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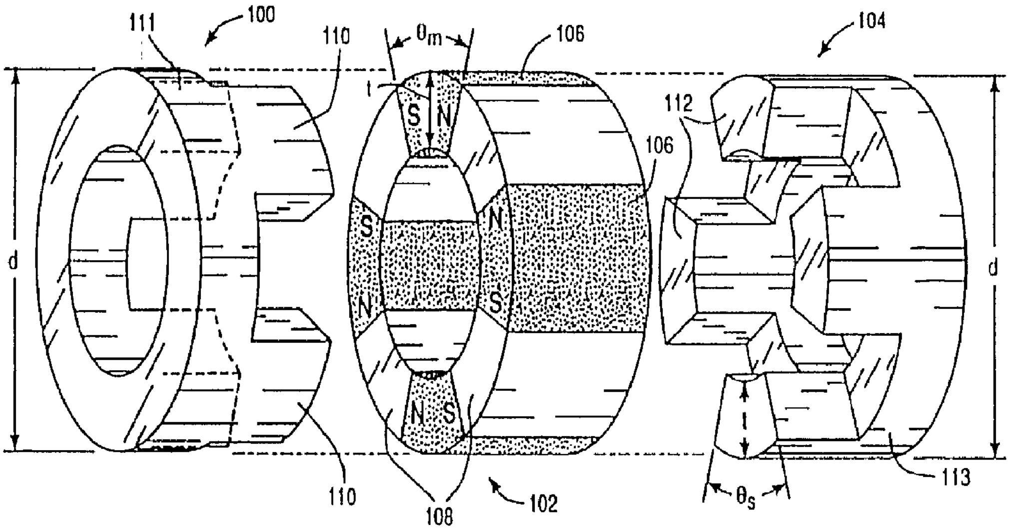
(54) MACHINE A AIMANT PERMANENT A DEUX PARTIES SAILLANTES

(54) DOUBLY-SALIENT PERMANENT-MAGNET MACHINE



(57) La présente invention concerne une machine à aimant permanent à deux parties saillantes et comportant un rotor annulaire (102) intercalé entre une paire de stators (100, 104) disposés latéralement. Le rotor (102) est constitué de plusieurs aimants permanents (106) alternant avec des pôles électromagnétiquement saillants (108) en acier. Chaque stator (100, 104), constitué d'une pluralité de pôles (110, 112) régulièrement espacés et orientés longitudinalement, supporte une pluralité de bobinages de cuivre (126, 128) raccordés en série. Les deux pluralités de bobinages comprennent un enroulement phase A et un enroulement phase B.

(57) A doubly-salient permanent-magnet machine includes an annular rotor (102) interposed between a pair of laterally disposed stators (100, 104). The rotor (102) includes a plurality of permanent magnets (106) alternating with electromagnetically-salient poles (108) made of steel. Each stator (100, 104) has a plurality of equally-spaced longitudinally-oriented poles (110, 112) and supports a plurality of copper coils (126, 128) connected in series. The two pluralities of copper coils comprise a phase-A winding and a phase-B winding.

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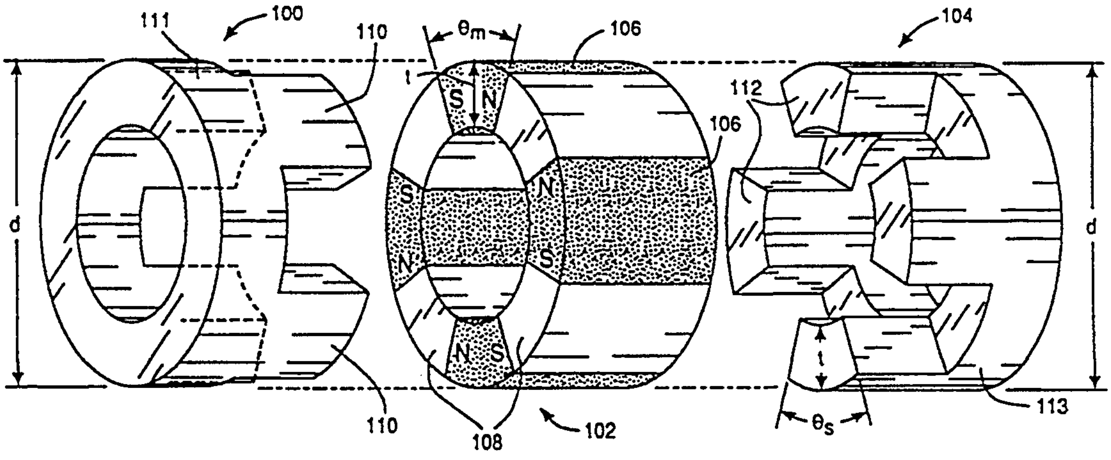

(57) Abstract

A doubly-salient permanent-magnet machine includes an annular rotor (102) interposed between a pair of laterally disposed stators (100, 104). The rotor (102) includes a plurality of permanent magnets (106) alternating with electromagnetically-salient poles (108) made of steel. Each stator (100, 104) has a plurality of equally-spaced longitudinally-oriented poles (110, 112) and supports a plurality of copper coils (126, 128) connected in series. The two pluralities of copper coils comprise a phase-A winding and a phase-B winding.

DOUBLY-SALIENT PERMANENT-MAGNET MACHINE

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to low-speed electric generators and particularly to an electric generator for direct-drive wind turbines.

Description of Related Art

In recent years wind turbines have received increased attention as environmentally safe and relatively inexpensive alternative energy sources. With this growing interest, considerable efforts have been made to develop wind turbines that are reliable and efficient.

Generally, a wind turbine includes a rotor having a plurality of blades. The rotor is horizontally mounted within a housing, which is positioned on top of a truss or monotube tower. The turbine's blades transform wind energy into a rotational force that drives one or more generators, rotationally coupled to the rotor through a gearbox. The gearbox is necessary to step up the inherently low rotational speed of the turbine rotor for the generator to efficiently convert mechanical energy to electrical energy, which is fed into a utility grid.

Many conventional wind turbines rotate at a constant speed to produce electricity at sixty cycles per second (60 Hz), which is the U.S. standard for alternating current. Because wind speeds change continuously, these wind turbines must have a system for maintaining a constant rotor speed. In one such system, the rotor speed is kept constant by increasing the pitch of the blades as the wind speed rises and decreasing the pitch of the blades as the wind speed drops.

Some turbines operate at variable speed by using a power converter to adjust their output. As the speed of the turbine rotor fluctuates, the frequency of the alternating current flowing from the generator also varies. The power converter, positioned between the generator and the utility grid, transforms the variable-frequency alternating current to direct current, and then converts it back to alternating current having a constant frequency of sixty cycles per second.

A wind turbine must be rugged and dependable. Since the gearbox of the turbine is expensive, heavy, and maintenance intensive, it is desirable to eliminate the gearbox by coupling the generator directly to the turbine rotor. Advantages associated with a direct-drive wind turbine are improved reliability, lower cost, decreased weight, quieter operation, greater efficiency, and an absence of a torque limit.

However, coupling the turbine rotor directly to the generator is problematic because conventional generators are unable to operate efficiently at low rotor speeds in the range of thirty to fifty rpm. One machine that may be utilized as a generator at low rotor speeds is disclosed in Weh, H.; May, H.; Shalaby, M.: "Highly Effective Magnetic Circuits for Permanent Magnet Excited Synchronous Machines", Proc. ICEM 1990, Vol. 3, pp. 1040-1045.

This transverse-flux (TF) machine, shown in Fig. 1, comprises an annular rotor 2 (only a section of which is shown), a stationary outer armature winding 4, a stationary inner armature winding 6, a plurality of outer stator-core flux guides 8, and a plurality of inner stator-core flux guides 10. Annular rotor 2 includes a first array of permanent magnets 12 and a second array of permanent magnets 14. A ring 16, made of a non-magnetic material such as fiber-reinforced resin, is sandwiched between the two permanent-magnet arrays. Annular rotor 2 is constructed such that permanent magnets 12 alternate with iron elements 18 and permanent magnets 14 alternate with iron elements 20.

Even though the TF machine can operate at low rotor speeds, it possesses several salient flaws. Specifically, the TF machine is susceptible to considerable slot-flux leakage, which adversely affects performance. To understand the nature of this problem, it is helpful to consider the relationship of

$P \equiv \Gamma\omega$, where

P = power rating of the machine
Γ = torque
ω = angular speed of the rotor

From the above relationship it is apparent that to achieve a high power rating (P) at low angular speed (ω), torque (Γ) produced by the machine should be maximized. It is commonly known in the art that to obtain a high torque it is necessary to maximize the flux capacity of the machine and to increase the electrical current in armature windings 4 and 6. To support additional current in windings 4 and 6 without undue energy losses caused by heat generation, the cross-sectional areas of armature windings 4 and 6 must be increased.

Furthermore, it is generally known in the art that the torque produced by a machine is proportional to the diameter squared (or cubed, or other powers greater than one) of the machine times the length of the machine. In other words,

$\Gamma = \kappa d^2 L$, where

Γ = torque
κ = constant
L = active material length of the machine
d = active material diameter of the machine

The above relationship indicates that to achieve high torque in a compact package, the optimal solution is to increase the diameter of the machine, rather than its length. In the prior-art system illustrated in Fig. 1, if the diameter of the TF machine is to be increased and the length is to remain constant, only slot depth D of stator-core flux guides 8 and 10, which contain armature windings 4 and 6, respectively, can be increased to maximize cross-sectional areas of armature windings 4 and 6 (since depth D is a function of the diameter of the machine), while slot width W of stator-core flux guides 8 and 10 (which is a function of the length of the machine) must remain the same.

Fig. 2 shows that as slot depth D increases, the cross-sectional area A_a of the slot air gap and the length of the flux path L_s through the steel of, e.g., outer stator-core flux guide 8, also increase, while the cross-sectional area A_s of outer stator-core flux guide 8 and the length of the flux path L_a through the slot air gap remain constant. Since reluctance $\Re$ (the resistance offered to magnetic flux by a magnetic circuit) is equal to $L/\mu A$, where

μ = permeability of the medium
L = flux-path length
A = cross-sectional area of the medium

it is apparent from Fig. 2 that as slot depth D grows, the reluctance through the steel of outer stator-core flux guide 8 increases, while the reluctance through the slot air gap decreases. Hence, increasing slot depth D leads to augmented flux leakage, whereby flux linkages, instead of following path L_s through outer stator-core flux guide 8, pass through the slot air gap along path L_a. Any flux that leaks through the slot air gap along path L_a instead of following path L_s does not link all the coils of the winding located in the slot air gap (e.g., winding 4 of Fig. 1) and thus does not participate in producing the rated torque of the machine, causing the power rating of the machine to decrease.

Another disadvantage of the TF machine is that due to the asymmetrical placement of the two stators (i.e., outer stator-core flux guides 8 and inner stator core flux guides 10), the reluctances seen by outer armature winding 4 and inner armature winding 6 (Fig. 1) are different, causing an electromagnetic imbalance between the two phases. The cause of the electromagnetic imbalance of the TF machine can be identified with respect to Fig. 3. An outer volume 22, which is defined by outer stator-core flux guides 8 alternating with air gaps 23, is larger than an inner volume 24, which is defined by inner stator-core flux guides 10 alternating with air gaps 25. Since both volumes 22 and 24 contain the same number of identical stator-core flux guides made of steel, but outer volume 22 is physically larger than inner volume 24, the ratio of steel to air in outer volume 22 is less than that in inner volume 24. Consequently, outer volume 22 has a larger reluctance to magnetic flux than inner volume 24, causing a magnetic imbalance between the two phases of outer armature winding 4 and inner armature winding 6 (not shown in Fig. 3). The magnetic imbalance between the two phases of the TF machine leads to circulating currents that contribute to heat losses, bearing currents that may cause failure of the rotor bearings, and uneven loading of the rotor, which compounds difficulties in the mechanical and electrical design of the machine.

Moreover, the possibility of manufacturing a large TF machine (which may be desirable since increasing the number of poles, and hence the size, of the machine would enhance its performance at low rotor speeds) proves to be an arduous task since maintaining small air gaps 26 and 28, as illustrated in Fig. 4, between annular rotor 2 and outer and inner stator-core flux guides 8 and 10 becomes more difficult as these components increase in size. (It is generally known in the art that air gaps between the moving and stationary components of electrical machines must be minimized for maximum power and efficiency.) Additionally, the TF machine is unsuitable for high-speed operation because the concentric orientation of stationary outer stator-core flux guides 8 and annular rotor 2 is such that as rotor speed increases, radial expansion of annular rotor 2 gradually reduces air gap 26 until annular rotor 2 strikes outer stator-core flux guides 8, leading to a catastrophic failure of the TF machine.

Furthermore, the TF machine is a relatively expensive, since it is difficult to manufacture the complicated stationary assemblies comprising outer and inner stator-core flux guides 8 and 10 and armature windings 4 and 6. The TF machine uses a large amount of copper in its windings, which further increases the manufacturing costs. The copper in the windings is utilized inefficiently because only the segments of armature windings 4 and 6, having thickness T (Fig. 4), are used in torque generation (since only these segments of the windings are linked by magnetic flux). The function of remaining segments having thickness G (where G>T) is simply to complete the electrical circuit.

