxiliary north pole. Although not shown herein, it may be recognized that the overall torque which is imparted to a rotor 101 in the embodiment shown in Figure 22A is similar to the overall rotational torque shown in Figure 14D, except that additional ripple components are provided between the positive peaks, although these additional ripple components are of reduced magnitude.

In the embodiment of Figure 22A, still additional auxiliary pole pieces can be provided between the main north and south pole pieces. Still further, the centrally disposed auxiliary pole pieces 107*c* and 108*c* can be omitted, if desired. the resultant air gap formed by removing these auxiliary pole pieces results in a magnetic flux distribution in the vicinity of this air gap having the waveform represented by the broken line shown in Figure 22B. Thus, additional ripples due to the auxiliary pole pieces 107*c* and 108*c* will be avoided. Still further, the air gap formed by removing these auxiliary pole pieces can be filled by a ferromagnetic material.

In the embodiment shown in Figure 22A, as well as in the described modifications thereof, the overall rotational torque remains positive over an angle of 360°, and is not reduced to zero at any point thereover.

Figure 23A illustrates yet another modification wherein the magnetic pole pieces included in a rotor 101 are formed as a single cylindrical anisotropic magnet 135. This anisotropic magnet 135 is surrounded by a cup-shaped yoke, and is magnetized so as to have four poles. Magnetic domains are provided at the 0° reference position and at a positional angle of 180°. A substantially continuous transition in the magnetic flux from north polarity to south polarity is provided at the 0° and 180° magnetic domains.

In regions X and Y, that is, at positional angles 90° and 270°, the magnetic flux density due to the anisotropic magnet 135 is reduced. The resultant magnetic flux distribution in a rotary path about the motor axis appears as shown in Figure 23B, with the reduced magnetic flux density in regions X and Y of Figures 23A being identified in Figure B. In view of the four poles which are provided by the anisotropic magnet 135, one complete cycle of the magnetic flux distribution, or 360 electrical degrees, is provided in a rotational angle of 180°. Hence, as the rotor 101 makes one complete rotation, the magnetic flux linking a reference position on a coil 110 or a coil 111 appears as shown in Figure 23B.

The reduced flux density at regions X and Y is similar to the reduced flux density shown in Figure 16B. Hence, the overall rotational torque imparted to the rotor 101 is substantially similar to the waveform shown in Figure 16D.

It may be recognized that the magnetic flux distribution shown in Figure 23B can be obtained by varying the intensity of magnetization of the anisotropic magnet 135 at regions X and Y. The use of an anisotropic magnet is particularly advantageous for a 4-pole alternate phase *dc* motor. Although Figure 23A shows two separate coils 110 and 111, each coil can be formed of a pair of series-connected coils, such as described previously with respect to Figure 18A.

In the embodiments shown in Figures 12 to 22, the angular extent or circumferential dimension, of the auxiliary pole pieces, air gaps, cut-out portions, shield plates and yokes are less than 180°. As examples, these elements have been shown to be about 80 electrical degrees; but other circumferential dimensions, or arcuate lengths can be used, as desired.

The angular separation, or distance, between the positive and negative paths of each coil has been shown to be less than 180° in the embodiments of Figures 12 to 23. As numerical examples, these angular separations have been described as 120° or 100° in specific embodiments. This angular separation may be represented as the electrical angle $\alpha$. A positional angle $\alpha'$ corresponds to the electrical angle $\alpha$. However, it is apparent that the positional angle which separates the positive and negative paths of a coil also may be represented by the supplemental $\beta$, wherein $\alpha' + \beta = 360°$. For example, and with reference to Figure 24A, the angular separation $\alpha'$ between positive path 110*a* and negative path 110*b* of a coil 110 is shown as 120°. However, the coil 110 may be formed such that a single turn is constituted by a conductor segment parallel to the motor axis and comprises the positive path 110*a*, followed by another conductor segment forming an arc of 240° followed by another conductor segment which is parallel to the motor axis and which comprises the negative path 110*b*, and finally followed by yet another conductor segment which forms an arc of 240° and which connects the path 110*b* and the path 110*a*. In that construction, the circumferential dimension of the coil 110, shown by solid lines in Figure 24A, that is, the angular separation between the positive path 110*a* and the negative path 110*b* is equal to 240°. A similar construction of a coil 111, shown by the broken line in

Figure 24A, results in a positive path 111*a* being separated from a negative path 111*b* by the angular distance of 240°.

Figure 24B is a perspective view of one turn of a coil 110 wherein a positive path 110*a* is separated from a negative path 110*b* by the angular distance of 240°. It may be appreciated that when coils 110 and 111 are both provided, portions of both coils overlaps with each other. That is, if the coils 110 and 111 are symmetrically disposed with respect to each other, diametrically opposed portions of the coil 110 will overlap with diametrically opposed portions of the coil 111, each for an angular distance of 60°.

Further, the positive and negative paths of the coil 110 (or the coil 111) may be separated from each other by the electrical angle $360° \times m + \alpha$, wherein *m* is a positive integer. With this angular separation, a graphical representation of rotational torque generated by the coil 110 (or the coil 111) is similar to curves *a* and *b* of Figure 16C, wherein these curves are shifted to the right by $360° \times m$. The resultant composite torque which is generated by the magnetic flux linking the coil 110 thus would be similar to curve A of Figure 16C.

In general, for an *n*-pole motor, the positional angle α′ by which the positive and negative paths of the coil 110 (or the coil 111) are separated may be expressed as

$$\alpha' = \frac{360° \times m + \alpha}{\frac{n}{2}}.$$

Thus, for the *n*-pole motor, the positional angular separation between the positive and negative paths of a coil may be expressed as α′ or by the supplementary positional angle β wherein

$$\beta = 360° - \frac{360° \times m + \alpha}{\frac{n}{2}}$$

As an example of the foregoing equation, Figure 24C represents a 4-pole motor. In this example, the electrical angle by which a positive path 110*a* is separated from a negative path 110*b* is assumed to be 100°, as in the embodiment shown in Figure 16A. Furthermore, in this 4-pole motor, the coils are wound in two phases, wherein one phase is formed of coils $110_A$ and $110_B$, shown by the solid lines in Figure 24C and being diametrically opposed to each other, and the other phase is formed of coils $111_A$ and coil $111_B$, being diametrically opposed to each other. All of the coils are symmetrically disposed about a core 109. Using the foregoing equation for the position angle α′, and with the assumption that $m = 1$, then the positional angle α′ between the positive and negative paths of the coil $110_A$ may be expressed as

$$\alpha' = \frac{360° + 100°}{\frac{4}{2}} = 230°$$

A similar positional angle $\alpha' = 230°$ separates the positive and negative paths of each of the remaining coils $110_B$, $111_A$ and $111_B$.

The positional angle by which the positive and negative paths of each coil are separated may be expressed as the supplemental angle β. That is, if the positional angle $\alpha' = 230°$, then the supplemental angle $\beta = 130°$. This positional angle β correspond to an electrical angular separation of 260° (since two pairs of poles are provided).

As also shown in Figure 24C, the coils $110_A$ and $110_B$ are separated from each other by a positional angle of 180°, which is equal to an electrical angle of 360°. Also, the coil $110_A$ is angularly spaced from the coil $111_A$ by the positional angle 90°, which is equal to the electrical angle 180°. A similar angular separation is provided between the coil $110_A$ and the coil $111_B$, between the coil $110_B$ and the coil $111_A$, and between the coil $110_B$ and the coil $111_B$.

Turning now to Figure 25, there is illustrated another embodiment of the present invention formed of a 4-pole, 2-phase motor. The same reference numerals are used in Figure 25 to identifiy the same component parts which have been identified previously Accordingly, a rotor 101 is seen to be formed of a cup-shaped yoke which circumscribes permanent magnet pole pieces, the rotor 101 being an outer rotor. One pair of poles is formed of a north pole piece $107_A$ and a south pole piece $108_A$, while the other pair of poles is formed of a north pole piece $107_B$ and a south pole piece $108_B$. Each pole piece is formed of segmental pole pieces, here shown as three segments each, each segmental pole piece in a pole being formed of different magnetic material. Thus, the north pole piece $107_A$ is formed of segments $107_{Ax}$, $107_{Ay}$ and $107_{Az}$. The south pole piece $108_A$ is formed of segments $108_{Ax}$, $108_{Ay}$ and $108_{Az}$. The north pole piece $107_B$ is formed of segments $107_{Bx}$, $107_{By}$ and $107_{Bz}$. Finally, the south pole piece $108_B$ is formed of segments $108_{Bx}$, $108_{By}$ and $108_{Bz}$.

The segments $107_{Ax}$, $108_{Ax}$, $107_{Bx}$ and $108_{Bx}$ all comprise rare earth metals and, as will be shown below, exhibit the greatest magnetization. The segments $107_{Ay}$, $108_{Ay}$, $107_{By}$ and $108_{By}$ all comprise ferrite and exhibit an intermediate magnetization. The segments $107_{Az}$, $108_{Az}$, $107_{Bz}$ and $108_{Bz}$ all comprise a magnetic rubber material and exhibit the lowest magnetization. Each segmental pole piece extends over an arc of 30°. Commencing with the pole piece $107_{Ax}$, and proceeding counterclockwise about the motor axis, the pole pieces are as follows: the north pole piece formed of rare earth metal, ferrite and magnetic rubber segments, the south pole piece formed of magnetic rubber, ferrite and rare earth metal segments, the north pole piece formed of rare earth metal, ferrite and magnetic rubber segments, and the south pole piece formed of magnetic rubber, ferrite and rare earth metal segments.

