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(54) Title: VIRTUAL POLE ELECTRIC MOTOR

(57) Abstract: An electric motor (10) comprising a first member (20) mounted for movement relative to a second member (40), the first member comprising a plurality of permanent magnets (21, 22, 23) spaced along a first member interface surface (24), at least two of the permanent magnets (21, 22) being immediately adjacent each other and separated by a virtual pole (60) having a first magnetic permeability and a first depth (71), the second member having a plurality of coils (A1, B1, C1, D1, A2, C2, D2, D2), each of the coils associated with one of a number of phases (A, B, C, D) and one of a number of second member interface surfaces (48, 49, 50), each of the second member interface surfaces having a second depth (72) and arranged generally opposite to a corresponding portion of the first member interface surface (24), the permanent magnets (21, 22, 23) arranged such that each magnet has a magnetic field orientation (27, 28, 29) that is in the same general direction relative to a proximate portion of the first member interface surface and is generally normal to the proximate portion of the first member interface surface, and wherein the first depth and the second depth may be about the same.

VIRTUAL POLE ELECTRIC MOTOR

TECHNICAL FIELD

[0001] The present invention relates generally to electric motors, and more particularly to improved permanent magnet-type motors with increased performance derived from making use of a virtual pole formed between two similarly oriented adjacent magnets.

BACKGROUND

[0002] Electric motors using permanent magnets may be generally known. For example, permanent magnet type electric motors may be shown and described in U.S. Patent Nos. 4,190,779 and 4,315,171, and PCT Application Number PCT/US2008/010246, the aggregate disclosures of which may be hereby incorporated by reference.

[0003] The permanent magnet-type stepping motors disclosed by Schaeffer have a large number of stator teeth and a large number of radially-magnetized magnets on the rotor to provide for small stepping angles. These motors have the advantage of high unpowered and powered detent torques, relatively-short axial motor lengths (*i.e.*, pancake style), small rotor inertias, and large through-hole solutions on the rotor. These motors have found great success in the last thirty years in space applications, such as in powering solar array drives and antenna pointing mechanisms. Such applications have required light masses, high powered and unpowered detent torques, small rotor inertias, large shafts and/or large numbers of harness feed-throughs on the rotor.

BRIEF SUMMARY OF THE INVENTION

[0004] With parenthetical reference to the corresponding parts, portions or surfaces of the disclosed embodiment, merely for purposes of illustration and not by way of limitation, the present invention broadly provides an electric motor (10) comprising a first member (20) mounted for movement relative to a second member (40); the first member having a plurality of permanent magnets (21, 22, 23) spaced along a first member interface surface (24); at least two of the permanent magnets (21, 22) being immediately adjacent each other and separated by a virtual pole (60) having a first magnetic permeability and a first depth (71); the second member having a plurality of coils (A1, B1, C1, D1, A2, C2, D2, D2); each of the coils associated with one of a number of phases (A, B, C, D) and one of a number of second member interface surfaces (48, 49, 50); each of the second member interface surfaces having a second depth and arranged generally opposite to a corresponding portion of said first member interface surface; and the permanent magnets arranged such that each magnet has a magnetic field orientation that is in the same general direction relative to a proximate portion of the first member interface surface and is generally normal to said proximate portion of the first member interface surface.

[0005] The first depth and the second depth may be about the same. The virtual pole may comprise a magnetic field strength generally equal to a magnetic field strength of each of the adjacent permanent magnets and a magnetic field orientation relative to a proximate portion of the first member interface surface generally opposite to the magnetic field orientation of the permanent magnets.

[0006] The magnetic flux passing through the virtual pole may be generally equal to a magnetic flux passing through each the adjacent permanent magnets when the coils may be not energized.

[0007] The first member and the second member may be configured and arranged to provide a torque vs. displacement curve profile for each unpowered detent interval that has generally the same shape. The first member and the second member may be configured and arranged to provide a torque vs. displacement curve profile for each powered detent interval that has generally the same shape.

[0008] The electric motor may be a rotary motor and one of the members may be a rotor and the other of the members may be a stator. The electric motor may be a linear motor. The number of phases may be two or three. The first member may comprise a plurality of virtual poles between a plurality of adjacent pairs of permanent magnets and may further comprise a set of first member poles defined by a pole from each of the permanent magnets and each of the virtual poles; and when each the second member interface surface associated with a coil in a first phase aligns with a first member pole, each the second member interface surface associated with a coil in a second phase aligns with a trailing edge of an associated first member pole and each the second member interface surface associated with a coil in a third phase aligns with a leading edge of an associated first member pole.