The TF machine is also flawed in that due to the lack of access to its inner portion, it is difficult to remove the heat generated in inner stator-core flux guides 10 during the operation of the machine, which decreases efficiency and reduces power output.

SUMMARY OF THE INVENTION

It is accordingly desirable to provide a doubly-salient permanent-magnet machine that overcomes the foregoing drawbacks, e.g., minimizes slot-flux leakage, has electromagnetically-balanced winding phases, is simple and inexpensive to manufacture, is capable of both low-speed and high-speed operation, facilitates heat removal, and is compact and efficient.

It is also desirable for a permanent magnet machine to achieve a high power density at low angular speed, to be able to accommodate high pole numbers, to utilize a conventional winding design with low-inductance windings, and to have a simple support structure.

Further advantages of the invention will become apparent after consideration of the ensuing description and the accompanying drawings.

In one embodiment, the doubly-salient axial-flux permanent-magnet machine of the present invention comprises a rotor, mounted between a pair of coaxially and laterally oriented stators. The rotor is constructed from a plurality of permanent magnets alternating with electromagnetically-salient poles made of steel. Each stator has a plurality of longitudinally-oriented salient poles. The stator poles support two pluralities of copper coils, whereby a single coil is wound around each stator pole. Each plurality of coils is linked in series, thus forming a two-phase winding.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings, where:

Fig. 1 is a perspective view of a prior-art transverse-flux (TF) machine.

Fig. 2 is a perspective view of a stator-core flux guide of the prior-art TF machine of Fig. 1.

Fig. 3 is a side view of the prior-art TF machine of Fig. 1.

Fig. 4 is a detail view of the prior-art TF machine of Fig. 3.

Fig. 5 is an exploded perspective view of the major components of a doubly-salient axial-flux permanent-magnet (DSAFPM) machine constructed according to the present invention.

Fig. 6 is a schematic side view of the rotor of the DSAFPM machine shown in Fig. 5.

Fig. 7 is a perspective view depicting a manufacturing technique for the stators shown in Fig. 5.

Fig. 8 is a perspective and partial cross-sectional view of the DSAFPM machine constructed according to the present invention.

Fig. 9 is a perspective view of a coil of the DSAFPM machine of Fig. 8.

Fig. 10 is a perspective view of the coil of Fig. 8 having end-windings of different lengths.

Fig. 11 is a schematic view representing a converter topology suitable for connecting the DSAFPM machine of Fig. 8 to a utility grid, wherein the DSAFPM machine is coupled to a wind-turbine rotor.

Fig. 12 is a detail schematic view of the converter topology of Fig. 11.

Fig. 13 is an electric-circuit equivalent of the DSAFPM machine of Fig. 8.

Fig. 14 is a plot illustrating torque production of the DSAFPM machine of Fig. 8 at normal speed.

Fig. 15 is a plot illustrating torque production of the DSAFPM machine of Fig. 8 at high speed.

Fig. 16 is a cross-sectional view of the DSAFPM machine of Fig. 8.

Figs. 17-24 show variations in flux distribution of the DSAFPM machine of Fig. 8.

Figs. 25 and 26 are plots of flux linkages corresponding to variations in flux distribution of the DSAFPM machine of Figs 17-24.

Fig. 27 is a schematic view representing a doubly-salient axial-flux permanent-magnet machine where each stator includes coils of phase-A and phase-B windings.

Fig. 28 is a cross-sectional view of a doubly-salient axial-flux permanent-magnet machine having a dual-rotor configuration.

Figs. 29 and 30 are schematic views depicting different rotor orientations of the machine of Fig. 28.

Fig. 31 is a cross-sectional view of a doubly-salient radial-flux permanent magnet machine according to the present invention.

For purposes of illustration, these figures are not necessarily drawn to scale. In all of the figures, like components are designated by like reference numerals.

DETAILED DESCRIPTION OF THE INVENTION

Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been shown or described to avoid unnecessarily obscuring the present invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

Fig. 5 depicts the major components of a doubly-salient axial-flux permanent-magnet machine according to the present invention. The machine comprises a first stator 100, a rotor 102, and a second stator 104, each having an annular shape. Stators 100 and 104 have an outer diameter d, which is the same as the outer diameter of rotor 102.

Rotor 102 includes a plurality of longitudinally-oriented permanent magnets 106, such as rare-earth permanent magnets or ferrite permanent magnets. Permanent magnets 106 are evenly spaced around rotor 102 and alternate with a plurality of electromagnetically-salient rotor poles 108, made of a magnetically-permeable material, e.g., laminated steel, and identical in number to permanent magnets 106. Each permanent magnet 106 defines a radial dimension t and an angular dimension θ_m. Permanent magnets 106 are polarized in a transverse direction, such that rotor poles 108 are identically polarized on both sides of the rotor, as shown in Fig. 6 which illustrates the directions of flux lines 107.

Stator 100 (Fig. 5) has a plurality of longitudinally-oriented salient stator poles 110 and a back iron 111. Stator 104 has a plurality of longitudinally-oriented salient stator poles 112 and a back iron 113. Stator poles 110 and 112 are evenly spaced around their respective stators

100 and 104. Each stator has a number of stator poles equal to the number of rotor poles 108. Each stator pole defines a radial dimension t and an angular dimension θ_S.

Stators 100 and 104 each comprise a plurality of discrete laminated steel layers and may be inexpensively manufactured by rolling up and punching out a ribbon of steel lamination, such as illustrated in Fig. 7.

Fig. 8 is a perspective cross-sectional view of the doubly-salient axial-flux permanent-magnet machine according to the invention. Rotor 102 of the machine is rigidly attached to a main shaft 114, which may be directly coupled to a wind turbine rotor (not shown). Main shaft 114 is supported within a cylindrical housing 116, having end faces 118 and 120. Shaft 114 rotates in bearings 122 and 124, centrally mounted in end faces 118 and 120, respectively.

Back iron 111 of stator 100 is rigidly attached to the inside surface of end face 118, while back iron 113 of stator 104 is rigidly attached to inside surface of end face 120. Such placement of stators 100 and 104 allows the heat, generated in the stators by eddy currents and coil currents, to be efficiently dissipated by conduction to housing 116 and then by convection to the surrounding atmosphere.

Stators 100 and 104 are oriented such that when stator poles 112 are completely aligned with permanent magnets 106, stator poles 110 are completely aligned with rotor poles 108 and vice versa. Stator poles 110 support copper coils 126 and stator poles 112 support copper coils 128, whereby one coil is located around the periphery of each stator pole. Coils 126 and 128 are of conventional shape and design, and therefore can be inexpensively and easily manufactured and installed into the slots defined by stator poles 110 and 112.

As shown in Fig. 9, coil 128 comprises an end-winding portion E and a conductor portion C. The length of end-winding portion E (which does not take part in torque generation) is small compared to the length of conductor portion C. Such configuration of coils 126 and 128 reduces inductance in the coils (inductance is the property of an electric circuit by which a varying current in it produces a varying magnetic field that induces voltages in the same circuit or in a nearby circuit), which is advantageous for converter-fed machines where the current is controlled by a pulse-width modulated voltage applied to the machine terminals. This advantage arises because a low-inductance winding allows fast dynamic current control since the current closely follows the applied or generated voltage without significant phase lag. Furthermore, because end-winding portion E is small, the copper in the windings is used efficiently and the cost of the machine is further reduced. Coils 126 and 128 may also have the configuration shown in Fig. 10, where end-windings E_1 and E_2 have different lengths.

As illustrated in Fig. 11, coils 126 are connected in series, comprising a phase-A winding 133. Coils 128 are also connected in series, comprising a phase-B winding 135. Phase-A and phase-B windings 133 and 135 are coupled to a power electronic converter 129, which comprises a three-phase DC-to-AC inverter 134, such as that described in US Patent No. 5,225,712 to William L. Erdman, and a bipolar two-phase inverter 136, which controls the magnitude of current in both directions through each phase winding. Current is produced when a wind turbine rotor 235 rotates shaft 114, which is rigidly connected to wind turbine rotor 235. Inverter 134 is electrically coupled to a utility grid 137 and inverter 136 is electrically coupled to phase-A and phase-B windings 133 and 135. Inverters 134 and 136 are interconnected by a DC link 138. Converter 129 provides phase current regulation through a pulse-width-modulated voltage wave form. Furthermore, converter 129 allows the machine to operate either as a motor or a generator and also permits a variable-voltage, variable-frequency operation of the machine while maintaining a constant-voltage, constant-frequency connection to the utility grid.

Fig. 12 is a schematic diagram of inverter 136, which includes a plurality of switches 137, such as insulated-gate bipolar transistors (IGBTs), a plurality of free-wheeling diodes 139, and a voltage source 140, e.g., a battery.

A linear model of the doubly-salient axial-flux permanent-magnet machine, developed based on an FEM (Finite Element Modeling) analysis can be used to study the performance of the machine and to investigate possible control strategies thereof. Assumptions made for this linear model are as follows: (1) variation of inductance versus rotor angle is linear; and (2) inductance is independent of current level. The electric circuit equivalent of the linear model of the doubly-salient axial-flux permanent-magnet machine, shown in Fig. 13, is derived as follows:

$$u_a = e_{ma} + i_a \times r_a + \frac{d\lambda_a}{dt}$$

$$u_b = e_{mb} + i_b \times r_b + \frac{d\lambda_b}{dt}$$

where

u_a = terminal voltage of phase A;
u_b = terminal voltage of phase B;
i_a = phase current of phase A;
i_b = phase current of phase B;
r_a = resistance of phase A;
r_b = resistance of phase B;
λ_a = armature-reaction flux linkage of phase A;

λ_b = armature-reaction flux linkage of phase B;

Furthermore,

$$e_{ma} = \frac{d\Psi_{ma}}{dt}$$

$$e_{mb} = \frac{d\Psi_{mb}}{dt}$$

where

Ψ_{ma} = permanent-magnet flux linked by phase A
Ψ_{mb} = permanent-magnet flux linked by phase B

Moreover,

$$\lambda_a = L_{aa} \times i_a + M_{ba} \times i_b$$

$$\lambda_b = M_{ab} \times i_a + L_{bb} \times i_b$$

where

M_{ab} = mutual inductance between phase A and phase B (flux linked by phase B divided by the excitation current of phase A);
M_{ba} = mutual inductance between phase A and phase B (flux linked by phase A divided by the excitation current of phase B);

From above,

$$\begin{bmatrix} L_{aa} & M_{ba} \\ M_{ab} & L_{bb} \end{bmatrix}\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \end{bmatrix} = \begin{bmatrix} r_a + \omega_r \frac{dL_{aa}}{d\theta_r} & \omega_r \frac{dM_{ba}}{d\theta_r} \\ \omega_r \frac{dM_{ab}}{d\theta_r} & r_b + \omega_r \frac{dL_{bb}}{d\theta_r} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} u_a \\ u_b \end{bmatrix} - \begin{bmatrix} e_{ma} \\ e_{mb} \end{bmatrix}$$

where

q_r = mechanical degrees of rotor rotation
w_r = angular velocity of the rotor

This set of equations is schematically represented in Fig. 13, where the following definitions apply:

e_{ma} = induced voltage of phase A produced by permanent-magnet flux variation;
e_{mb} = induced voltage of phase B produced by permanent-magnet flux variation;
e_{ra} = reluctance voltage of phase A produced by the variation of self inductance of phase A;
e_{rb} = reluctance voltage of phase B produced by the variation of self inductance of phase B;
e_{rma} = reluctance voltage of phase A produced by the variation of mutual inductance between phase A and phase B;
e_{rmb} = reluctance voltage of phase B produced by the variation of mutual inductance between phase A and phase B;
L_{aa} = self-inductance of phase A;
L_{bb} = self-inductance of phase B;
M_{ab} = mutual inductance between phase A and phase B;

The torque is given by:

$$e_{ma} \times i_a + e_{mb} \times i_b = \omega_r (T_{ma} + T_{mb})$$

where

$$T_{ma} = \dot{i}_a \times \frac{d\Psi_{ma}}{d\theta_r} = \text{mechanical torque produced by phase A}$$

$$T_{mb} = \dot{i}_b \times \frac{d\Psi_{mb}}{d\theta_r} = \text{mechanical torque produced by phase B}$$

Under normal operating conditions, the self-reluctance torques of phase A and phase B will cancel each other, as shown in Fig. 14. The mutual reluctance torque has zero average value. The peak reluctance torque is small because the variation in mutual inductance is comparatively small as a result of the double air-gap structure of the doubly-salient axial-flux permanent-magnet machine. As a result, torque production is very smooth.

When the operating speed of the machine is higher than the rated value, the self-reluctance torque can be used to compensate for the power loss due to the irregular current wave form by using control strategies illustrated in Fig. 15. Therefore, the doubly-salient axial-flux permanent-magnet machine is capable of higher speeds than known permanent magnet machines. At higher speeds, the mutual reluctance still contributes to zero average torque.