The coils are formed of two phases, one phase comprising the coils $110_A$ and $110_B$, and the other phase comprising the coils $111_A$ and $111_B$. The positive and negative paths of each coil are separated from each other by 120°. Furthermore, these phases are spaced from each other by 180 electrical degrees. That is, the coil $110_A$ is spaced from the coil $111_A$ by the positional angle of 90° which, since the motor is formed of two pairs of poles, is equal to an electrical angle of 180°. The coils $110_A$ and $110_B$ are connected in series and are diametrically opposed to each other, thus being spaced by 360 electrical degrees; and the coils $111_A$ and $111_B$ likewise are connected in series and are spaced from each other by 360 electrical degrees.

As mentioned above, the magnetization of the respective magnetic materials, that is, the rare earth metal, the ferrite and the magnetic rubber, differ from each other. Figure 26 is a graphical representation of the demagnetizing curves for each of these magnetic materials. Each demagnetizing curve is illustrated in the second quadrant of the corresponding magnetization curve. The abscissa represents magnetic field intensity (H), and the ordinate represents magnetic flux (B). The intersection of each curve with the abscissa ($H_c$) represents the coercive force of the corresponding magnetic material, and the intersection of the demagnetizing curve with the ordinate ($B_r$) represents the residual magnetic flux density for that magnetic material. The curves X, Y and Z are the demagnetizing curves for rare earth metal, ferrite and magnetic rubber, respectively. As shown, the coercive force $H_C$ (X) of rare earth metal is greater than the coercive force $H_C$ (Y) of ferrite which, in turn, is greater than the coercive force $H_c$ (Z) of magnetic rubber. Similarly, the residual magnetic flux density $B_r$ (X) of rare earth metal is greater than the residual magnetic flux density $B_r$ (Y) of ferrite which, in turn, is greater than the residual magnetic flux density $B_r$ (Z) of magneric rubber. If energy is represented as $B \times H$, then the energy of rare earth metal is greater than the energy of ferrite which, in turn, is greater than the energy of magnetic rubber.

The magnetic flux in the air gap between the pole pieces and the core 109 is represented by an operating line $P_m$ drawn on the graph of Figure 26. The magnetic flux densities in this air gap are found at the intersection of the operating line $P_m$ with the demagnetizing curves X, Y and Z. Thus, the linking magnetic flux densities due to the segmental pole pieces are expressed as $B_{d(X)}$, $B_{d(Y)}$ and $B_{d(Z)}$, wherein these linking magnetic flux densities are less than the corresponding residual magnetic flux densities, and wherein $B_{d(X)}$ is greater than $B_{d(Y)}$ which, in turn, is greater than $B_{d(Z)}$.

The rotor shown in Figure 25 is illustrated in a developed view in Figure 27A. The magnetic flux which is generated in a rotary path about the motor axis by the segmental pole pieces is shown as a sawtooth waveform. This flux decreases from a maximum of south polarity to zero at an electrical angle of 180°, and then increases to a maximum value of north polarity. At an electrical angle of 360°, the flux rapidly changes over from a maximum value of north polarity to a maximum value of south polarity. Then, the flux decreases to zero at an electrical angle of 180°, followed by an increase in flux of north polarity. At the next electrical angle of 360°, the polarity of the flux changes over once again. Although the magnetic flux density $B_{d(X)}$, $B_{d(Y)}$ and $B_{d(Z)}$ differ in a step-wise manner, the magnetic flux distribution shown in Figure 27A is seen to vary substantially linearly from a maximum south polarity to a maximum north polarity. This linear variation, as opposed to a staircase type of variation, is due to the interaction of the magnetic flux generated by each segmental pole piece. Thus, the step-wise changes in flux are averaged over the rotary path about the motor axis.

It is appreciated that the sawtooth flux distribution shown in Figure 27A is due to the variation in magnetic flux intensity generated by each segmental pole piece. Rather than forming the respective pole pieces of different magnetic material, each segment piece can be formed of the same magnetic material, but the intensity of the flux generated by each such segmental piece can vary. The various means described hereinabove for varying the magnetic flux intensity can be used with such segmental pole pieces.

The component of torque $T_a$ which is generated by the magnetic flux which links the positive path $110_a$ of the coil $110_A$ when the coil $110_A$ is energized is shown in Figure 27B. When the coil $110_A$ is energized, negative current flows through the negative path $110_b$ of this coil. The component of torque $T_b$ which is generated by the flux which links this negative path is shown by the broken curve in Figure 27B. The composite overall torque which is produced if the coil $110_A$ is energized for a 360° degree rotation is shown as curve $T_A$. It is seen that the torque $T_A$ is positive over a range which is greater than 180 electrical degrees. A similar torque, shifted by 180 electrical degrees, is generated when, for example, the coil $111_A$ is energized. This torque, produced by the coil $111_A$, may be represented as $T_B$. Since the coil $110_B$ is displaced by 360 electrical degrees from the coil $110_A$, a similar torque $T_A$ is produced when the coil $110_B$ is energized. Likewise, since the coil $111_B$ is displaced by 360 electrical degrees from the coil $111_A$, the torque $T_B$ is produced when the coil $111_B$ is energized.

A position sensing element, such as an element 115, as described above, may be provided to sense when the coil $110_A$ and then when the coil $111_A$ reaches a predetermined angular position. At that time, the position sensing element 115 triggers a current change-over circuit to energize the coils $110_A$, $110_B$ and then the coils $111_A$, $111_B$, respectively. The energizing currents flowing through the coils $110_A$ and $110_B$ are represented as the A-phase currents and the energizing currents through the coils $111_A$ and $111_B$ are designated the B-phase currents in Figure 27C. Thus, the coils $110_A$ and $110_B$ are energized for a duration of 180° within the range that the torque $T_A$ is positive, and then the coils $111_A$ and $111_B$ are energized for duration of 180° within the range that the torque $T_B$ is positive. As a result, a substantially constant composite torque is imparted to the rotor 101 over a 360° rotation of the rotor 101, as shown in Figure 27B. It is appreciated that the composite rotational torque exhibits negligible ripple.

Figure 28 shows a modification of the magnetic pole pieces which are formed of segmental pole pieces in Figure 25. Thus, each of pole pieces $107_A$, $108_A$, $107_B$ and $108_B$ in Figure 28 is formed of progressively changing thickness. This means that the air gap between a pole piece and a core 109 progressively increases (or decreases). As a result of this change in the air gap, the flux density linking the coils $110_A$, $110_B$, $111_A$ and $111_B$ has the waveform shown in Figure 27A. That is, by changing the thickness of the respective pole pieces, the intensity of the magnetic flux generated thereby correspondingly changes. Hence the composite rotational torque which is produced by the embodiment shown in Figure 28 is similar to the composite torque whose waveform is shown in Figure 27D.

Although each pole piece shown in Figure 28 has gradually varying thickness, the thickness of a pole piece, such as each south pole piece, may be formed of segmental elements which differ in a step-wise manner from each other in thickness. Each such segmental pole piece of different thickness may extend over an arc of 30°. Still other techniques can be use, some of which having been described above, for varying the flux intensity generated by the respective pole pieces so as to form a magnetic flux distribution of sawtooth waveform, of the type illustrated in Figure 27A.

Figure 29A is a developed view of yet another embodiment of the construction of the magnetic pole pieces which can be used in place of the segmental pole pieces illustrated in Figure 25. Accordingly, each of pole pieces $107_A$, $108_A$, $107_B$ and $108_B$ may have a trapedoizal shape. The shorter side of the trapezoidal north pole piece $107_A$ is adjacent to the shorter side of the trapezoidal south pole piece $108_A$, and the longer side of the trapezoidal north pole piece $107_A$ is adjacent to the longer side of the trapezoidal south pole piece $108_B$. Similarly, the shorter side of the trapezoidal north pole piece $107_B$ is adjacent to the shorter side of the trapezoidal south pole piece $108_B$, and the longer side of the trapezoidal north pole piece $107_B$ is adjacent to the longer side of the trapezoidal south pole piece $108_A$. Because of the configurations of the respective magnetic pole pieces shown in Figure 29A, the waveshape of the magnetic flux distribution varies along different paths. For example, the magnetic flux distribution along a path *c* in Figure 29A appears as a broken curve *c* in Figure 29B. The magnetic flux distribution along a path *d* in Figure 29A appears as shown by a solid curve *d* in Figure 29D. If the axis of the motor in which the magnetic pole pieces shown in Figure 29A form the rotor is normal to the paths *c* and *d*, the composite magnetic flux distribution which links the stator coils is proportional to the summation of the flux distribution shown as the curves *c* and *d* in Figure 29B. Hence, the composite magnetic flux distribution has the sawtooth waveform shown in Figure 29C.

Therefore, the composite rotational torque which is imparted to a rotor 101 of Figure 29A has the waveform shown in Figure 27D.