[0009] The number of phases may be four. The first member may comprise a plurality of virtual poles between a plurality of adjacent pairs of permanent magnets and may comprise a set of first member poles defined by a pole from each of the permanent magnets and each of the virtual poles; and when each the second member interface surface associated with a coil in a first phase aligns with a first member permanent magnet pole, each the second member interface surface associated with a coil in a second phase aligns with a trailing edge of an associated a first member permanent magnet pole, each the second member interface surface associated with a coil in a third phase aligns with a leading edge of an associated first member permanent magnet pole, and each the second member interface surface associated with a coil in a fourth phase aligns with a virtual pole.

[0010] The first member may have a core configured to allow flux to pass between the virtual pole and one of the adjacent permanent magnets.

[0011] The electric motor may be configured and arranged to have a step angle equal to

$$\text{step angle} = \frac{360^\circ}{(\text{no. of phases}) \times (\text{no. of permanent magnet poles})}$$

when driven with a unipolar driver.

[0012] The electric motor may be configured and arranged to have a step angle equal to

$$\text{step angle} = \frac{360^\circ}{2 \times (\text{no. of phases}) \times (\text{no. of permanent magnet poles})}$$

when driven with a bipolar driver.

[0013] The core may comprise magnetic steel laminations or composite magnetic steel. The coils may be spaced generally equidistantly along the second member.

[0014] The first member may comprise a plurality of virtual poles between a plurality of adjacent pairs of the permanent magnets and the total number of coils may be equal to a product of the number of phases and a sum of a total number of the virtual poles and the permanent magnets in the first member.

[0015] The electric motor may be a stepper motor or a DC motor.

[0016] Each permanent magnet may be formed from two adjacent magnetic portions having their magnetic field orientations slightly different than a direction normal to the first member interface surface and whereby flux paths passing across the first member interface may be concentrated towards the center of each permanent magnet.

[0017] The first member may comprise an elongated cylindrical rotor and the second member may comprise a stator and the magnetic field orientation may be radially outward.

[0018] Accordingly, the general object of the invention is to provide improved electric motors.

[0019] This and other advantages will become apparent from the foregoing and ongoing written specification, the drawings and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] FIG. 1 is a cross-sectional view of a first embodiment electric motor.

[0021] FIG. 2 is a cross-sectional flux diagram view the electric motor shown in FIG. 1 without the coils.

[0022] FIG. 3 is a flux diagram of the electric motor shown in FIG. 1 with the Phase B coils energized.

[0023] FIG. 4 is a torque vs. displacement curve for the motor shown in FIG. 1 configured with a unipolar driver.

[0024] FIG. 5 is a cross-sectional view of a second embodiment electric motor.

[0025] FIG. 6 is a flux diagram of the electric motor shown in FIG. 5 with none of the coils energized.

[0026] FIG. 7 is a cross-sectional view of a third embodiment electric motor with fingers on the second member arms.

[0027] FIG. 8 is a cross-sectional view of a fourth embodiment electric motor with an increased number of poles and arms.

[0028] FIG. 9 is a close up close up view of the electric motor shown in FIG. 8.

[0029] FIG. 10 is a chart showing a four phase unipolar energization scheme.

[0030] FIG. 11 is a coil wiring schematic of a four phase unipolar configuration.

[0031] FIG. 12 is a chart showing a two phase bipolar energization scheme.

[0032] FIG. 13 is a coil wiring schematic of a two phase bipolar configuration.

[0033] FIG. 14 is a chart showing a three phase biploar energization scheme.

[0034] FIG. 15 is a wiring schematic for a three phase bipolar configuration.

[0035] FIG. 16 is a top sectional view of the motor shown in FIG. 1 taken along a horizontal centerline.

[0036] FIG. 17 is a cross-sectional view of a fifth embodiment electric motor.

[0037] FIG. 18 is a cross-sectional view of a sixth embodiment electric motor.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0038] At the outset, it should be clearly understood that like reference numerals may be intended to identify the same structural elements, portions or surfaces consistently throughout the several drawing figures, as such elements, portions or surfaces may be further described or explained by the entire written specification, of which this detailed description is an integral part. Unless otherwise indicated, the drawings may be intended to be read (*e.g.*, cross-hatching, arrangement of parts, proportion, degree, etc.) together with the specification, and may be to be considered a portion of the entire written description of this invention. As used in the following description, the terms "horizontal", "vertical", "left", "right", "up" and "down", as well as adjectival and adverbial derivatives thereof (*e.g.*, "horizontally", "rightwardly", "upwardly", etc.), simply refer to the orientation of the illustrated structure as the particular drawing figure faces the reader. Similarly, the terms "inwardly" and "outwardly" generally refer to the orientation of a surface relative to its axis of elongation, or axis of rotation, as appropriate.