A nonlinear model of the doubly-salient axial-flux permanent-magnet machine may be obtained if λ_a and λ_b are defined as follows:

$$\lambda_a = f(\theta_r, i_a, i_b)$$
$$\lambda_b = f(\theta_r, i_a, i_b)$$

Because stators 100 and 104 are identically shaped, the reluctances seen by the phase-A winding and the phase-B winding are equal, establishing an electromagnetic balance between the two phases.

Electromagnetic balance of the two phases is beneficial in that circulating currents, bearing currents, and uneven loads on the rotor are theoretically eliminated, thus enhancing the efficiency and reliability of the machine.

As shown in Fig. 16, an air gap 130 exists between rotor 102 and poles 110 (outlines of which are indicated with dashed lines) of stator 100. Similarly, an air gap 132, having the same width as air gap 130, exists between rotor 102 and stator poles 112. It is widely known that minimizing the air gap between the rotor and the stator of an electrical machine leads to increased power and efficiency. The axial configuration of stator 100, rotor 102, and stator 104 allows small air gaps 130 and 132 regardless of the size of rotor 102 and stators 100 and 104, thus reducing the manufacturing cost of a physically large machine. Such a machine could accommodate a large number of poles, allowing it to have a high output at low rotor speeds. Additionally, because of the aforementioned axial configuration, radial expansion of rotor 102 does not reduce air gaps 130 and 132 at high rotor speeds, which, combined with the fact that the smooth shape of rotor 102 reduces windage (losses due to air friction), provides an additional advantage of high-speed operation capability.

Furthermore, the slot-flux leakage of the doubly-salient axial-flux permanent-magnet machine is minimized since in order to obtain high torque generation, a width W_C of the coils 126 and 128 is increased, rather than a slot depth D_S. As discussed in detail in the foregoing section of the specification, minimizing slot depth D_S leads to decreased slot-flux leakage.

The operation of the above-described embodiment of the invention is illustrated with respect to Figs. 17-24. When rotor poles 108 are fully aligned with stator poles 110, permanent magnets 106 are fully aligned with stator poles 112 (Fig. 17). This orientation of rotor 102 (corresponding to 0° of rotor rotation) causes all magnetic flux linkages 127 produced by permanent magnets 106 to link the phase-A winding (not shown in Fig. 17) of stator 100. No flux links the phase-B winding (not shown in Fig. 17) of stator 104 at that instance.

When rotor 102 has rotated 22.5° (Fig. 18), poles 110 and 112 are partially aligned with poles 108 of rotor 102, such that flux linkages 127 produced by permanent magnets 106 is equally distributed between stator 100 and stator 104. At this instance, the flux linking the phase-A winding (not shown in Fig. 18) is equal to that linking the phase-B winding (not shown in Fig. 18).

At 45° (Fig. 19) rotor 102 is positioned such that stator poles 110 are fully aligned with permanent magnets 106 and stator poles 112 are fully aligned with rotor poles 108. In this orientation of rotor 102 all flux linkages 127 produced by permanent magnets 106 links the phase-B winding (not shown in Fig. 19) of stator 104.

Flux distributions at 67.5°, 90°, 112.5°, 135°, and 157.5° of rotation of rotor 102 are shown in Figs. 20, 21, 22, 23, and 24, respectively. Plots of flux linkages 127 of phase-A and phase-B windings corresponding to 0 through 180 mechanical degrees rotation are represented in Figs. 25 and 26, respectively. The phase shift between the phase-A and phase-B currents of the doubly-salient axial-flux permanent-magnet machine is 90° electrical.

Thus, a permanent-magnet machine is provided that overcomes the foregoing drawbacks, e.g., minimizes slot-flux leakage, has electromagnetically balanced phases, is simple and inexpensive to manufacture, is capable of both low-speed and high-speed operation, facilitates heat removal, and is compact and efficient.

The doubly-salient axial-flux permanent-magnet machine is also advantageous because of its ability to achieve a high power density at low angular speed, to accommodate high pole numbers, to utilize a conventional winding design with low-induction windings, and to utilize a simple support structure.

Many other modifications of the apparatus, some of which are described herein, are possible. For instance, the doubly-salient axial-flux permanent magnet machine may have any even number of stator poles greater than two. Furthermore, the ratio of stator poles (e.g., of stator 100) to rotor poles is not required to be one to one. Depending on the size of the machine, this ratio may be altered according to the following formula:

$R = S + 2$, where

S = number of stator poles
R = number of rotor poles

In addition, other suitable stator/rotor pole arrangements are possible. For example, it is feasible to have a combination of 2 stator poles and any other even number of rotor poles above 4, e.g., 2/6, 2/8, ... 2/100, etc. Other combinations, e.g., 4/8, 4/10, 4/12, etc., 6/10, 6/12, 6/14, etc., and so on, can also be provided.

Furthermore, coils of phase-A and phase-B windings may be located such that each stator contains phase-A as well as phase-B coils. Fig. 27 schematically illustrates a doubly-salient axial-flux permanent-magnet machine having a 6-pole rotor 150, a first two-piece stator 152, and a second two-piece stator 156. Rotor 150 includes permanent magnets 155 and electromagnetically-salient poles 157. Stator 152 comprises a phase-A piece 160, having poles 151, and a phase-B piece 162, having poles 153. Stator 156 comprises a phases-B piece 164, having poles 154 and a phase A piece 168, having poles 158. Poles of phase-A pieces 160 and 168 support coils 170 linked in series and comprising the phase-A winding. Poles of phase-B pieces 162 and 164 bear coils 172 linked in series and comprising the phase-B winding. In Fig. 27, the orientation of rotor 150 with respect to stators 152 and 156 is such that all magnetic flux linkages 127 produced by permanent magnets 155 are linking coils 170 of the phase-A winding. Another implementation of the topology of this embodiment is where the number of rotor poles, R, is an integer multiple of ten, while the number of stator poles, S, is calculated according to the formula $S = R(4/5)$.

Fig. 28 shows an embodiment of the doubly-salient axial-flux permanent magnet machine having a dual-rotor configuration. The machine comprises a first stator 200, a first rotor 202, a second stator 204, a second rotor 206, and a third stator 208, each having an annular shape. Stators 200, 204, and 208 include back iron 210, 212, and 214, respectively. Stator 200 has a plurality of longitudinally-oriented salient stator poles 216 and stator 208 has a plurality of longitudinally-oriented salient stator poles 218. Poles 216 and 218 are evenly spaced around their respective stators 200 and 208. Stator 204 has two juxtaposed pluralities of longitudinally oriented salient poles 220(a) and 220(b), where poles 220(a) and 220(b) are evenly spaced around stator 204.

Pluralities of copper coils 222, 224(a) and (b), and 226 are linked such that coils 222 and 226 comprise the phase-A winding and coils 224(a) and (b) comprise the phase-B winding. Individual coils 222 and 226 are located around stator poles 216 and 218. Individual coils 224(a) and (b) are located around stator poles 220(a) and (b).

Fig. 29 illustrates that rotors 202 and 206 are constructed from pluralities of longitudinally-oriented permanent magnets 203 and 205, respectively, alternating with pluralities of electromagnetically-salient rotor poles 207 and 209, respectively, made, e.g., of laminated steel. Gaps G_1, G_2, G_3, and G_4 separate stator 200 and rotor 202, rotor 202 and stator 204, stator 204 and rotor 206, and rotor 206 and stator 208.

As shown in Fig. 28, rotors 202 and 206 are rigidly attached to a rotor support 228, e.g., by screw-type fasteners 230 and 231. Rotor support 228 is fixed with respect to a main shaft 232, e.g., by a weld (not shown). Shaft 232 is rotationally supported within housing 234, having end faces 236 and 238 and a cylindrical body 240, and may be directly coupled, e.g., to wind turbine rotor 235. Stators 200 and 208 are rigidly attached to end faces 236 and 238, respectively, e.g., with screw-type fasteners 242 and 244. Stator 204 is rigidly attached to cylindrical body 240, e.g., with screw-type fasteners 246.

In the case when the number of stator poles equals the number of rotor poles (Fig. 29), stators 200, 204, and 208 are oriented such that when poles 207 and 209 are fully aligned with poles 220 of stator 204, permanent magnets 203 are fully aligned with poles 216 and permanent magnets 205 are fully aligned with poles 218. This orientation of rotors 202 and 206 causes flux linkages 127 produced by permanent magnets 203 and 205 to link coils 224(a) and (b) (not shown in Fig. 28) of the phase-B winding. Similarly, when permanent magnets 203 and 205 are fully aligned with poles 220 (Fig. 30), poles 207 and 209 are fully aligned with poles 216 and 218, respectively. This orientation of rotor 202 and 206 causes flux linkages 127 produced by permanent magnets 203 and 205 to link coils 222 and 226 (not shown in Fig. 30) of the phase-A winding.

The doubly-salient axial-flux permanent-magnet machine is not limited to single or dual-rotor configurations. Variations having three and more rotors and different ratios of rotor to stator poles are also possible.

Furthermore, a radial-flux version of the doubly-salient permanent-magnet machine, illustrated in Fig. 31, can also be implemented. Such a machine comprises an outer stator 300 and an inner stator 302, concentrically oriented with respect to outer stator 300. Stator 300 includes a plurality of radially-oriented equally-spaced salient poles 304, facing inward. A plurality of copper coils 306, wrapped around poles 304 and connected in series, comprises an A-phase winding. Stator 302 includes a plurality of radially-oriented equally-spaced salient poles 308, facing outward. A plurality of copper coils 310, wrapped around poles 308 and connected in series, comprises a B-phase winding. Stators 300 and 302 have back iron 312 and 314, respectively.

A concentric rotor 316 is located between outer stator 300 and inner stator 302. Rotor 316 comprises a plurality of permanent magnets 318 alternating with an equal number of electromagnetically-salient rotor poles 320, made, e.g., of laminated steel. Permanent magnets are evenly spaced around rotor 316 and equal in number to poles 304 and 308. Rotor 316 may be directly coupled to a wind-turbine rotor (not shown). The principle of operation of this embodiment of the invention is the same as that of the doubly-salient axial-flux permanent-magnet machine described above.

As with axial-flux embodiments of the invention, the relationship between the number of rotor poles and the number of stator poles may vary. Furthermore, the coils of this machine need not be connected such that the coils of one stator comprise the A-phase winding and the coils of the other stator comprise the B-phase winding.

The above configurations of doubly-salient permanent-magnet machine are given only as examples. Therefore, the scope of the invention should be determined not by the examples given, but by the appended claims and their equivalents.

CLAIMS

WHAT IS CLAIMED IS:

1. A doubly-salient permanent-magnet machine comprising:
   at least two stators fixed coaxially with respect to each other;
   at least one rotor interposed between said at least two stators; and
   a two-phase winding supported by said at least two stators.

2. The doubly-salient permanent-magnet machine of Claim 1 wherein each of said at least two stators includes a plurality of salient stator poles and has a symmetry axis.

3. The doubly-salient permanent-magnet machine of Claim 2 wherein said salient stator poles are formed longitudinally with respect to said symmetry axis.

4. The doubly-salient permanent-magnet machine of Claim 2 wherein said salient stator poles are formed radially with respect to said symmetry axis.

5. The doubly-salient permanent-magnet machine of Claim 1 wherein said at least one rotor includes a plurality of permanent magnets.

6. The doubly-salient permanent-magnet machine of Claim 5 wherein said permanent magnets alternate with electromagnetically-salient rotor poles made of a magnetically-permeable material.

7. The doubly-salient permanent-magnet machine of Claim 6 wherein each of said electromagnetically-salient rotor poles has a first and a second side, said permanent magnets polarized such that said first side has the same magnetic polarization as said second side.

8. The doubly-salient permanent-magnet machine of Claim 1 wherein said two-phase winding comprises a first and a second plurality of coils.

9. A doubly-salient axial-flux permanent-magnet machine comprising:
at least two stators coaxially and laterally disposed with respect to each other;
at least one rotor interposed between said at least two stators; and
a winding having a first phase and a second-phase, said winding supported by said at least two stators.

10. The doubly-salient axial-flux permanent-magnet machine of Claim 9 wherein each of said at least two stators has a plurality of salient stator poles and a symmetry axis.

11. The doubly-salient axial-flux permanent-magnet machine of Claim 10 wherein said salient stator poles are evenly spaced around each of said at least two stators and formed longitudinally with respect to said symmetry axis.

12. The doubly-salient axial-flux permanent-magnet machine of Claim 9 wherein said at least one rotor includes a plurality of permanent magnets evenly spaced around said at least one rotor and interposed with a plurality of electromagnetically-salient rotor poles made of a magnetically-permeable material, each of said electromagnetically-salient rotor poles having a first and a second side, said permanent magnets polarized such that said first side has the same magnetic polarization as said second side.

13. The doubly-salient axial-flux permanent-magnet machine of Claim 9 wherein said first phase comprises a first plurality of coils linked in series and said second phase comprises a second plurality of coils linked in series.