Figure 30A illustrates yet another modification of the permanent magnet pole pieces which can be substituted for the pole pieces shown in Figure 25. Accordingly, each of north and south pole pieces $107_A$, $107_B$, $108_A$ and $108_B$ is trapezoidally shaped. Auxiliary pole pieces $107_A'$, $108_A'$, $107_B'$ and $108_B'$ are triangular. The longer vertical side of each trapezoidal pole piece is twice as long as the other vertical side thereof. As shown in Figure 30A, the magnetic flux changes polarity at the shorter boundary between, for example, the north pole piece $107_A$ and the south pole piece $108_A$. Aligned with this boundary is the boundary formed between the triangular auxiliary pole pieces $107_A'$ and $108_A$ The magnetic flux generated by these auxiliary pole pieces changes polarity in the opposite direction. Hence, at the boundary between the north pole piece $107_A$ and the south pole piece $108_A$, the magnetic flux is reduced substantially to zero. At the boundary between the north pole piece $107_A$ and the south pole piece $108_B$, magnetic flux of maximum north polarity changes over to a magnetic flux of maximum south polarity. Then, at the boundary between the south pole piece $108_B$ and the north pole piece $107_B$, the magnetic flux is reduced substantially to zero. Hence, the waveform of the magnetic flux distribution due to the pole structure shown in Figure 30A appears as a sawtooth waveform of the type shown in Figure 27A. Consequently, the composite rotational torque which is imparted to a rotor 101 has the waveform shown in Figure 27D.

At the upper or lower edge of the rotor 101 shown in Figure 30A, the polarity of the magnetic flux is seen to change at intervals equal to 180 electrical degrees. Hence, a Hall-effect defice can be used as a position-sensing element to detect such flux polarity changes and thus can be used to control the energizing current change-over operation for the stator coils.

Figure 30B shows yet another embodiment of magnetic pole pieces which can be used to generate magnetic flux distribution of a sawtooth waveform. Each pole piece is triangular with the hypotenuse of a south pole piece $108_A$ overlying the hypotenuse of a north pole piece 107. The shorter side of the triangular pole piece $107_A$ is adjacent the shorter side of a triangular pole piece $108_B$, and the hypotenuse of the latter overlies the hypotenuse of a triangular north pole piece $107_B$. It is appreciated that the magnetic flux which is generated by the respective triangular pole pieces is reduced from a maximum south polarity at the left-most edge of the south pole piece $108_A$ to substantially zero at the boundary between the south pole piece $108_A$ and the north pole piece $107_A$. Then, the polarity of the magnetic flux is reversed and increases gradually until the right-most edge of the north pole piece $107_A$. At that point, the magnetic flux intensity is changed from a maximum north polarity to a maximum south polarity. Then, the magnetic flux decreases in intensity to substantially zero at the boundary between the south pole piece $108_B$ and the north pole piece $107_B$. Thence, the magnetic flux increases with north polarity. Consequently, the generated magnetic flux has a sawtooth waveform, and the composite rotational torque which is imparted to a rotor 101 has the waveform shown in Figure 27D.

While the present invention has been particularly shown and described with reference to certain preferred embodiments, various changes and modifications in form and details can be made without departing from the scope of the invention. For example, the rotor structure of the *dc* motor has been described as being of the outer rotor type. It is contemplated that, if desired, the teachings of the present invention can be equally applicable to an inner rotor type of motor. As another example, the permanent magnet pole pieces may, if desired, constitute the stator structure, and the rotor assembly of the *dc* motor may be formed of energizable coils. In such an alternative, the *dc* motor may be provided with brushes.

WHAT WE CLAIM IS:-

1. A *dc* motor comprising:

an armature comprising at least two coils wound on an armature core, each of said coils being curved about the axis of the motor so as to provide an arcuate surface in contact with said armature core and each of said coils having a first current path portion through which current flows in a first direction and a second current path portion through which current flows in a second, opposite direction, one of said first and second current path portions being separated from the other on said armature core by an angle different from 180 electrical degrees;

commutation means for alternately energising said coils; and

a field system comprising at least one pair of magnetic poles for producing a magnetic flux distribution that alternates in magnetic field polarity in a rotary path about the axis of the motor such that the polarity of the flux changes at two position spaced 180 electrical degrees apart, the form of said field system in two regions each of 80 electrical degrees extent and respectively centered on said positions differing one from the other in such a way that the flux distributions within said respective regions differ from each other whereby the flux distribution is asymmetric.

2. A motor according to claim 1 wherein said current path portion and said second current path portion of each coil are disposed on substantially the same cylindrical surface concentric about an axis of the motor, and wherein said first and second current path portions are separated from each other by less than 180 electrical degrees.

3. A motor according to claim 2 wherein said at least one pair of magnetic poles comprises a north magnetic pole and a south magnetic pole, each having a circumferential dimension less than 180 electrical degrees to form the asymmetric flux distribution.

4. A motor according to claim 3 further comprising auxiliary magnetic poles adjacent to said north and south magnetic poles, the total circumferential dimension of said north, south and auxiliary magnetic poles being equal to 360 electrical degrees.

5. A motor according to claim 4 wherein said auxiliary magnetic poles comprise an auxiliary south pole adjacent to said north magnetic pole and an auxiliary north pole piece adjacent to said south magnetic pole, said auxiliary south and north pole pieces having circumferential dimensions smaller than those of said south and north magnetic poles, respectively.

6. A motor according to claim 4 wherein said auxiliary magnetic poles comprise alternating south and north pole pieces adjacent to said north magnetic pole and alternating north and south pole pieces adjacent to said south magnetic pole, said respective alternating pole pieces having circumferential dimensions smaller than said respective south and north magnetic poles.

7. A motor according to claim 3 comprising an air gap separating said north and south magnetic poles, the total circumferential dimension of said north and south magnetic poles and said air gap being equal to 360 electrical degrees, wherein the intensity of said magnetic flux linking said coils is reduced in the vicinity of said air gap.

8. A motor according to claim 3 comprising a magnetic path forming member comprising ferromagnetic material separating said north and south magnetic poles, the total circumferential dimension of said north and south magnetic poles and said magnetic path forming member being equal to 360 electrical degrees, wherein the intensity of said magnetic flux linking said coils is reduced in the vicinity of said magnetic path forming member.

9. A motor according to claim 2 wherein said at least one pair of magnetic poles comprises a north magnetic pole and a south magnetic pole, each having a circumferential dimension equal to 180 electrical degrees; and including intensity reducing means to reduce the intensity of said magnetic flux linking said coils in the vicinity of the 180 electrical degree position.

10. A motor according to claim 9 wherein said intensity reducing means comprising a cut-out portion formed in said north and south poles at a boundary thereof, said cut-out portion having a circumferential dimension of less than 180 electrical degrees.

11. A motor according to claim 9 wherein said intensity reducing means comprises a magnetic shield portion provided in said north and south magnetic poles at a boundary thereof, said shield portion having a circumferential dimension of less than 180 electrical degrees.

12. A motor according to claim 21 wherein said field system comprises a yoke member on which said magnetic poles are attached; and said intensity reducing means comprises a cut-out portion in said yoke member at a boundary of said north and south magnetic poles, said cut-portion having a circumferential dimension of less than 180 electrical degrees.

13. A motor according to claim 2 wherein said at least one pair of magnetic poles includes only a single pair of said magnetic poles.

14. A motor according to claim 2, claim 3 or claim 7 wherein said at least one pair of magnetic poles includes a plurality of pairs of said magnetic poles and wherein the number of coils is equal to the number of magnetic poles, said coils being arranged symmetrically with respect to said axis.

15. A motor according to claim 2 or claim 9 wherein said flux generating means comprises an anisotropic magnet concentric about said axis, said anisotropic magnet being formed with a plurality of pairs of magnetic poles and having the intensity of magnetisation between adjacent pairs reduced with respect to the intensity of magnetisation between magnetic poles in the same pair.

16. A motor according to claim 2 wherein said first and second current path portions of each coil are separated from each other by the electrical angle $\theta$, where $\theta = 360° m + \alpha$, $m$ being a positive integer and $\alpha$ being less than 180 electrical degrees.

17. A motor according to claim 2 wherein said first and second current path portions of each coil are separated from each other by the electrical angle $\beta$, where $\beta = 350° - (360°m + \alpha)/n$, $m$ being a positive integer, $\alpha$ being less than 180 electrical degrees and $n$ being the

number of pairs of magnetic poles.

18. A motor according to claim 2 wherein each said magnetic pole generates a magnetic flux of progressively changing intensity, such that the generated magnetic flux of alternating magnetic field polarity appears as a sawtooth configuration in said rotary path about said axis.

19. A motor according to claim 18 wherein each said magnetic pole is formed of a plurality of magnetic elements of different material, each generating magnetic flux of progressively decreasing intensity.

20. A motor according to claim 18 wherein each said magnetic pole is formed of a plurality of magnetic elements spaced from the cylindrical surface on which said coils are disposed by progressively increasing amounts.

21. A motor according to claim 18 said magnetic pole is formed of a magnetic element having a surface spaced from the cylindrical surface on which said coils are disposed by a progressively increasing amount.

22. A motor according to claim 18 wherein each pair of magnetic poles comprises a north pole piece and a south pole piece, each trapezoidally shaped when viewed in developed form.

23. A motor according to claim 22 further comprising a triangular shaped auxiliary south pole piece adjacent to said trapezoidally shaped north pole piece and a triangular shaped auxiliary north pole piece adjacent to said trapezoidally shaped south pole piece, said auxilary pole pieces also being adjacent to each other.

24. A motor according to claim 18 wherein each pair of magnetic poles comprises a triangular shaped north pole piece adjacent to a triangular shaped south pole piece.

25. A motor according to claim 18 wherein at least two pairs of magnetic poles are spaced axially from said coils, each pair of magnetic poles having north and south magnetized surfaces with surface areas which face said first and second current path portions that vary in a rotary path about said axis.