[0039] Referring now to the drawings, and more particularly to FIG. 1 thereof, this invention provides an electric motor, a general embodiment of which is generally indicated at 10. Electric motor 10 generally includes first member 20 and second member 40, which are configured to rotate relative to one another about an axis. Second member 40 is configured to be a stator attached to a ground reference, and first member 20 is configured to be a rotor rotating about a central axis.

[0040] First member 20 is circular and has cylindrical outer interface surface 24. Outer interface surface 24 faces second member 40 and is separated from second member 40 by an air gap. Six permanent magnets, such as permanent magnets 21, 22, and 23, are arranged equidistantly along interface surface 24. The magnetic field orientations of all of the first member magnets, such as magnet field orientation 27, 28, and 29, face radially outwards. The magnetic field orientations of all the first member magnets are a direction normal to the proximal region of interface surface 24. As used in this specification, a pole, refers to a region of the interface surface 24 that has a distinctive strength of magnetic field that is higher than other regions, and is oriented generally normal to interface surface 24, and may be either directly flowing from a permanent magnet, or the indirect flux flow from adjacent permanent magnet. The pole direction can be either inwards or outwards relative to interface surface 24.

[0041] First member 20 contains core 30, which is made of a relatively high magnetic permeability material and acts as a conduit for magnetic flux. A virtual pole is defined as a region producing little or no magneto motive force of its own, however, having a magnetic field and/or flux profile that is characteristic of a permanent magnet pole. A virtual pole is formed between each adjacent permanent magnet, making a total of six virtual poles. For example, virtual pole 60 is formed between magnet 21 and magnet 22. Similarly, virtual pole 61 is formed between magnet 22 and magnet 23. Virtual pole 63 has a circumferential width 25 which is the same for each virtual pole. Note that the virtual pole width is a function of the magnetic characteristics and is not necessarily equal to the width between adjacent permanent magnets.

[0042] As shown in FIG. 2, the unpowered motor flux lines within and/or across each virtual pole is generally oriented in the radial direction. However, as can be recognized in FIG. 2, the orientation of the magnetic field at each virtual pole, such as virtual poles

60 and 61, is oppositely orientated relative to interface surface 24, as the magnetic field orientations of each permanent magnet. While the permanent magnet magnetic field orientations are all radially outwards, all of the virtual pole magnetic field orientations are generally radially inwards. Each of the permanent magnets are generally structurally and magnetically identical, each permanent magnet having a width and, as shown in FIG. 16, a depth 71. First member 20 also has depth 71.

[0043] Second member 40 has circular outer core 52, which is made of a relatively high magnetic permeability. Outer core 52 acts to magnetic flux conduit for magnetic flux entering and exiting the radially outer regions of the eight arms, such as arms 41, 42, 43, which are arranged equidistantly along outer core 52. The arms each have a central end facing first member interface surface 24, such as ends 45, 46, and 47. Each end has an interface surface separated by a narrow air gap from a proximal portion of interface surface 24. For example, arm 41 has end 45 with interface surface 48 which is substantially parallel to a portion of interface surface 24 immediately proximate virtual pole 60. Similarly, arm 43 has end 47 with interface surface 50, which is adjacent a portion of first member interface surface 24 which is proximate permanent magnet 23.

[0044] Each arm has a coil wound around it. For example, arm 41 has coil C1 would around it, and arm 42 has coil B1 wound it. Second member 40 has a total of eight arms and eight respective coils, including coils A1, B1, C1, D1, A2, B2, C2, and D2. These coils may be electrically connected as shown in FIG. 11: with coils A1 and A2 connected in series; coils B1 and B2 connected in series; coils C1 and C2 connected in series; coils D1 and D2 connected in series; one end of coils A2, B2, C2, and D2 connected as common terminal CT; and opposite ends of A1, B1, C1, and D1 acting as phase A, phase B, phase C, and phase D leads respectively. Alternatively, second member 40 coils may be connected in a bipolar configuration as shown in FIG. 13: coils A1 and A2 connected in series; coils B1 and B2 connected in series; coils C1 and C2 connected in series; coils D1 and D2 connected in series; A1 connected in parallel to C1 to form a first phase A terminal; A2 connected in parallel to C2 to form a second phase A terminal; B1 connected in parallel to D1 to form a first phase B terminal; and B2 connected to D2 to form a second phase B terminal. Note that in this bipolar configuration, all of the C coils in FIG. 1 may be labeled as A coils and all of the D coils labeled as B coils, since the bipolar wiring is effectively only two phases, A and B.