14. The doubly-salient axial-flux permanent-magnet machine of Claim 13 wherein said first plurality of coils is supported by one of said at least two stators, and said second plurality of coils is supported by the other of said at least two stators.

15. A doubly-salient axial-flux permanent-magnet machine comprising:

at least two stators coaxially and laterally disposed with respect to each other, each of said at least two stators having a symmetry axis and S salient stator poles, where S is an even integer equal to or greater than two, said salient stator poles uniformly spaced around each of said at least two stators, said salient stator poles formed longitudinally with respect to said symmetry axis;

at least one rotor interposed between said at least two stators, said at least one rotor including P permanent magnets, where P is an even integer equal to or greater than two, said permanent magnets being uniformly spaced around said at least one rotor and alternating with R electromagnetically-salient rotor poles made of a magnetically-permeable material, where R is an integer equal to P; and

a winding having a first phase and a second phase, said winding supported by said at least two stators, said first phase comprising a first plurality of coils linked in series, said second phase comprising a second plurality of coils linked in series.

16. The doubly-salient axial-flux permanent-magnet machine of Claim 15 wherein R = S.

17. The doubly-salient axial-flux permanent-magnet machine of Claim 15 wherein R = S + 2.

18. The doubly-salient axial-flux permanent-magnet machine of Claim 15 wherein R = S + X, where X is an even integer equal to or greater than four.

19. The doubly-salient axial-flux permanent-magnet machine of Claim 15 wherein said first plurality of coils is wound around the salient stator poles of one of said at least two stators, said second plurality of coils wound around the salient stator poles of the other of said at least two stators.

20. The doubly-salient axial-flux permanent-magnet machine of Claim 15 wherein said first plurality of coils is wound around the salient stator poles of both said at least two stators, said second plurality of coils also wound around the salient stator poles of both said at least two stators.

21. The doubly-salient axial-flux permanent-magnet machine of Claim 20 wherein R is a multiple of 10 and S = R(4/5).

22. The doubly-salient axial-flux permanent-magnet machine of Claim 15 wherein said coils comprise of copper, said magnetically-permeable material comprises steel, and said at least two stators comprise a steel lamination.

23. A doubly-salient axial-flux permanent-magnet machine comprising:
    at least three stators coaxially and laterally disposed with respect to each other;
    at least two rotors interposed among said at least three stators; and
    a winding having a first phase and a second phase, said winding supported by said at least three stators.

24. The doubly-salient axial-flux permanent-magnet machine of Claim 23 wherein said at least three stators define a first lateral stator, a second lateral stator, and a middle stators, each of said at least three stators

having S salient stator poles, where S is an even integer equal to or greater than two, said first phase comprising a first plurality of coils and said second phase comprising a second plurality of coils, said first plurality of coils wound around the salient stator poles of said middle stator, said second plurality of coils wound around the salient stator poles of said first lateral and said second lateral stators.

25. The doubly-salient axial-flux permanent-magnet machine of Claim 24 wherein each of said at least two rotors has P permanent magnets, where P is an even integer equal to or greater than 2, said permanent magnets alternating with R electromagnetically-salient rotor poles made of a magnetically-permeable material, where R is an integer equal to P.

26. The doubly-salient axial-flux permanent-magnet machine of Claim 25 wherein R = S.

27. The doubly-salient axial-flux permanent-magnet machine of Claim 25 wherein R = S + 2.

28. The doubly-salient axial-flux permanent-magnet machine of Claim 25 wherein R = S + X, where X is an even integer equal to or greater than four.

29. A doubly-salient permanent-magnet machine for a direct-drive wind turbine comprising:

at least two stators coaxially disposed with respect to each other;

at least one rotor interposed between said at least two stators and rigidly connected to a wind turbine rotor; and

a two-phase winding supported by said at least two stators and electrically coupled to a utility grid by an electronic converter.

30. The doubly-salient permanent-magnet machine of Claim 29 wherein said electronic converter comprises a three-phase inverter electrically coupled to said utility grid and a two-phase inverter electrically coupled to said two-phase winding, said three-phase inverter interconnected with said two-phase inverter by a DC link.

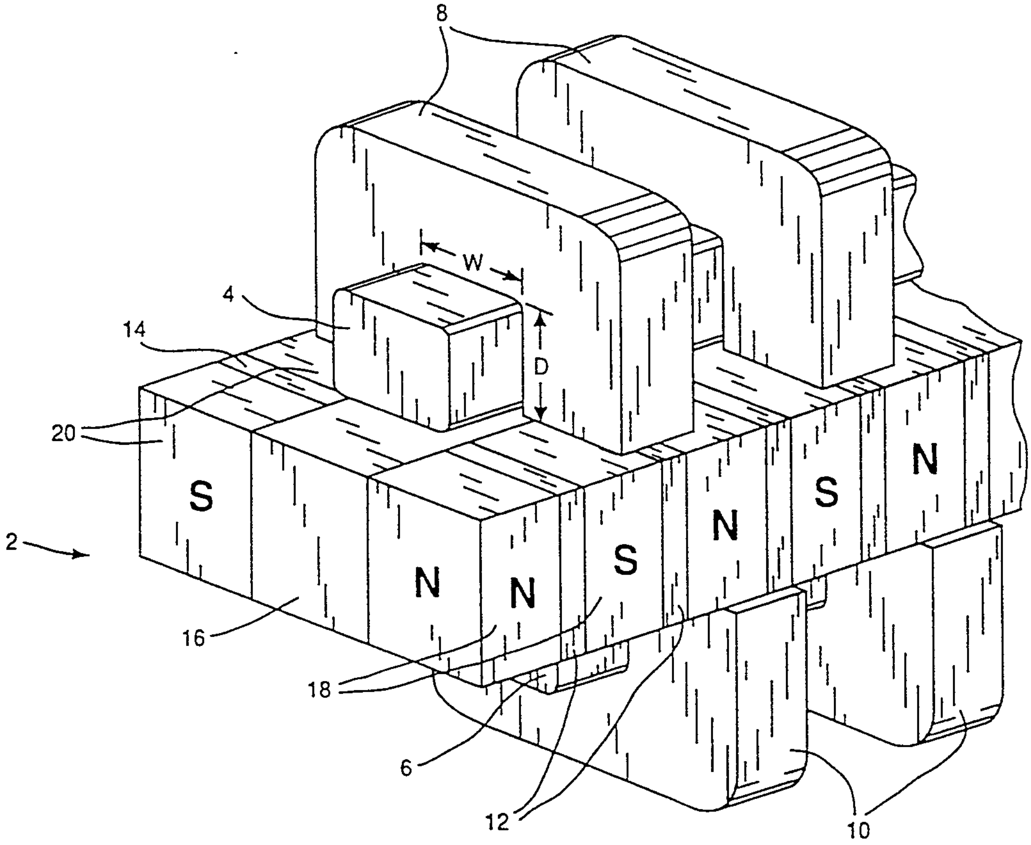

FIG_1 (PRIOR ART)

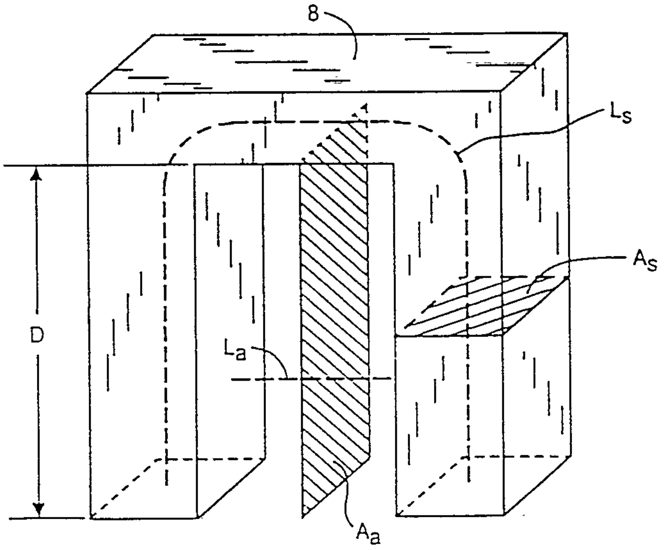

FIG_2 (PRIOR ART)

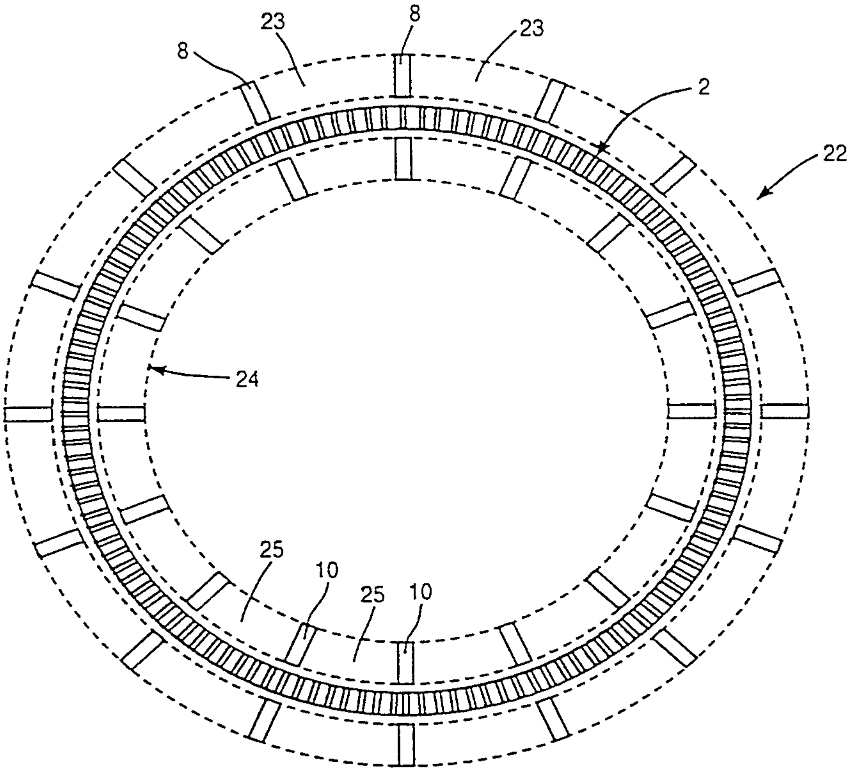

FIG_3 (PRIOR ART)

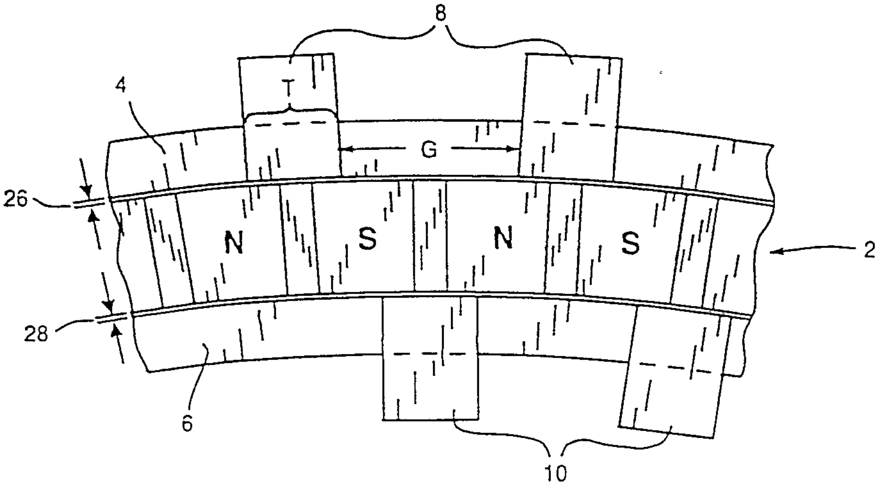

FIG_4 (PRIOR ART)