26. A motor according to claim 2 wherein said at least one pair of magnetic poles circumferentially disposed about said axis generates magnetic flux of uniformly alternating north and south polarity in a rotary path about said axis, and said field system has means for modifying a portion of said magnetic flux to vary the uniformity thereof over a predetermined angle less than 180 electrical degrees when the polarity of said magnetic flux changes in one direction; and said commutation means energizes a respective coil for a duration substantially equal to 180 electrical degrees commencing when said coil is linked with the modified portion of said flux.

27. A motor according to claim 2 wherein said at least one pair of magnetic poles circumferentially disposed about said axis generates magnetic flux of alternating north and south polarity having an intensity of sawtooth shaped configuration extending over 360 electrical degrees; and said commutation means energizes a respective coil for a duration substantially equal to 180 electrical degrees commencing when said coil is linked with a predetermined portion of said sawtooth shaped flux.

28. A brushless *dc* motor substantially as any one of the embodiments hereinbefore described with reference to Figures 12 to 30 of the accompanying drawings.

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FIG.1A

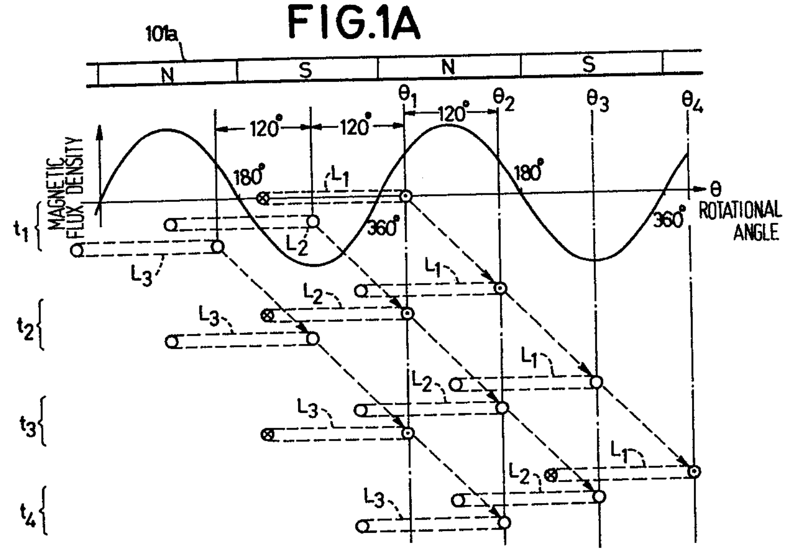

101a
N
S
N
S
θ1
θ2
θ3
θ4
120°
120°
120°
MAGNETIC FLUX DENSITY
180°
180°
360°
360°
θ
ROTATIONAL ANGLE
L1
L2
L3
t1
t2
t3
t4

FIG.1B

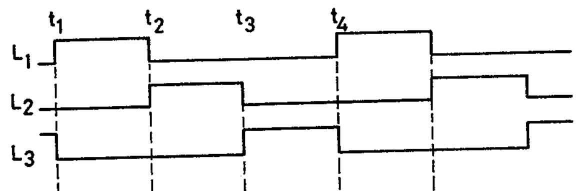



FIG.1C

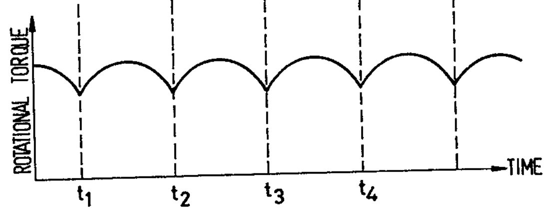


FIG.2A

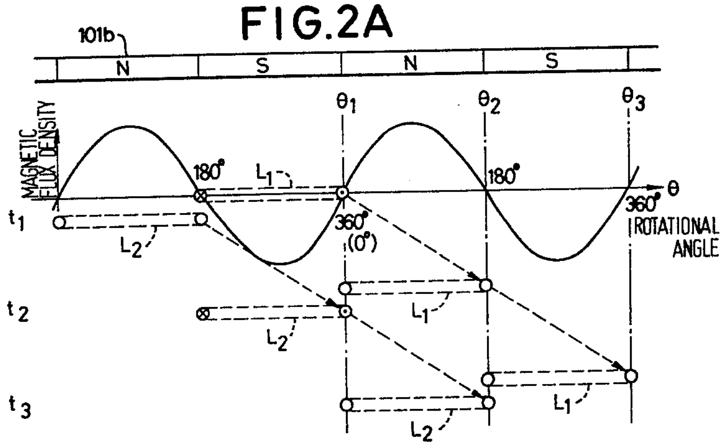

101b
N
S
N
S
θ1
θ2
θ3
MAGNETIC FLUX DENSITY
180°
L1
180°
θ
t1
360°
(0°)
360°
ROTATIONAL ANGLE
L2
t2
L1
L2
t3
L1
L2

FIG.2B

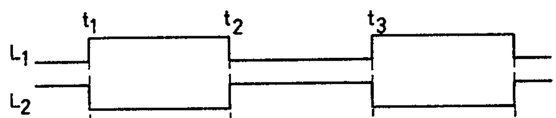



FIG.2C

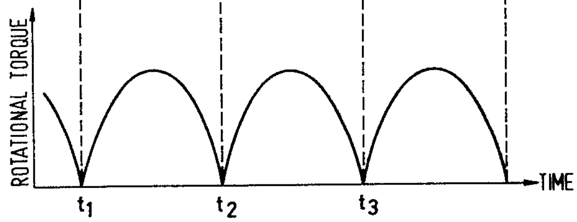


FIG.3

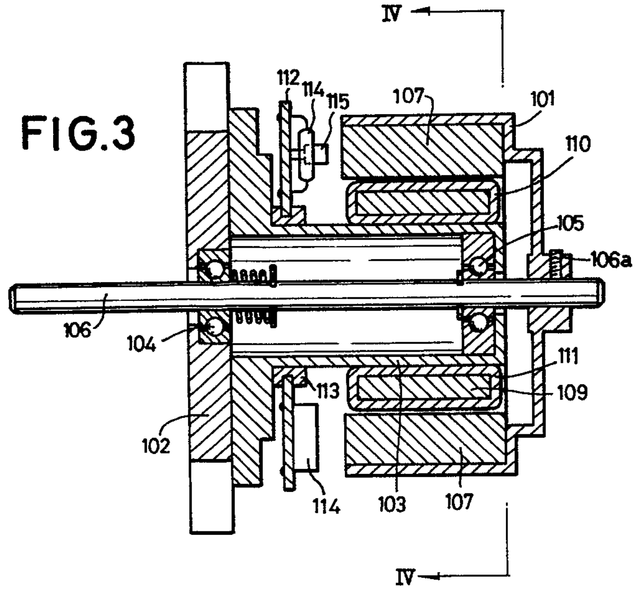

IV
112
114
115
107
101
110
105
106a
106
104
113
111
109
102
114
103
107
IV

FIG.4

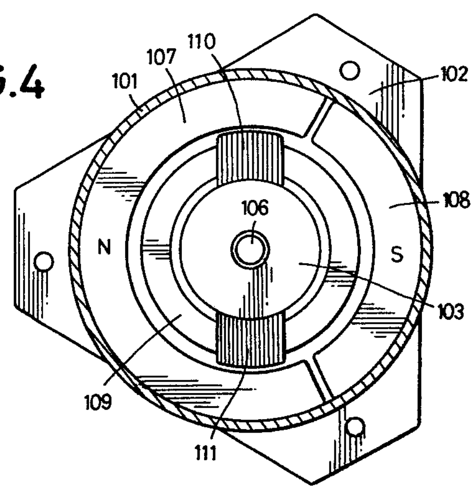

110
107
101
102
106
N
S
108
103
109
111

FIG.5A

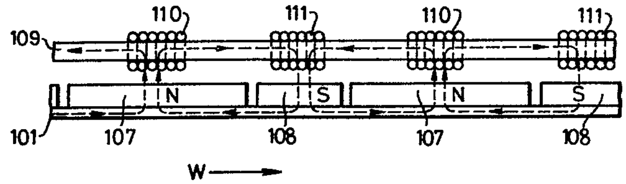

110
111
110
111
109
N
S
N
S
101
107
108
107
108
W

FIG.5B

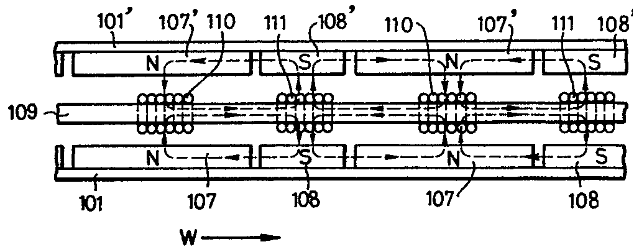
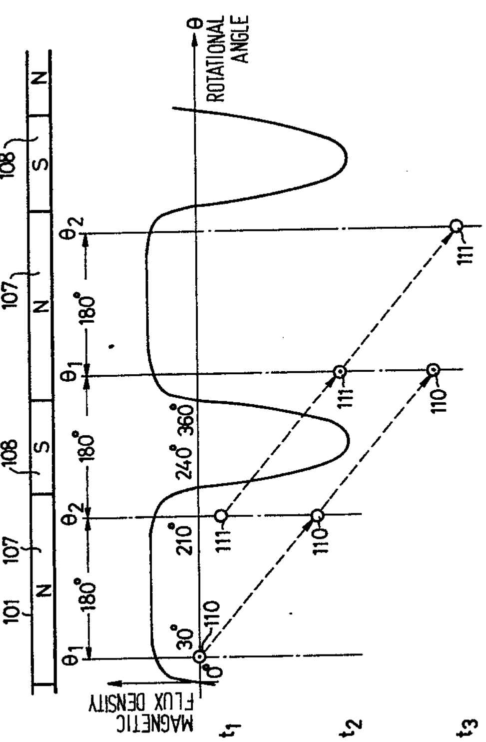