[0045] FIG. 16 is a top sectional view of FIG. 1 taken along a horizontal centerline Z-Z. As shown, permanent magnet 23 and first member 20 have depth 71. The depth of each virtual pole and each permanent magnet is equivalent to depth 71. Arm 43's interface surface 50 has depth 70 which is about the same depth as depth 71. Depth 70 may be slightly larger than depth 71 to maximize efficiency. Each second member interface surface has a depth equal to depth 70.

[0046] FIG. 3 is a flux diagram of the motor shown in FIG. 2, connected in a unipolar configuration as shown in FIG. 12, with coils B1 and B2 (i.e. B phase) energized. Note that in this configuration, coil B1 is energized to produce a magnetic field oriented radially inwards, the opposite direction of the permanent magnets in first member 20. Similary, coil B2 also produces a magnetic field oriented radially inwards. This causes arm end 46 to be attracted to virtual pole 61 and arm end 56 to be attracted to virtual pole 63, creating clockwise torque 81 applied by second member 40 onto first member 20.

[0047] FIG. 4 shows plot 110 of the stall torque vs. angular displacement of electric motor 10 in the unipolar configuration, for both unpowered (Detent) and powered for each phase (Phase A, Phase B, Phase C, Phase D). Unpowered detent torque curve 75 is periodic over each detent interval, such as detent intervals 85, and 86.

[0048] Various characteristics of electric motor 10 have been optimized. For example, the permanent magnet width, the magnetic permeability of the material for core 30, the shape of the permanent magnets, along with other features of electric motor 10 shown in FIGS. 1 and 18 may be optimized such that the magnetic field strength within each virtual pole when the first member is isolated from the rest of the motor is substantially equal to the magnetic field strength of each permanent magnet. Additionally, the permanent magnet width, the magnetic permeability of the material for core 30, the shape of the permanent magnets, along with other features of electric motor 10 shown in FIGS. 1 and 18 may be also optimized such that the total magnetic flux passing through a virtual pole is substantially equal to the magnetic flux passing through each virtual pole when said first member 20 is isolated from second member 40. Further, the permanent magnet width, the magnetic permeability of the material for core 30, the shape of the permanent magnets, along with other features of electric motor 10 shown in FIGS. 1 and 18 may be also optimized such that the powered and unpowered torque curves of the electric motor is the same shape and periodic over each detent interval.

[0049] Alternate forms of electric motor 10 may be made by adjusting the number of arms, permanent magnets, and phases, in order to change the electric motor's step size, torque, efficiency, and ripple characteristics. The step angle of electric motor 10 and such modified alternate forms configured with a unipolar driver is given by the equation

$$\text{step angle} = \frac{360^\circ}{(\text{no. of phases}) \times (\text{no. of permanent magnets})}$$

[0050] Use of this equation is not limited to stepping motors, but also is useful to describe the "step" or periodic interval, or interval between phase excitation polarities of a DC electric motor. For example, use of this equation with electric motor 10 configured with a unipolar driver provides that the step angle is 30 degrees, which is confirmed in the periodicity of the torque curves in FIG. 4.

[0051] FIG. 5 shows a second embodiment electric motor in which each permanent magnet pole is comprised of two interior adjacent permanent magnets separated by a width much less than the distance between adjacent permanent magnet poles (called an Interior Permanent Magnet or "IPM" motor). Also, as shown in FIG. 5, the magnetic field orientation of each permanent magnet pole is oriented radially outwards. However, the magnetic field orientation of each permanent magnet in a permanent magnet pole are oriented slightly off of the direction pointing exactly radially outwards, in order to concentrate the magnetic flux flowing from each permanent magnet pole across the first member interface surface into a smaller region.

[0052] The second embodiment IPM rotor has a number of advantages when compared to the traditional surface mounted rotor. The second embodiment rotor does not require rotor surface grinding to maintain the desired air gap. Also, it does not need additional sleeves to contain the fragile permanent magnets. Further, the permanent magnets in an IPM rotor are self-contained to resist high shock and vibration environments.

[0053] FIG. 6, shows the flux lines of the second embodiment motor when none of the coils are energized. The angular deviation of the magnetic field orientation of each permanent magnet, the permanent magnet separation width between the two permanent magnets within a single pole, and the width between adjacent permanent magnet poles can be optimized to produce desired flux patterns, and torque displacement curves with desired characteristics.

[0054] FIG. 7 shows a third embodiment motor having multiple interface surfaces, or fingers at the end of each arm. This configuration allows an individual coil to interact with multiple first member poles at one in order to increase torque.