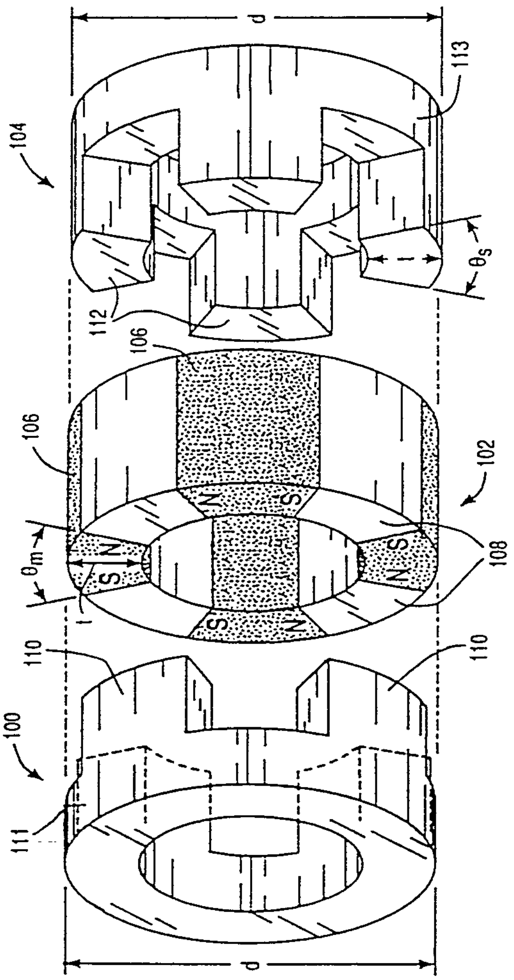

FIG_5

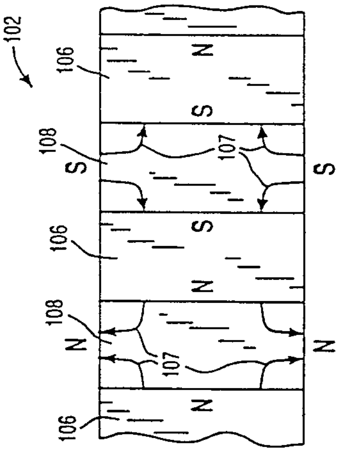

FIG_6

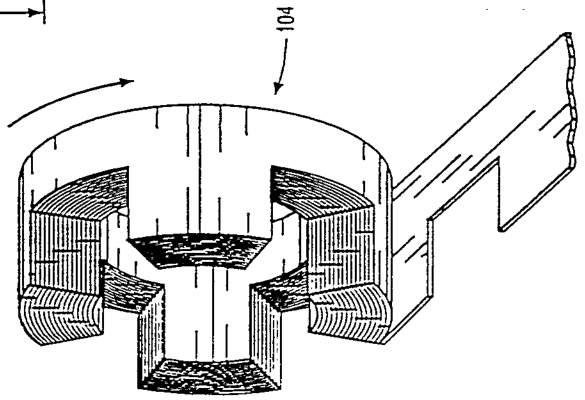

FIG_7

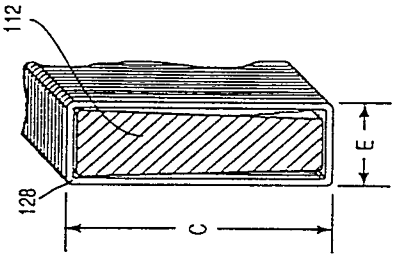

FIG_9

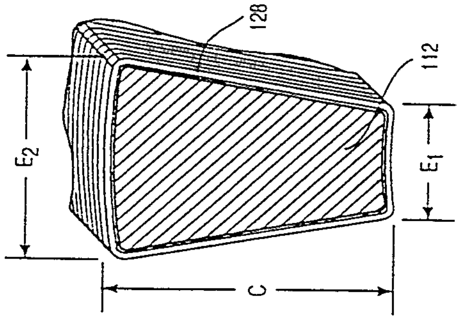

FIG_10

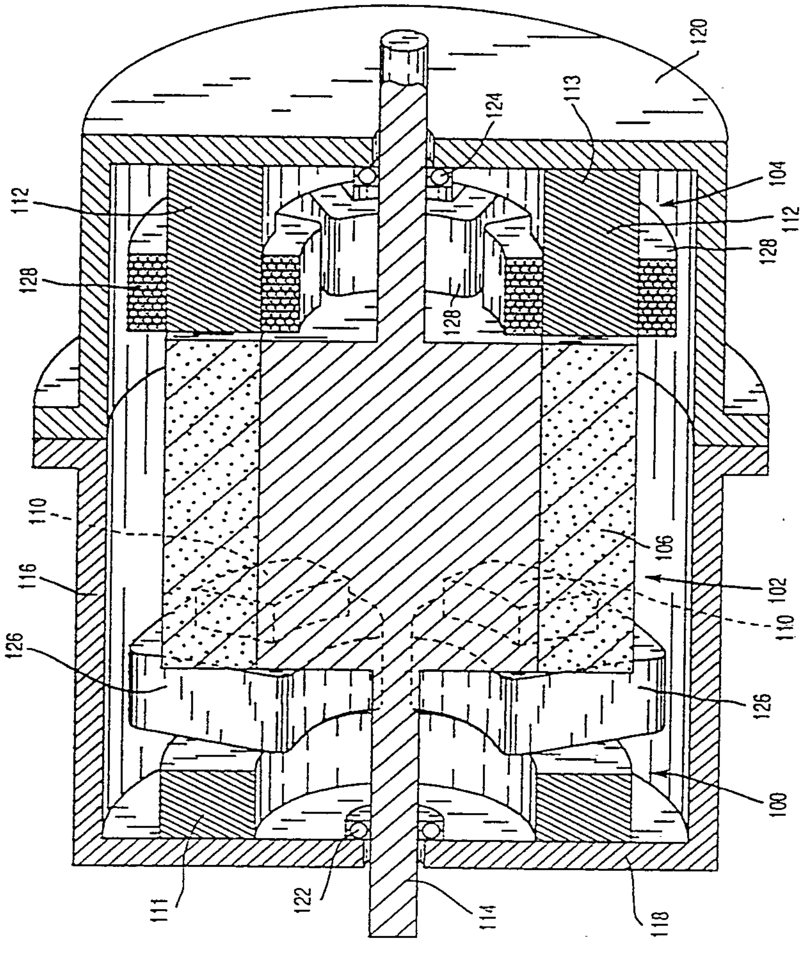

FIG_8

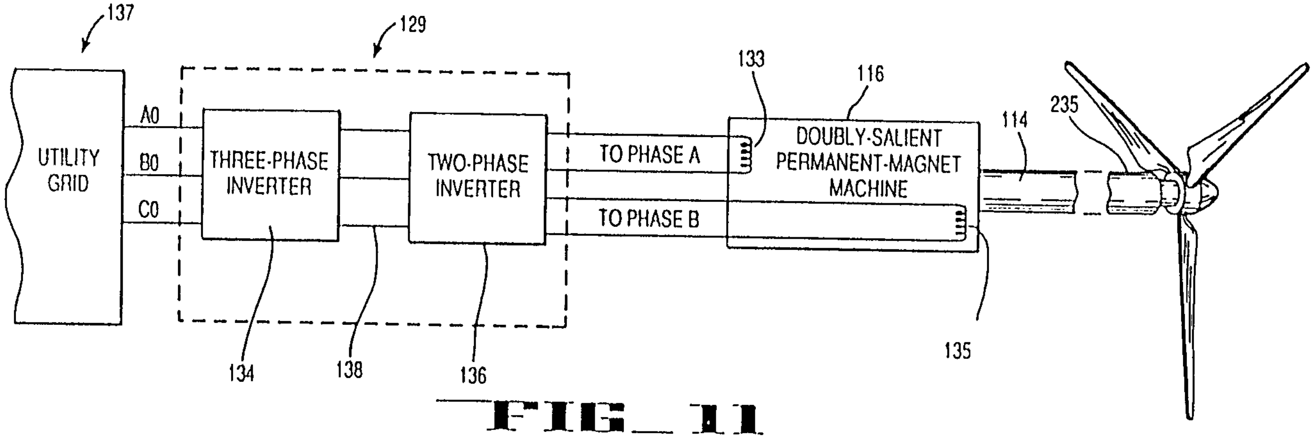
137
129
133
116
114
235
UTILITY GRID
A0
B0
C0
THREE-PHASE INVERTER
TWO-PHASE INVERTER
TO PHASE A
TO PHASE B
DOUBLY-SALIENT PERMANENT-MAGNET MACHINE
134
138
136
135

FIG_11

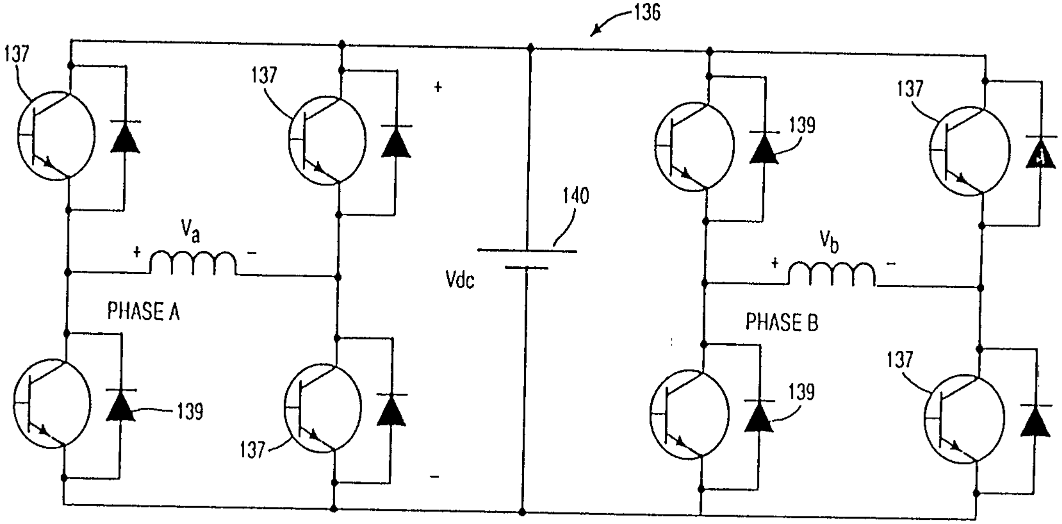
136
137
137
137
+
139
140
V_a
V_b
+
-
+
-
Vdc
PHASE A
PHASE B
139
139
137
137
139
-