101'
107'
110
111
108'
110
107'
111
108'
N
S
N
S
109
N
S
N
S
101
107
108
107
108
W

FIG.6A


MAGNETIC FLUX DENSITY
ROTATIONAL ANGLE
θ
101
107
108
N
S
θ1
θ2
180°
0°
30°
210°
240°
360°
110
111
t1
t2
t3

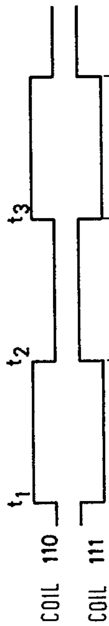



FIG.6B

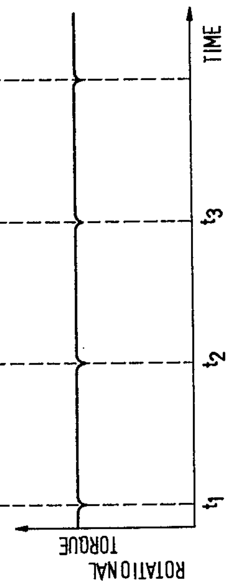



FIG.6C

FIG.7A

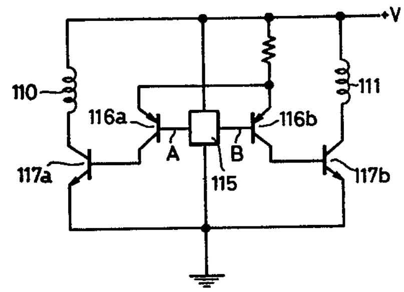



FIG.7B

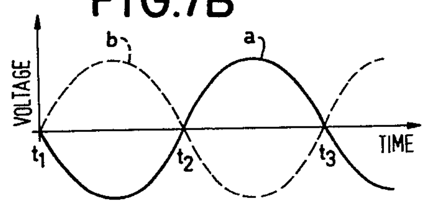


FIG.8A

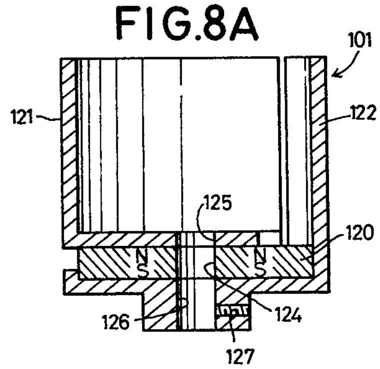

101
121
122
125
120
N
S
N
S
126
124
127

FIG.8B

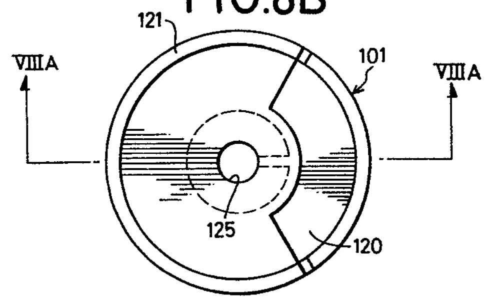

121
101
VIIIA
VIIIA
125
120

FIG.8C

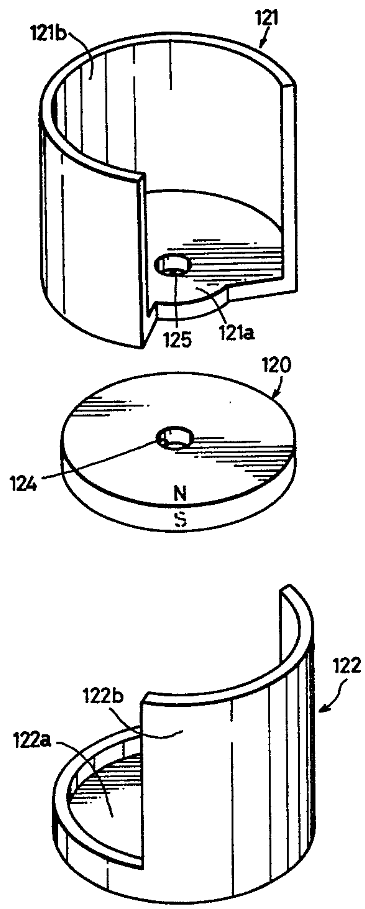


FIG.9

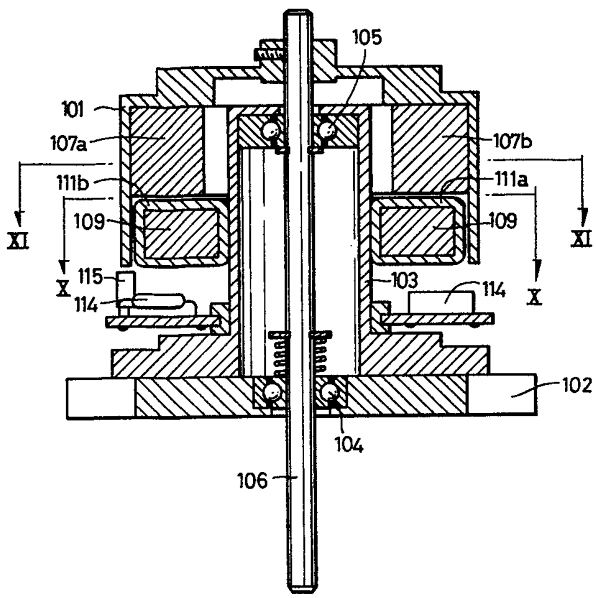

105
101
107a
107b
111b
111a
109
109
XI
XI
X
X
115
114
114
103
102
104
106

FIG.11

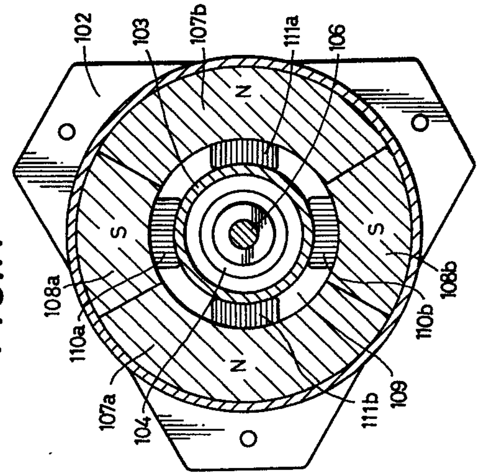

102
103
107b
111a
106
N
S
S
N
108a
110a
107a
104
111b
109
110b
108b

FIG.10

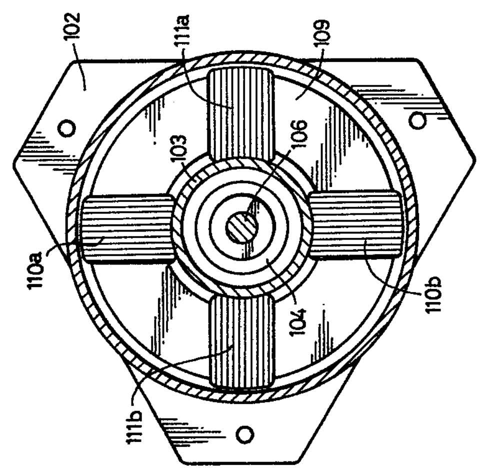

102
111a
109
103
106
110a
104
110b
111b

FIG.12

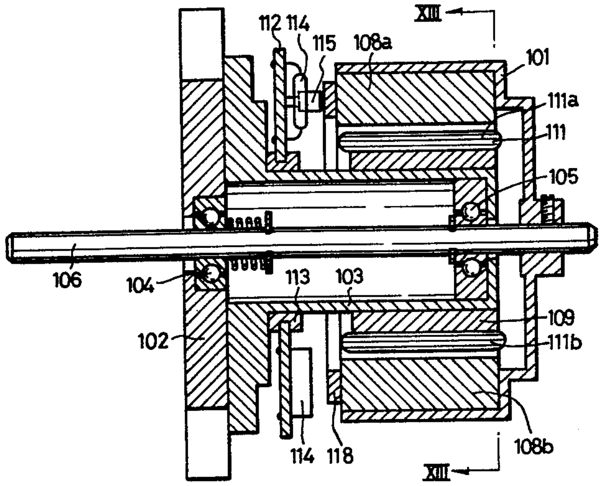

XIII
112
114
115
108a
101
111a
111
105
106
104
113
103
109
111b
102
114
118
108b
XIII