[0055] FIG. 8 shows a fourth embodiment motor having a three phase configuration, with 24 arms, two interface surfaces per arm, eighty permanent magnets, and eighty virtual poles. FIG. 9 is a close up partial view of FIG. 8, showing the alignment of the interface surfaces of each arm. While the interfaces surfaces for arm A1 are perfectly aligned with permanent magnet poles of the first member, arm B1's interface surfaces are oriented slightly counter clockwise to the closest corresponding permanent magnet poles. Arm C1's two interface surfaces are sligned slightly clockwise to the closest corresponding permanent magnet poles. Since a given phase group of second member interface surfaces may align either with a permanent magnet pole, or a virtual pole for opposite coil energizations, the electric motor effectively has double the resolution of a motor using alternating permanent magnets without virtual poles.

[0056] The three phase fourth embodiment may have its coils wired according to FIG. 15, in the common "Y" orientation and excited with the common six phase bipolar excitation scheme shown in FIG. 14.

[0057] FIG. 17 shows a fifth embodiment electric motor optimized for DC motor operation. The fifth embodiment electric motor has eight permanent magnet poles, 48 slots or coils which are associated with one of three phases. The fifth embodiment motor has a number of advantages over a similar design having alternating orientation permanent magnets. The torque ripples for the fifth embodiment electric motor are significantly reduced compared to an alternating permanent magnetic field design.

Additionally, the cogging torque magnitude of this design is smaller than an alternative permanent magnetic field design. Further, the cogging torque profile in the fifth embodiment motor is more like a sinusoidal waveform than the saw tooth profile that is typical of an alternating permanent magnetic field design, making cogging torque correction easier through motor control. Perhaps most important, the torque magnitude in the fifth embodiment motor is higher than a comparable alternative permanent magnetic field design.

[0058] FIG. 18 shows a sixth embodiment electric motor similar to the fifth embodiment in FIG. 17 but optimized for different operating characteristics, such as saving the amount of permanent magnet material used. The sixth embodiment motor has four permanent magnet poles and 48 coils associated with one of three phases.

[0059] A number of forms of a new electric motor was developed as disclosed herein. Referring now to the figures, and more particularly to FIG. 1, a first embodiment of the invention is shown at 10.

[0060] The permanent magnet poles can be spaced equally about the first member with adjacent poles and can be made with pre-magnetized members that may be bonded to the surface of the supporting first member core, which can be made of soft magnetic steel(s), electrical steel lamination(s), or various combinations of these materials. Alternatively, the magnetic poles can be made with unmagnetized magnetic materials applied to the rotor outer surface, and locally magnetized to have the desired polarities.

[0061] The selection of the numbers of stator teeth and the number of fingers on each tooth will affect the motor detent torque, the motor running torque, and the winding resistance if the windings may be first wound on a mandrel and then transferred onto the stator teeth.

[0062] A linear stepping motor can be constructed that is analogous to each or the disclosed rotary motors. By opening up a stepping motor and straightening the stator and rotor, a rotational electric motor becomes a linear electric motor. Virtual poles are formed in a linear motor between adjacent permanent magnets oriented in the same direction in the same way virtual poles are formed in the described rotary motors.

[0063] Several other variations of stepping motor designs based on the principles of this invention may be constructed. For example: (a) sectional or fractional electric motors, where only portions of the entire 360° stator and rotor may be used; (b) electric motors with reversed, rotational and stationary members, where the inner stationary member is a stator and the other rotational member is a rotor; and (c) electric motors with axial air gap(s), where the rotor and the stator, both in planar forms, may be aligned side by side on a common axis. In comparison with the electric motors disclosed having radial air gaps, and axial air gap design should have axially magnetized magnetic field directions for the rotor poles instead of radial directions disclosed, and the stator teeth and fingers arranged to face toward the rotor poles in the axial directions. In these design variations, the winding schemes and the alignment of stator tooth fingers and rotor poles will remain the same as in the discussed electric motors.

[0064] Bifilar windings and redundant windings may be yet other features that can be easily implemented for all the above winding schemes.

[0065] Use of solid soft magnetic steel(s), to fabricate one-piece solid stator stack with teeth, or even to fabricate one-piece solid stator housings and teeth, is yet another feature that can be implemented for low stepping rate applications for some of the embodiments disclosed herein. Solid soft magnetic steels may include, but may are limited to, molded iron-powder composite materials, low carbon steels (such as American Iron and Steel Institute (AISI) designated 1010, 1015, or 1018 steel, etc.), solid martensitic corrosion-resistant steels (such as 416 stainless steel, etc.), or solid high-permeability nickel-iron or iron-cobalt alloys, etc. Those solid soft magnetic steels may be distinguished from the commonly used electrical steel lamination materials (*e.g.*, AISI M-15, M-19, etc.), or high-permeability nickel-iron or iron-cobalt alloys, etc. for high-frequency magnetic circuit applications. Those solid soft magnetic steels may be known to magnetic designers for low frequency applications where eddy currents and hysteresis losses may be insignificant. This feature has proven to be extremely useful for low stepping rate motors and actuators, because it eliminates de-lamination problems, cuts down costs (specially when using common 1018 low-carbon steel or 416 stainless steel), and simplifies fabrication processes.