FIG_12

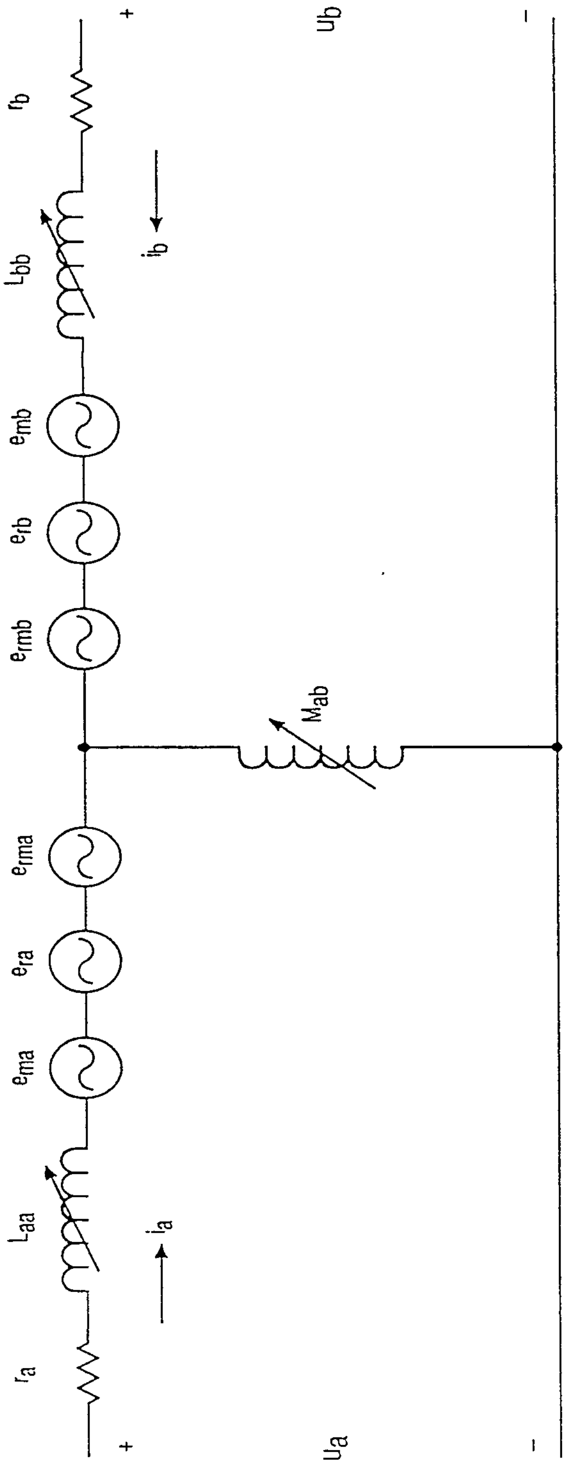

FIG_13

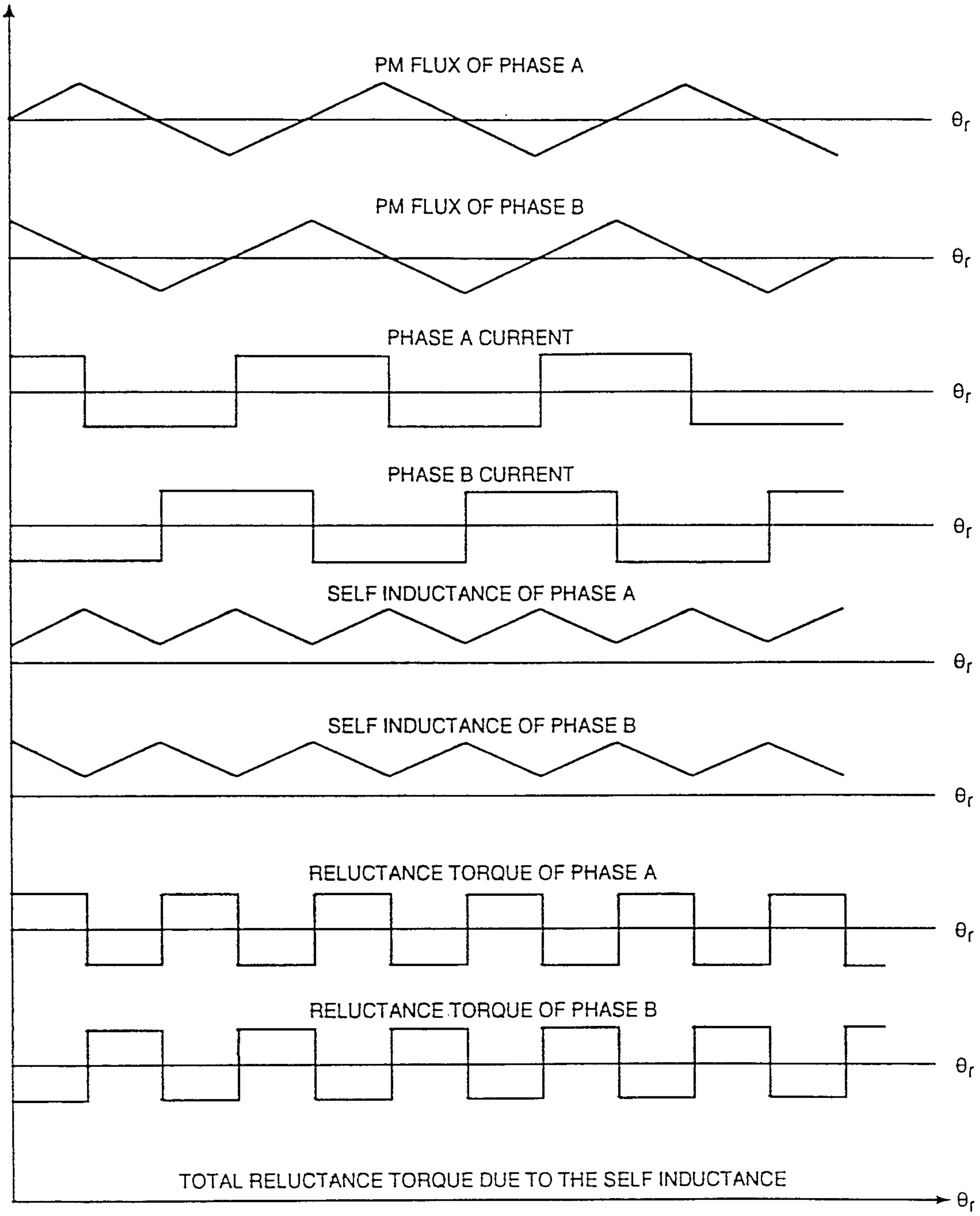
PM FLUX OF PHASE A
θ_r
PM FLUX OF PHASE B
θ_r
PHASE A CURRENT
θ_r
PHASE B CURRENT
θ_r
SELF INDUCTANCE OF PHASE A
θ_r
SELF INDUCTANCE OF PHASE B
θ_r
RELUCTANCE TORQUE OF PHASE A
θ_r
RELUCTANCE TORQUE OF PHASE B
θ_r
TOTAL RELUCTANCE TORQUE DUE TO THE SELF INDUCTANCE
θ_r

FIG_14

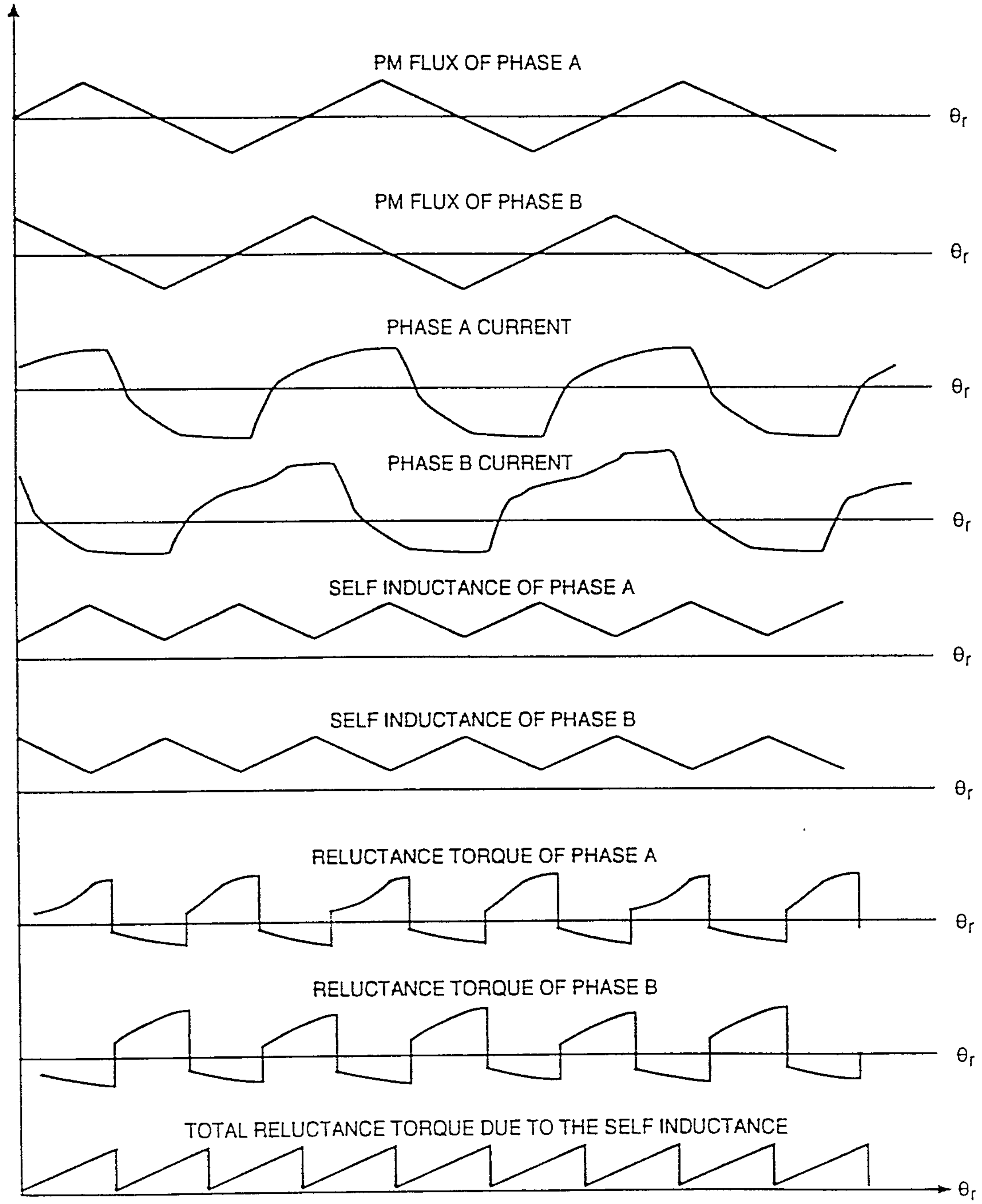
PM FLUX OF PHASE A
θr
PM FLUX OF PHASE B
θr
PHASE A CURRENT
θr
PHASE B CURRENT
θr
SELF INDUCTANCE OF PHASE A
θr
SELF INDUCTANCE OF PHASE B
θr
RELUCTANCE TORQUE OF PHASE A
θr
RELUCTANCE TORQUE OF PHASE B
θr
TOTAL RELUCTANCE TORQUE DUE TO THE SELF INDUCTANCE
θr

FIG_15

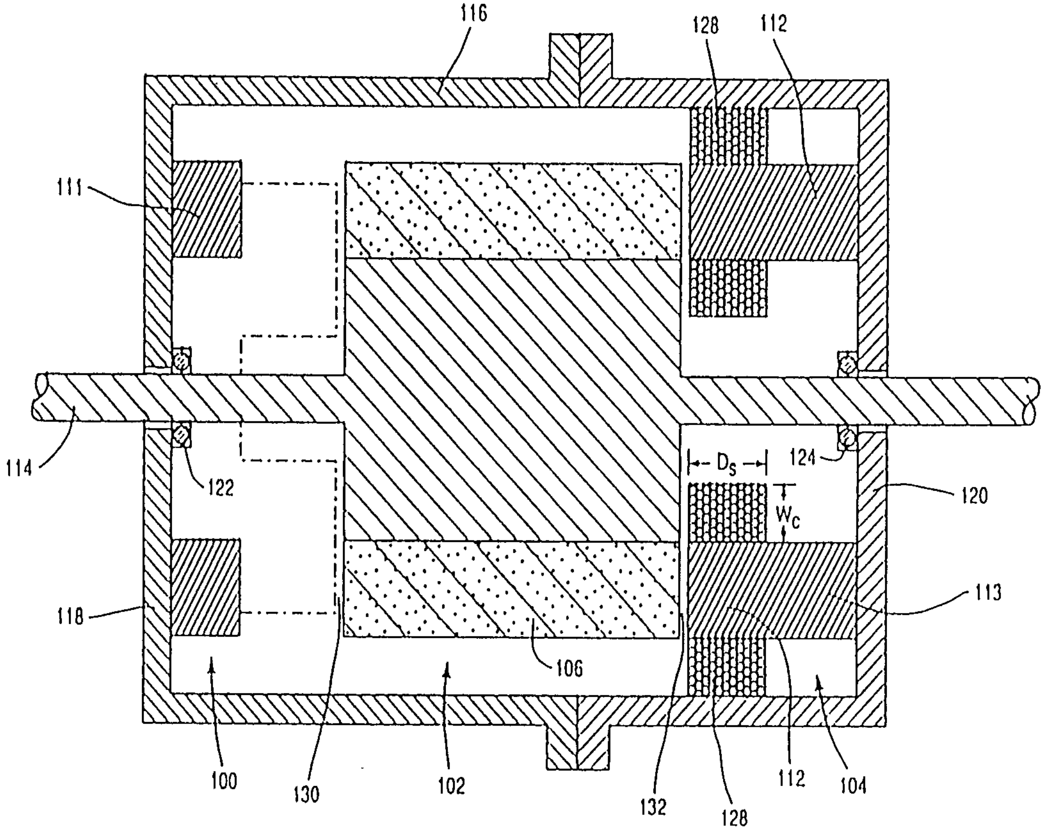
116
128
112
111
114
122
124
120
D_S
W_C
118
113
106
100
130
102
132
128
112
104