FIG.13

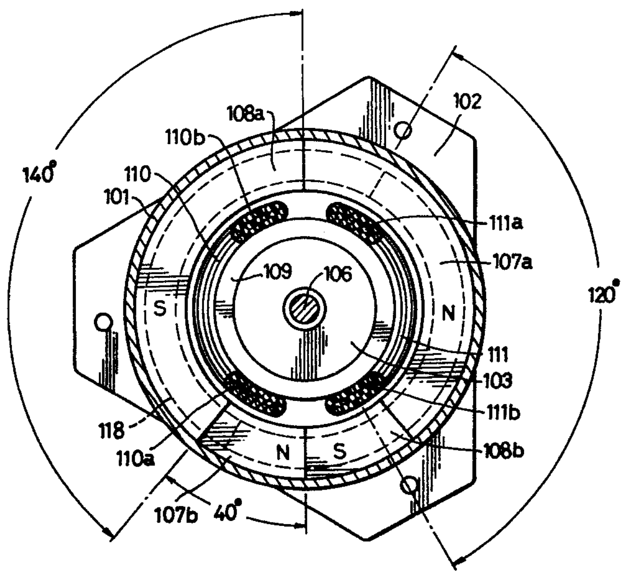

102
108a
110b
140°
110
101
111a
107a
109
106
S
N
120°
111
103
118
111b
110a
N
S
108b
107b
40°

FIG.14A

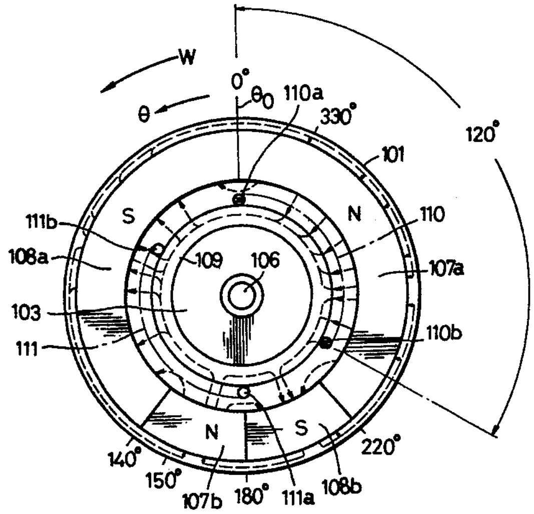
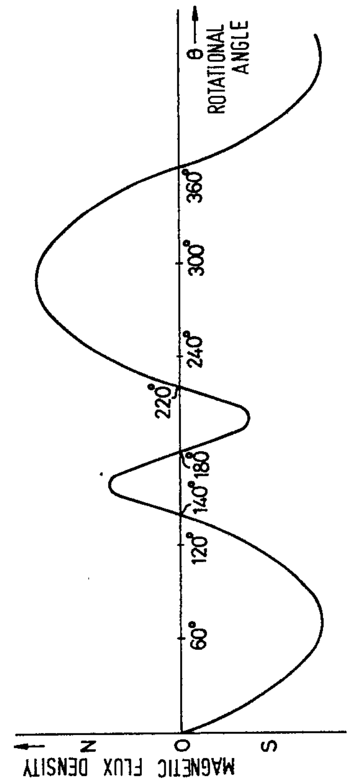

W
θ
0°
θ0
110a
330°
120°
101
S
N
110
111b
108a
109
106
107a
103
110b
111
N
S
220°
140°
150°
107b
180°
111a
108b