[0066] Therefore, while a number of embodiments of the virtual pole electric motors have been shown and described, and certain changes and modifications thereto discussed, persons skilled in this art will readily appreciate that various additional changes and modifications may be made without departing from the spirit of the invention, as defined and differentiated by the following claims.

CLAIMS

1. An electric motor (10), comprising:

a first member (20) mounted for movement relative to a second member (40);

said first member comprising a plurality of permanent magnets (21, 22, 23) spaced along a first member interface surface (24);

at least two of said permanent magnets (21, 22) being immediately adjacent each other and separated by a virtual pole (60) having a first magnetic permeability and a first depth (71);

said second member having a plurality of coils (A1, B1, C1, D1, A2, C2, D2, D2);

each of said coils associated with one of a number of phases (A, B, C, D) and one of a number of second member interface surfaces (48, 49, 50);

each of said second member interface surfaces having a second depth and arranged generally opposite to a corresponding portion of said first member interface surface; and

said permanent magnets arranged such that each magnet has a magnetic field orientation that is in the same general direction relative to a proximate portion of said first member interface surface and is generally normal to said proximate portion of said first member interface surface.

2. The electric motor as set forth in claim 1, wherein said first depth and said second depth may be about the same.

3. The electric motor as set forth in claim 2, wherein said virtual pole comprises a magnetic field strength generally equal to a magnetic field strength of each of said adjacent permanent magnets and a magnetic field orientation relative to a proximate portion of said first member interface surface generally opposite to said magnetic field orientation of said permanent magnets.

4. The electric motor as set forth in claim 2, wherein a magnetic flux passing through said virtual pole is generally equal to a magnetic flux passing through each said adjacent permanent magnets when said coils may be not energized.

5. The electric motor as set forth in claim 2, wherein said first member and said second member may be configured and arranged to provide a torque vs. displacement curve (100) profile for each unpowered detent interval (81, 82) that has generally the same shape (79).

6. The electric motor as set forth in claim 2, wherein said first member and said second member may be configured and arranged to provide a torque vs. displacement curve profile for each powered detent interval that has generally the same shape.

7. The electric motor as set forth in claim 2, wherein said electric motor is a rotary motor and one of said members is a rotor and the other of said members is a stator.

8. The electric motor as set forth in claim 2, wherein said electric motor is a linear motor.

9. The electric motor as set forth in claim 2, wherein said number of phases is two.

10. The electric motor as set forth in claim 2, wherein said number of phases is three.

11. The electric motor as set forth in claim 10, wherein:

said first member comprises a plurality of virtual poles between a plurality of adjacent pairs of permanent magnets and comprises a set of first member poles defined by a pole from each of said permanent magnets and each of said virtual poles; and

when each said second member interface surface associated with a coil in a first phase aligns with a first member pole, each said second member interface surface associated with a coil in a second phase aligns with a trailing edge of an associated first member pole and each said second member interface surface associated with a coil in a third phase aligns with a leading edge of an associated first member pole.

12. The electric motor as set forth in claim 2, wherein said number of phases is four.

13. The electric motor as set forth in claim 12, wherein:

said first member comprises a plurality of virtual poles between a plurality of adjacent pairs of permanent magnets and comprises a set of first member poles defined by a pole from each of said permanent magnets and each of said virtual poles; and

when each said second member interface surface associated with a coil in a first phase aligns with a first member permanent magnet pole, each said second member interface surface associated with a coil in a second phase aligns with a trailing edge of an associated a first member permanent magnet pole, each said second member interface surface associated with a coil in a third phase aligns with a leading edge of an associated first member permanent magnet pole, and each said second member interface surface associated with a coil in a fourth phase aligns with a virtual pole.

14. The electric motor as set forth in claim 1, wherein said first member has a core configured to allow flux to pass between said virtual pole and one of said adjacent permanent magnets.

15. The electric motor as set forth in claim 7, wherein said electric motor is configured and arranged to have a step angle equal to

$$\text{step angle} = \frac{360^\circ}{(\text{no. of phases}) \times (\text{no. of permanent magnet poles})}$$

when driven with a unipolar driver.