FIG_1G

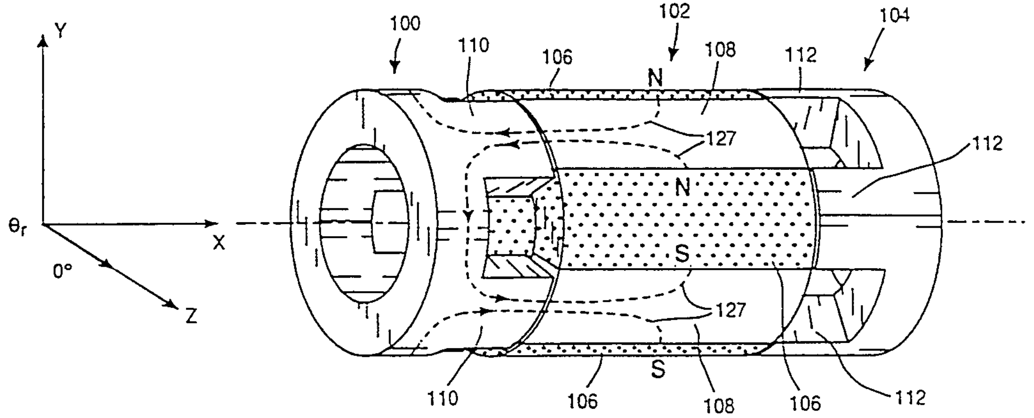

FIG_17

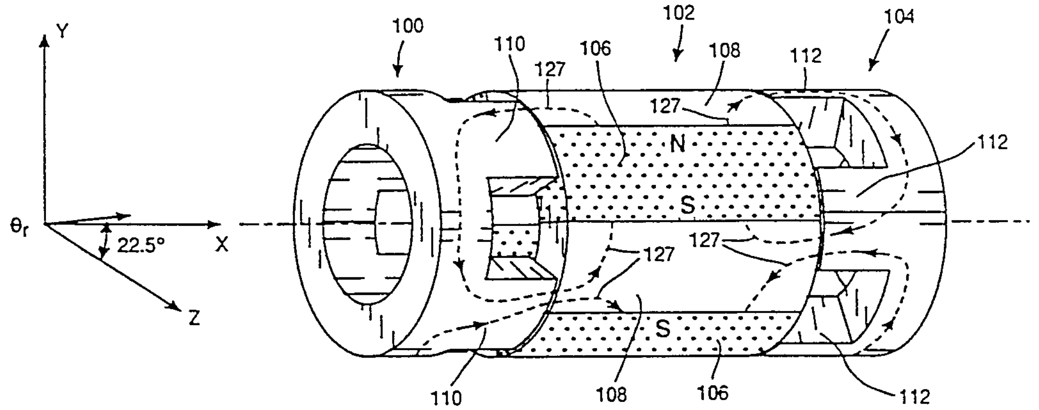

FIG_18

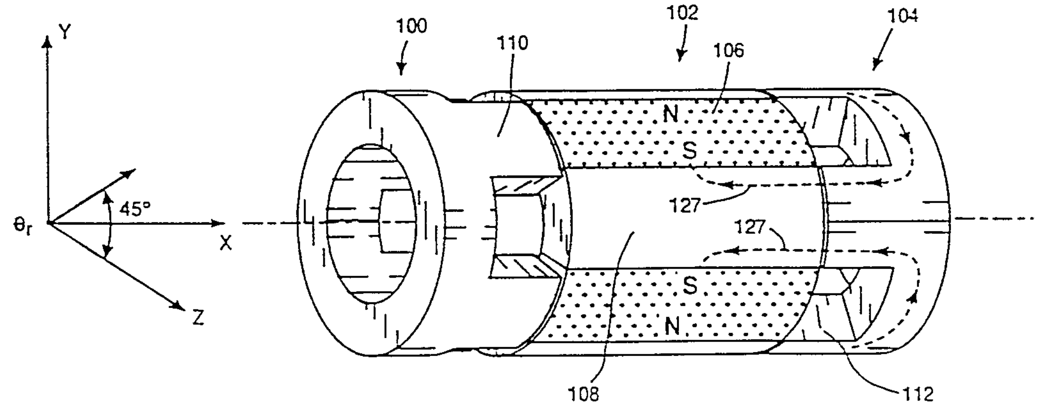

FIG_19

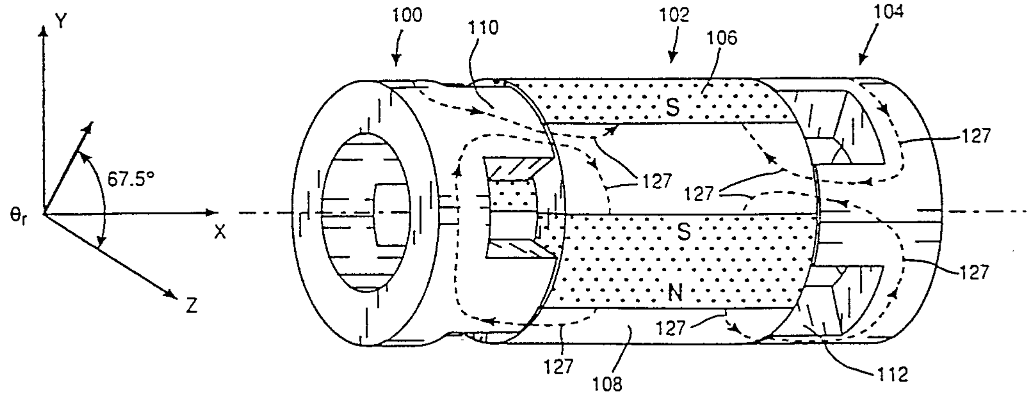

FIG_20

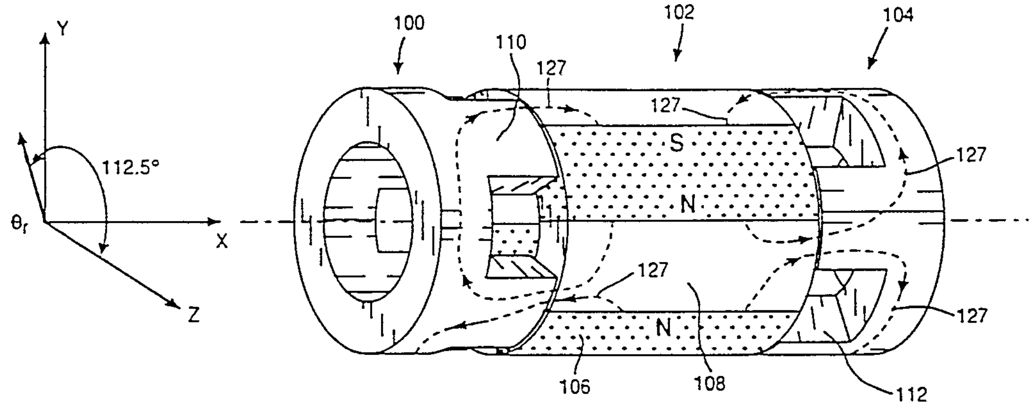

FIG_21

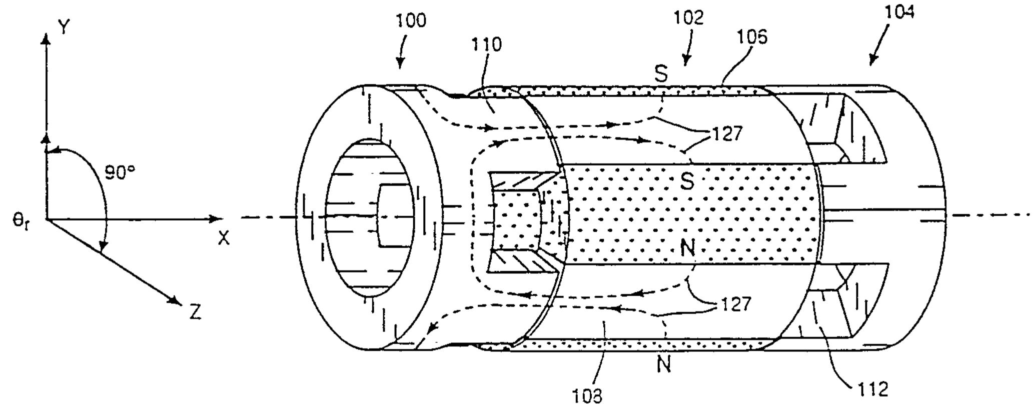

FIG_22

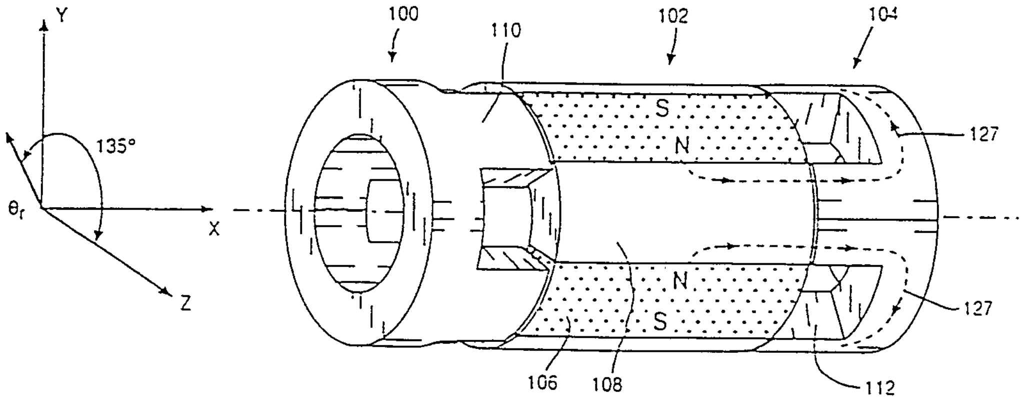
Y
135°
θr
X
Z
100
110
102
104
S
N
N
S
127
127
106
108
112

FIG_23

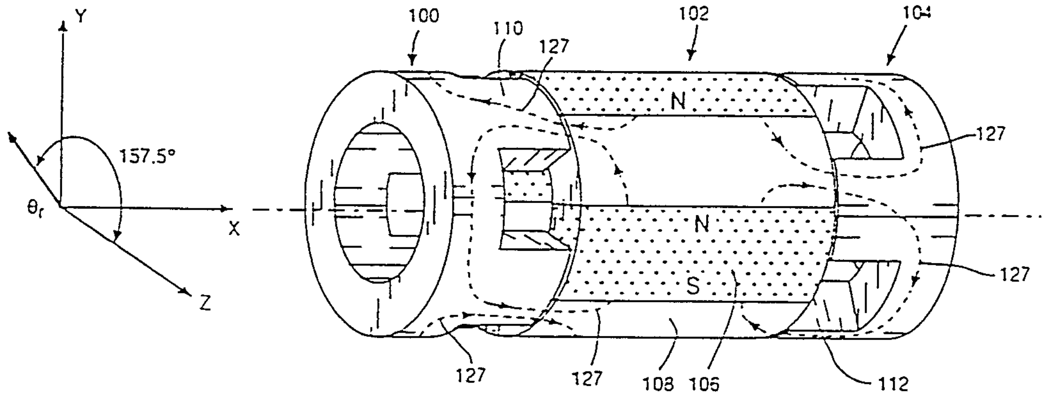
Y
157.5°
θr
X
Z
100
110
127
102
104
N
N
S
127
127
127
127
108
106
112