FIG.14B


θ
ROTATIONAL ANGLE
60°
120°
140°
180°
220°
240°
300°
360°
N
O
S
MAGNETIC FLUX DENSITY

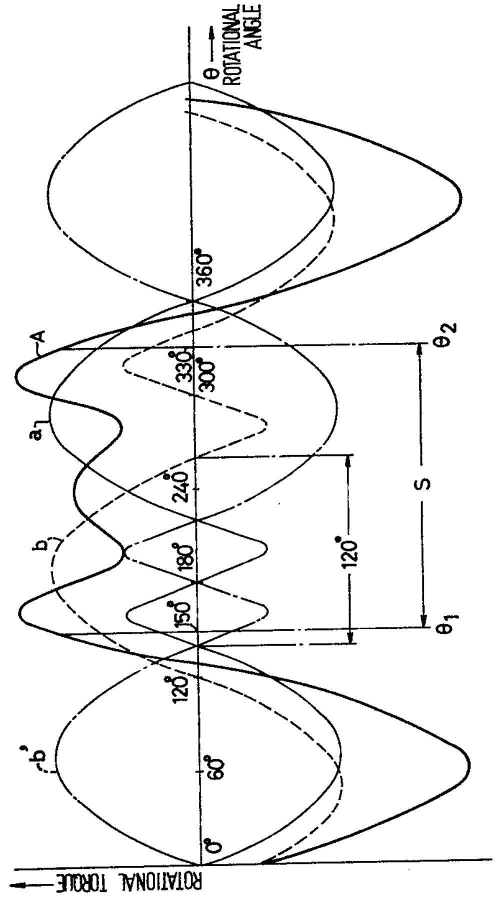

ROTATIONAL TORQUE
θ ROTATIONAL ANGLE
0°
60°
120°
150°
180°
240°
300°
330°
360°
A
a
b
b'
120°
S
θ1
θ2

FIG.14 C

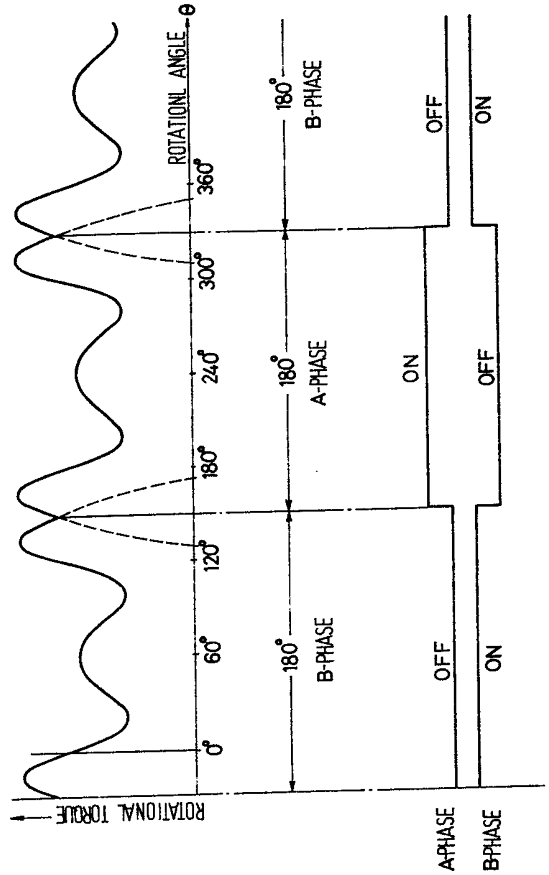



FIG.14D

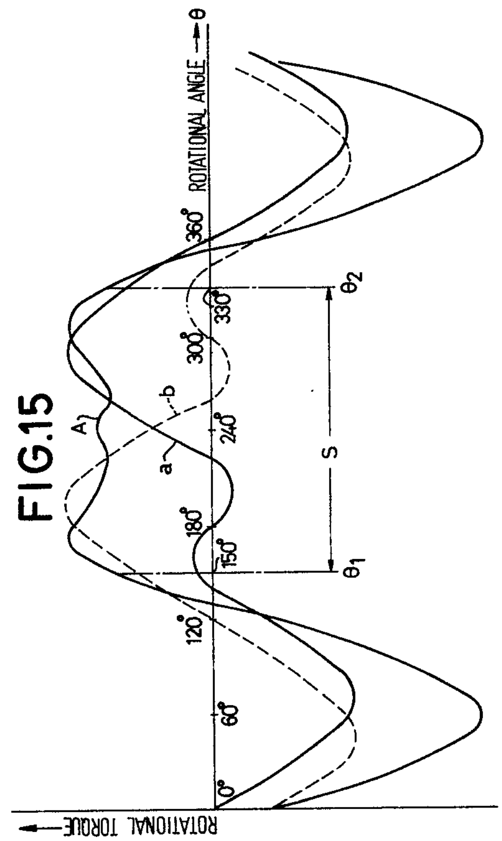
FIG.14E

1604122 COMPLETE SPECIFICATION

36 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 19

FIG.15



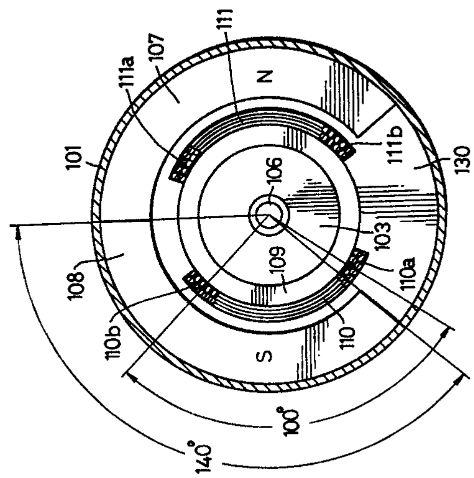



FIG.16A

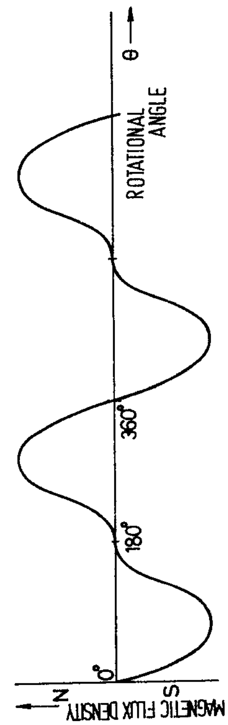



FIG.16B

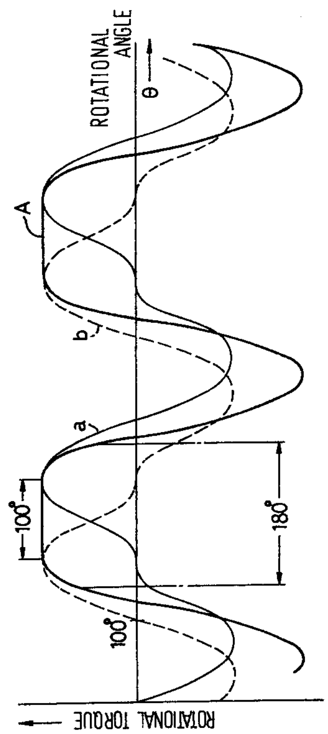



FIG.16C

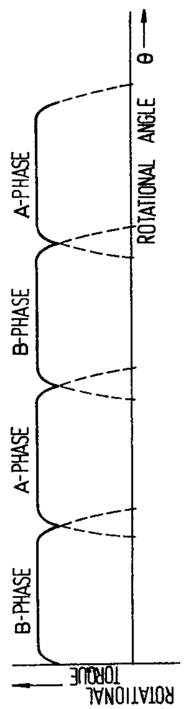



FIG.16D

FIG.17B

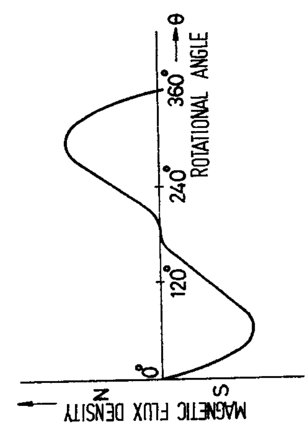



FIG.17A

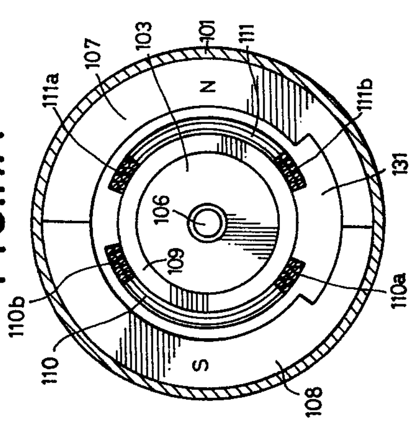


FIG.18B

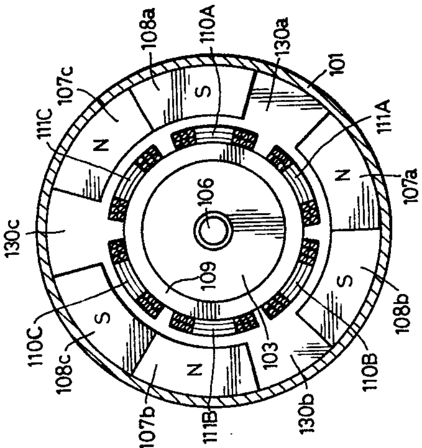
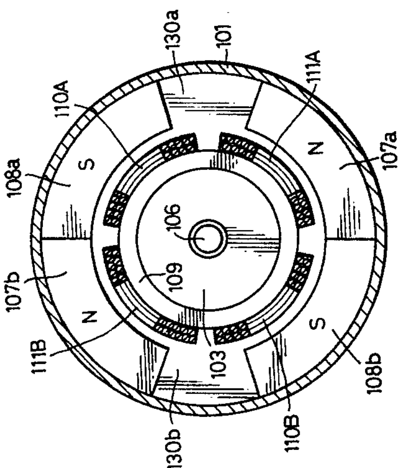