16. The electric motor as set forth in claim 7, wherein said electric motor is configured and arranged to have a step angle equal to

$$\text{step angle} = \frac{360^\circ}{2 \times (\text{no. of phases}) \times (\text{no. of permanent magnet poles})}$$

when driven with a bipolar driver.

17. The electric motor as set forth in claim 14, wherein said core comprises magnetic steel laminations.

18. The electric motor as set forth in claim 14, wherein said core comprises composite magnetic steel.

19. The electric motor as set forth in claim 2, wherein said coils may be spaced generally equidistantly along said second member.

20. The electric motor as set forth in claim 2, wherein said first member comprises a plurality of virtual poles between a plurality of adjacent pairs of said permanent magnets and said total number of coils is equal to a product of said number of phases and a sum of a total number of said virtual poles and said permanent magnets in said first member.

21. The electric motor as set forth in claim 2, wherein said electric motor is a stepper motor.

22. The electric motor as set forth in claim 2, wherein said electric motor is a DC motor.

23. The electric motor as set forth in claim 2, wherein each said permanent magnet is formed from two adjacent magnetic portions having their magnetic field orientations slightly different than a direction normal to said first member interface surface and whereby flux paths passing across said first member interface may be concentrated towards the center of each said permanent magnet.

24. The electric motor set forth in claim 2, wherein said first member comprises an elongated cylindrical rotor and said second member comprises a stator and said magnetic field orientation is radially outward.

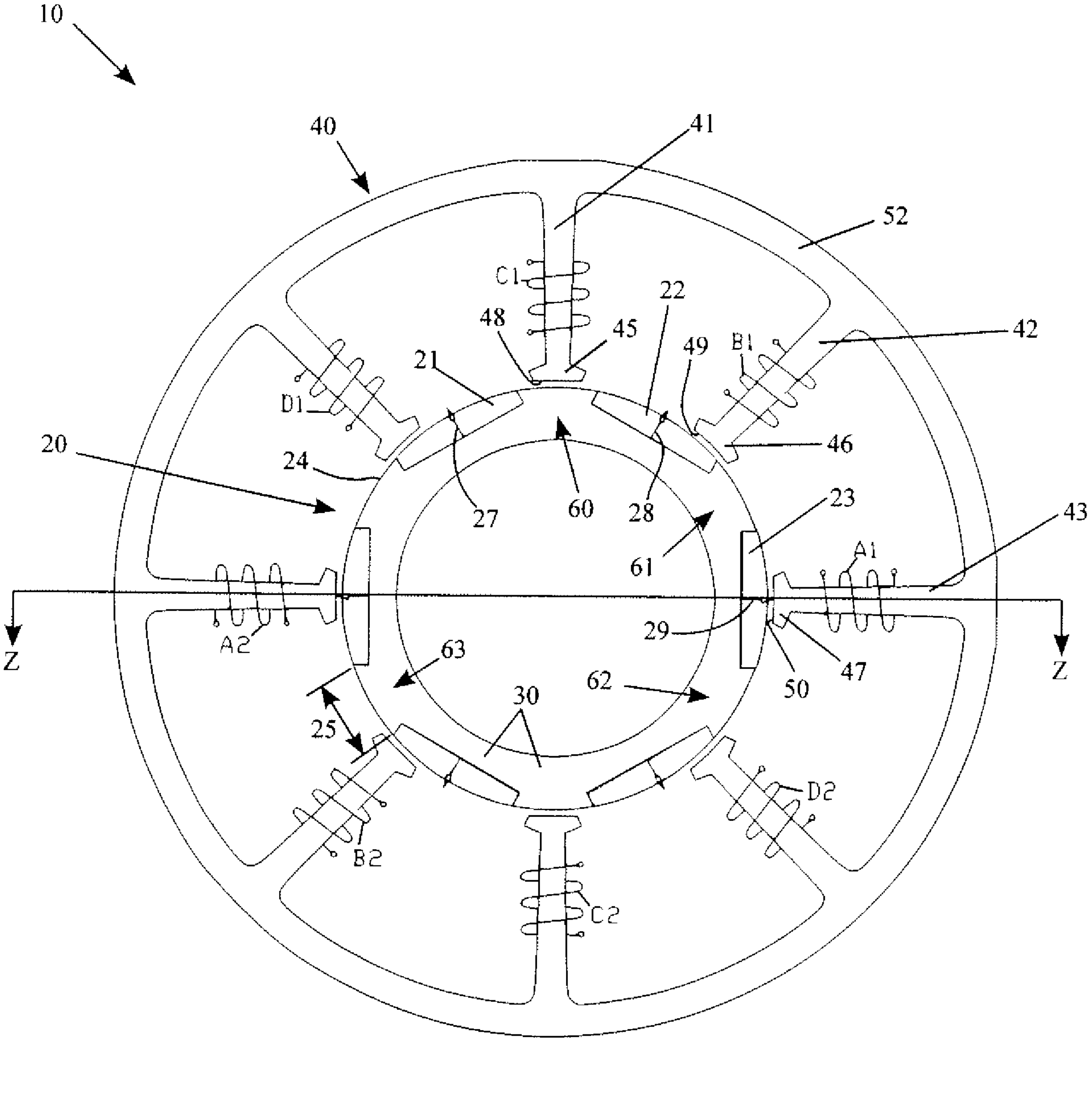
10
40
41
52
C1
22
48
45
49
B1
42
21
D1
46
20
24
27
60
28
23
43
61
A1
A2
29
Z
Z
63
62
50
47
30
25
D2
B2
C2