FIG_24

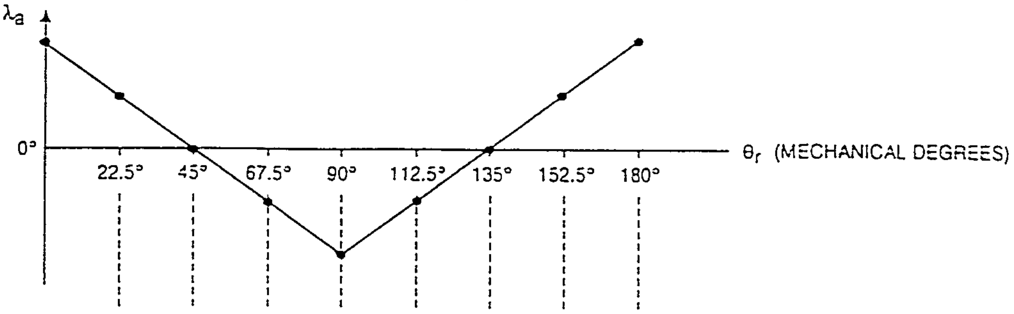

FIG_25

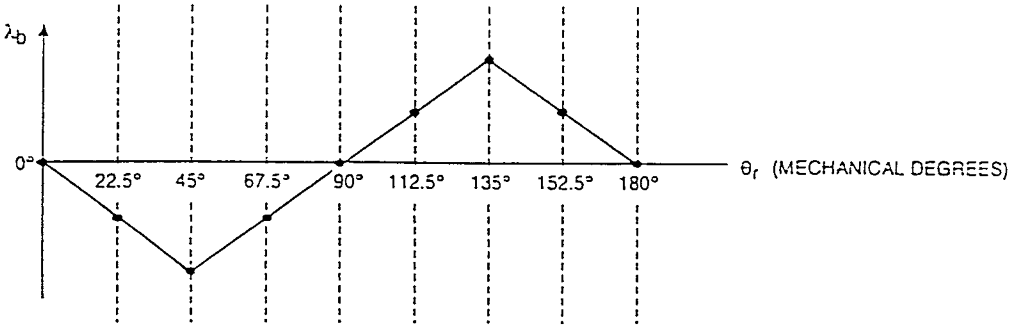

FIG_26

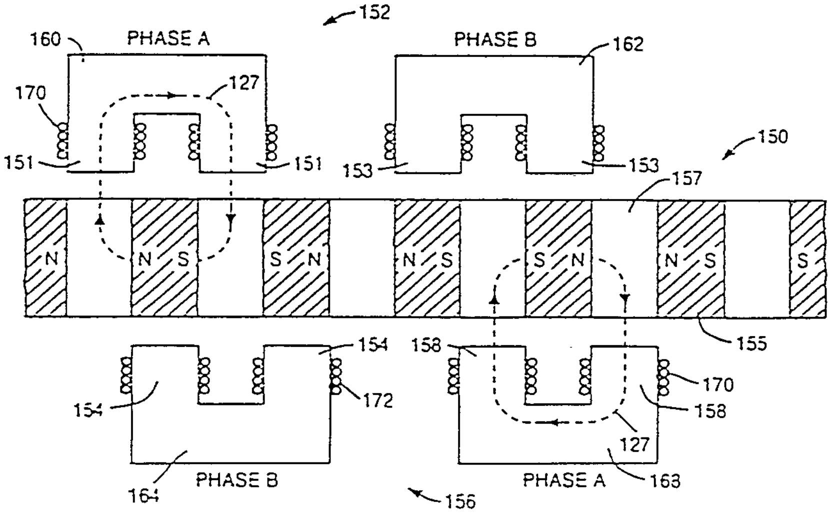

FIG_27

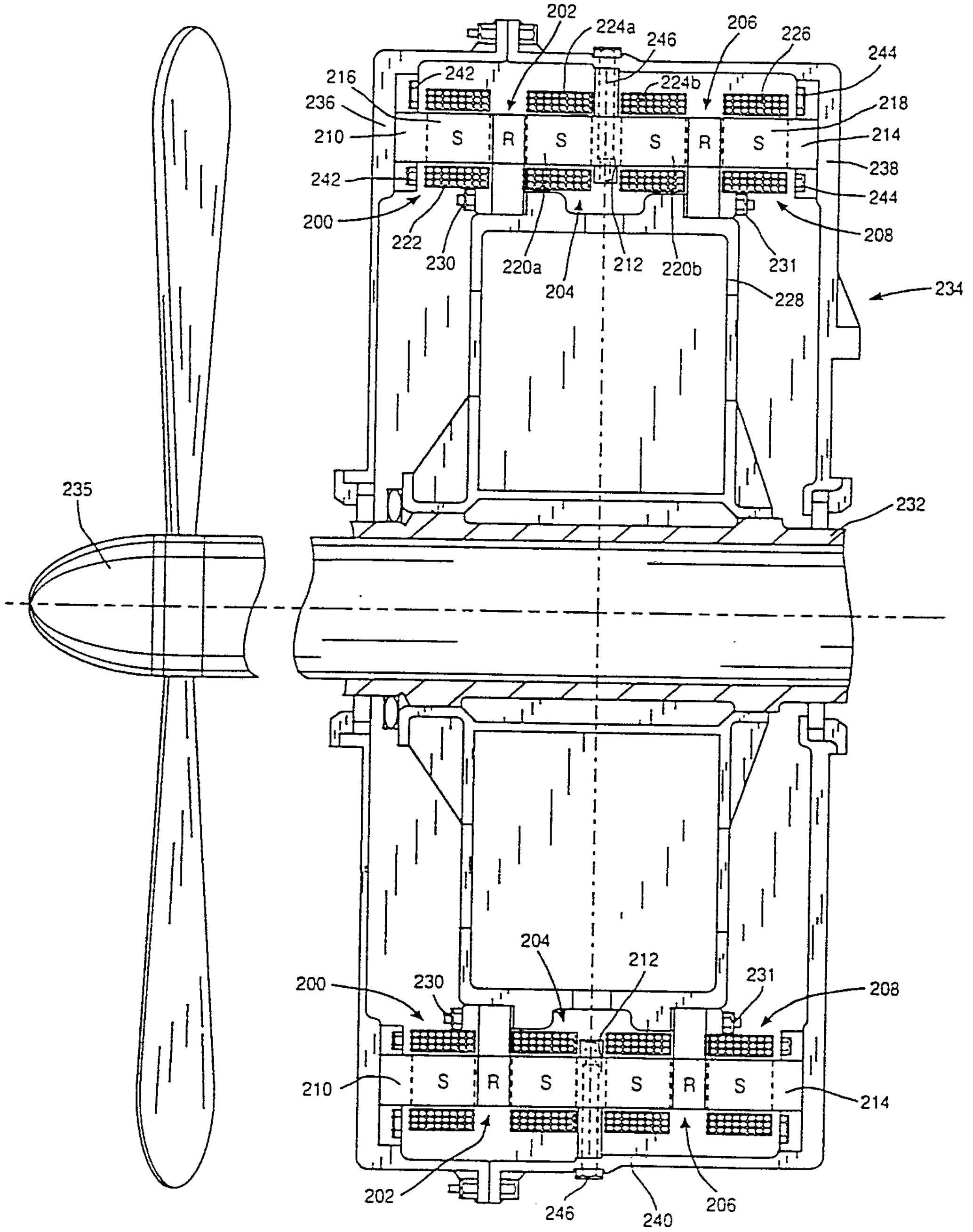
202
224a
246
206
226
244
242
216
224b
236
218
210
S
R
S
S
R
S
214
242
238
244
200
208
222
230
220a
212
220b
231
204
228
234
235
232
204
212
231
200
230
208
210
S
R
S
S
R
S
214
202
246
240
206

FIG_28

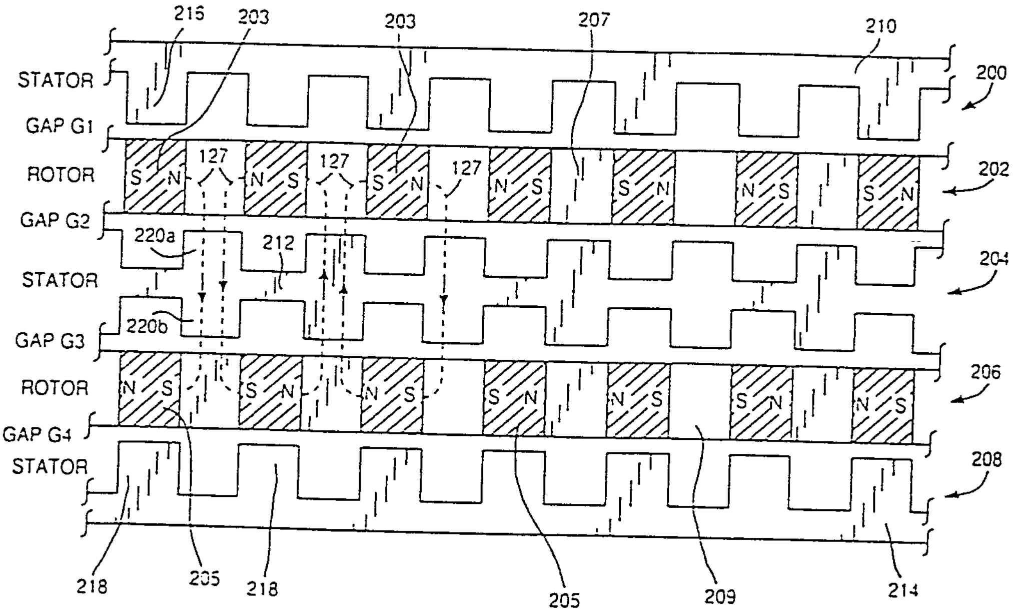
216
203
203
207
210
STATOR
200
GAP G1
ROTOR
S N
127
N S
127
S N
127
N S
S N
N S
S N
202
GAP G2
220a
212
STATOR
204
220b
GAP G3
ROTOR
N S
S N
N S
S N
N S
S N
N S
206
GAP G4
STATOR
208
218
205
218
205
209
214

FIG_29

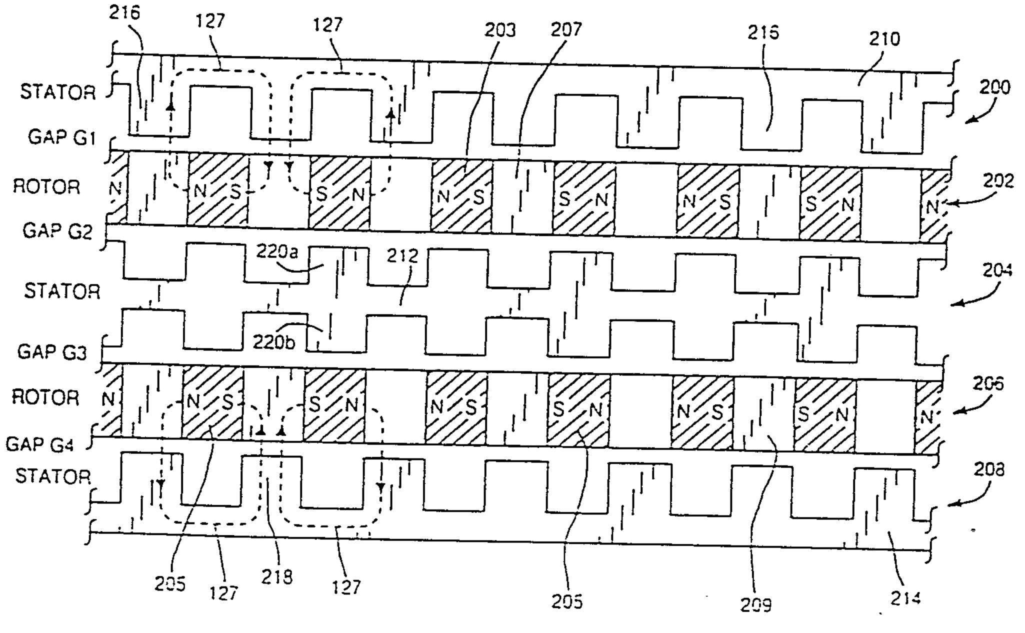
216
127
127
203
207
216
210
STATOR
200
GAP G1
ROTOR
N
N S
S N
N S
S N
N S
S N
N
202
GAP G2
220a
212
STATOR
204
220b
GAP G3
ROTOR
N
N S
S N
N S
S N
N S
S N
N
206
GAP G4
STATOR
208
205
127
218
127
205
209
214

FIG_30

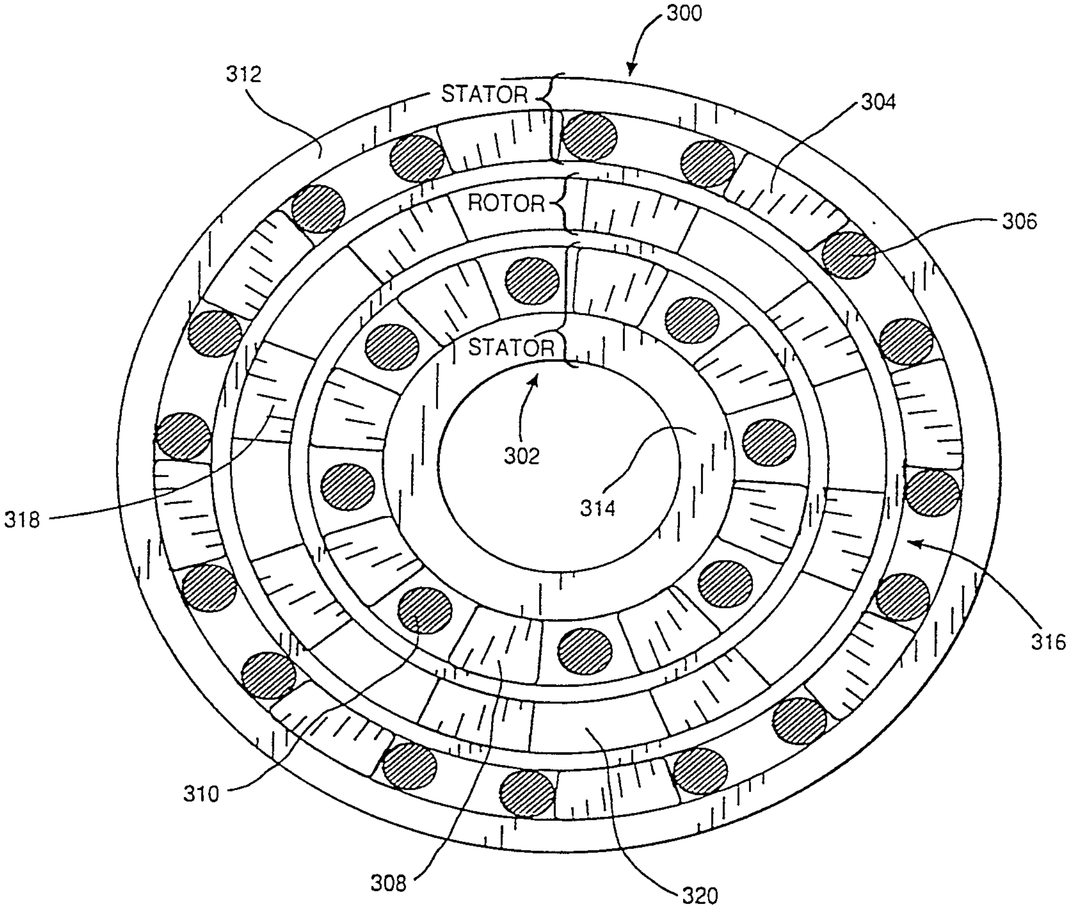
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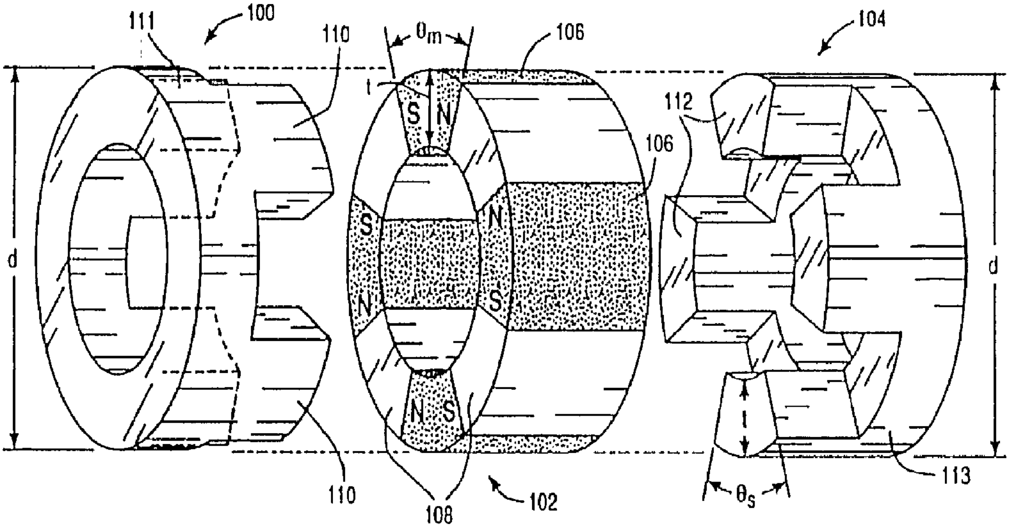
FIG_31



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