FIG.18A



1604122 COMPLETE SPECIFICATION

36 SHEETS *This drawing is a reproduction o the Original on a reduced scale*

Sheet 24

FIG.19B

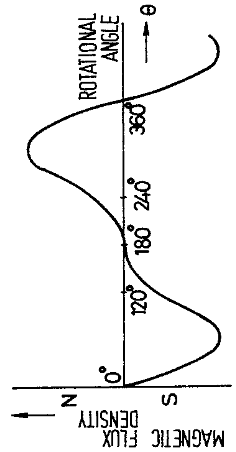



FIG.19A

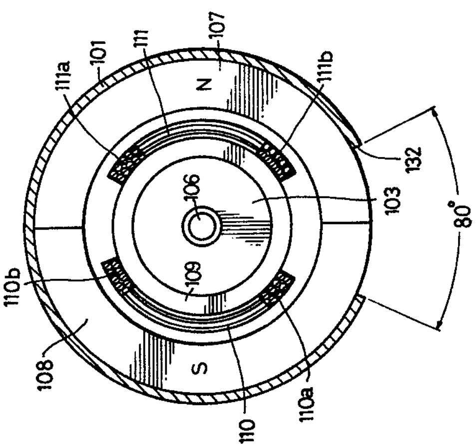


FIG.20A

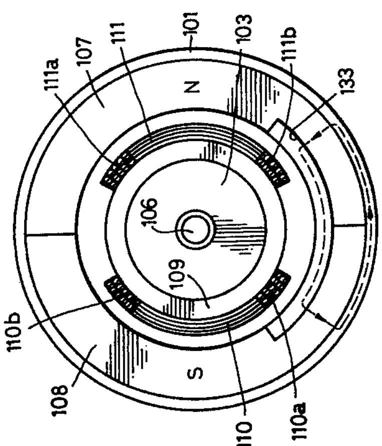



FIG.20B

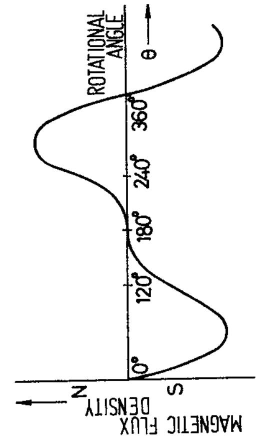


FIG.21B

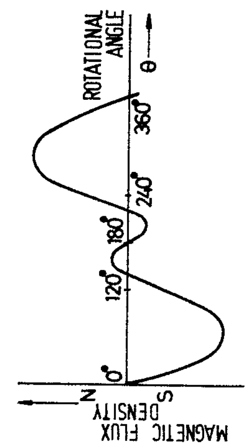



FIG.21A

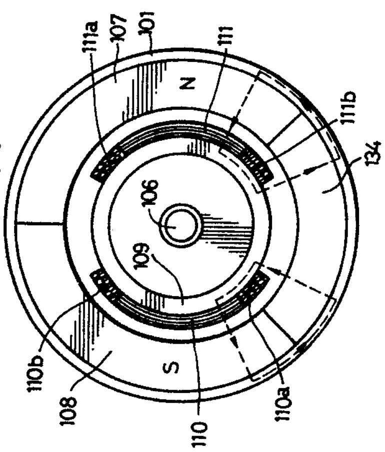


FIG.22B

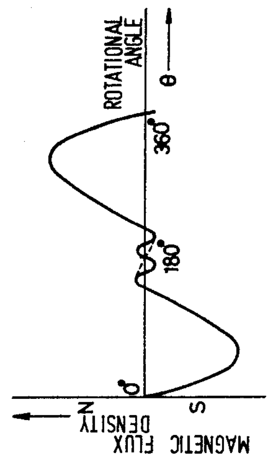



FIG.22A

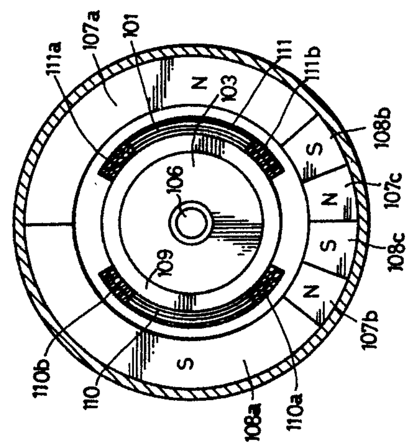


FIG.23A

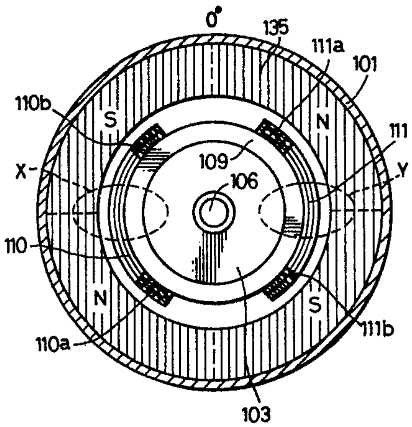



FIG.23B

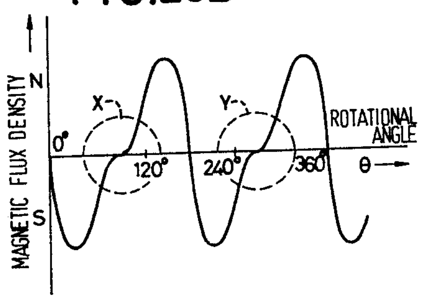


FIG.24A

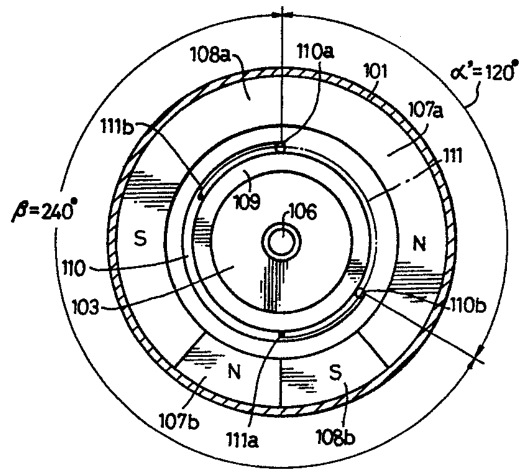



FIG.24B

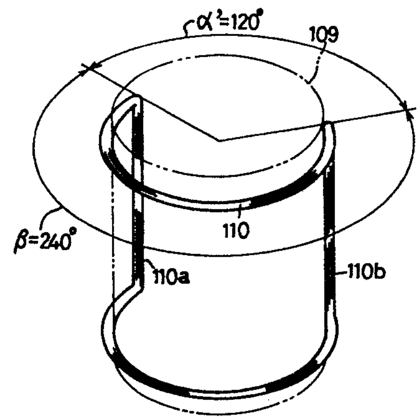


FIG.24C

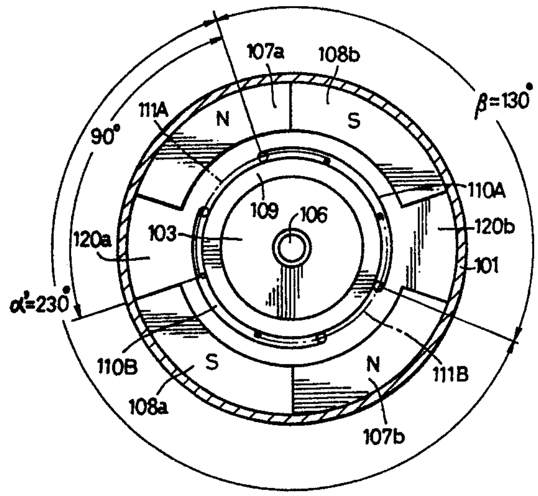

107a
108b
β=130°
111A
N
S
90°
110A
109
106
120b
120a
103
101
α°=230°
110B
S
N
111B
108a
107b

FIG.25

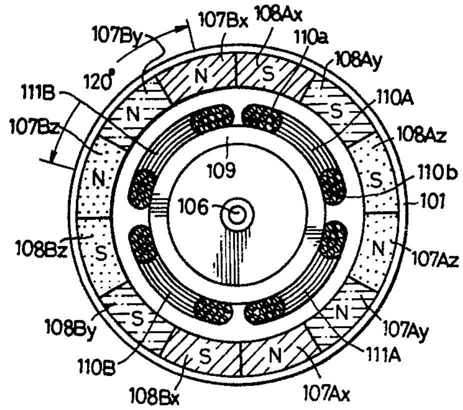

107By
107Bx
108Ax
110a
108Ay
120°
111B
110A
107Bz
108Az
109
110b
106
101
108Bz
107Az
108By
107Ay
111A
110B
108Bx
107Ax
N
S
N
S
N
S
S
N
S
N
S
N

FIG.26

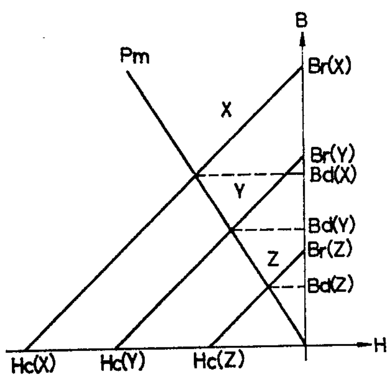
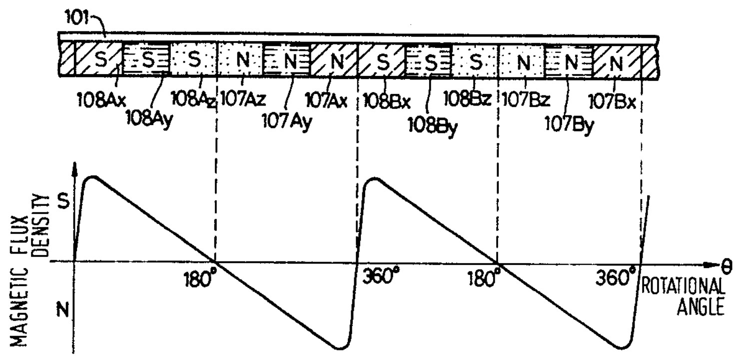

B
Pm
Br(X)
X
Br(Y)
Bd(X)
Y
Bd(Y)
Z
Br(Z)
Bd(Z)
H
Hc(X)
Hc(Y)
Hc(Z)

FIG. 27A


101
S
S
S
N
N
N
S
S
S
N
N
N
108Ax
108Ay
108Az
107Az
107Ay
107Ax
108Bx
108By
108Bz
107Bz
107By
107Bx
MAGNETIC FLUX DENSITY
S
N
180°
360°
180°
360°
θ
ROTATIONAL ANGLE

1604122 COMPLETE SPECIFICATION

36 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 33

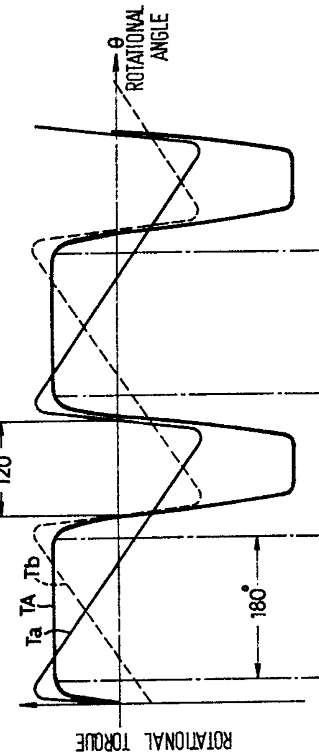



FIG.27B

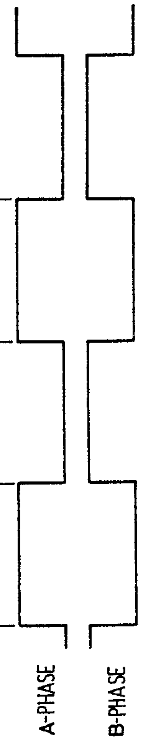



FIG.27C

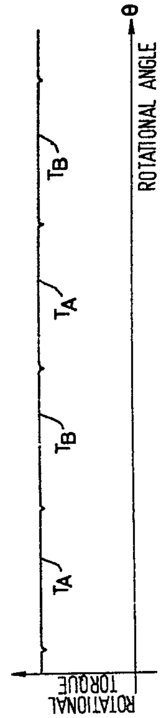
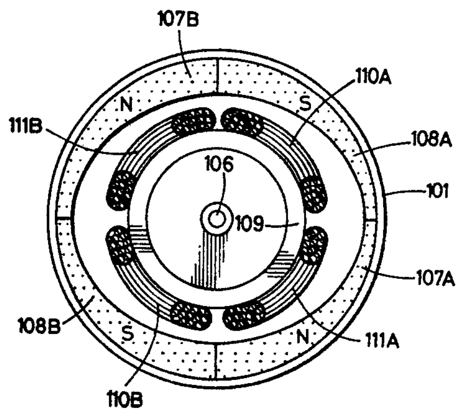



FIG.27D

FIG. 28



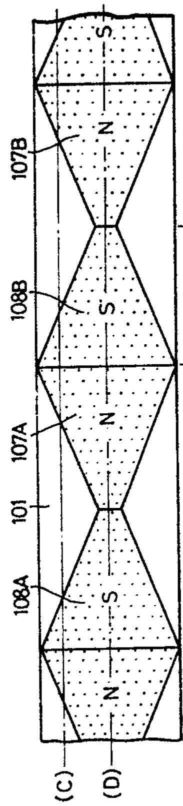



FIG.29A

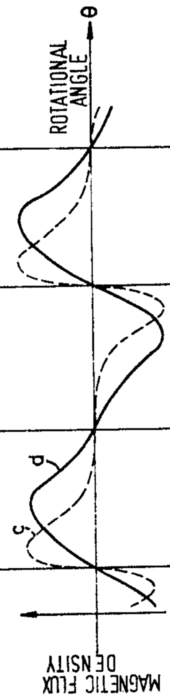



FIG.29B

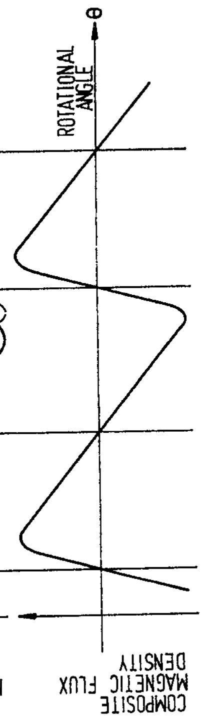



FIG.29C

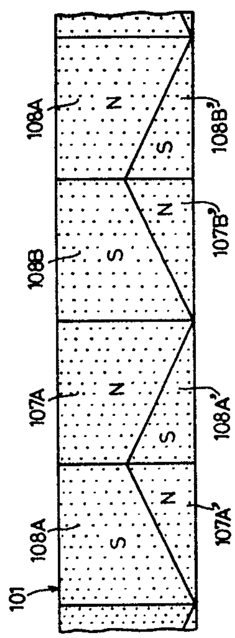



FIG.30A

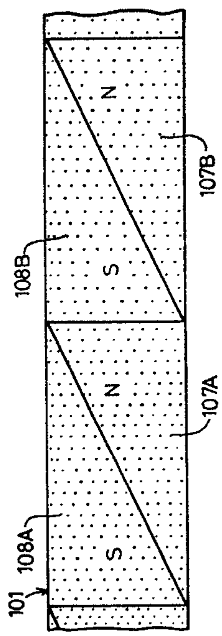



FIG.30B