FIG. 1

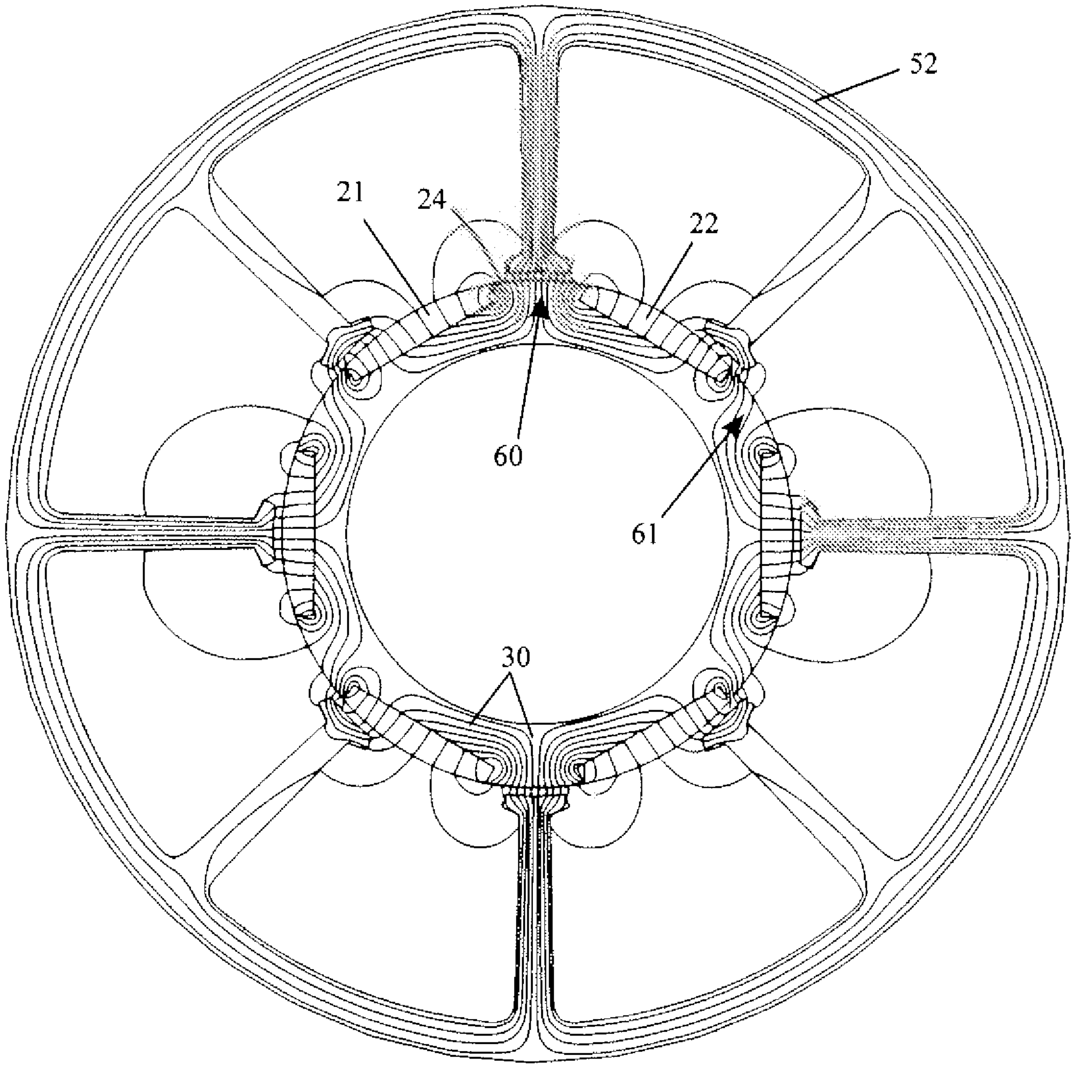

FIG. 2

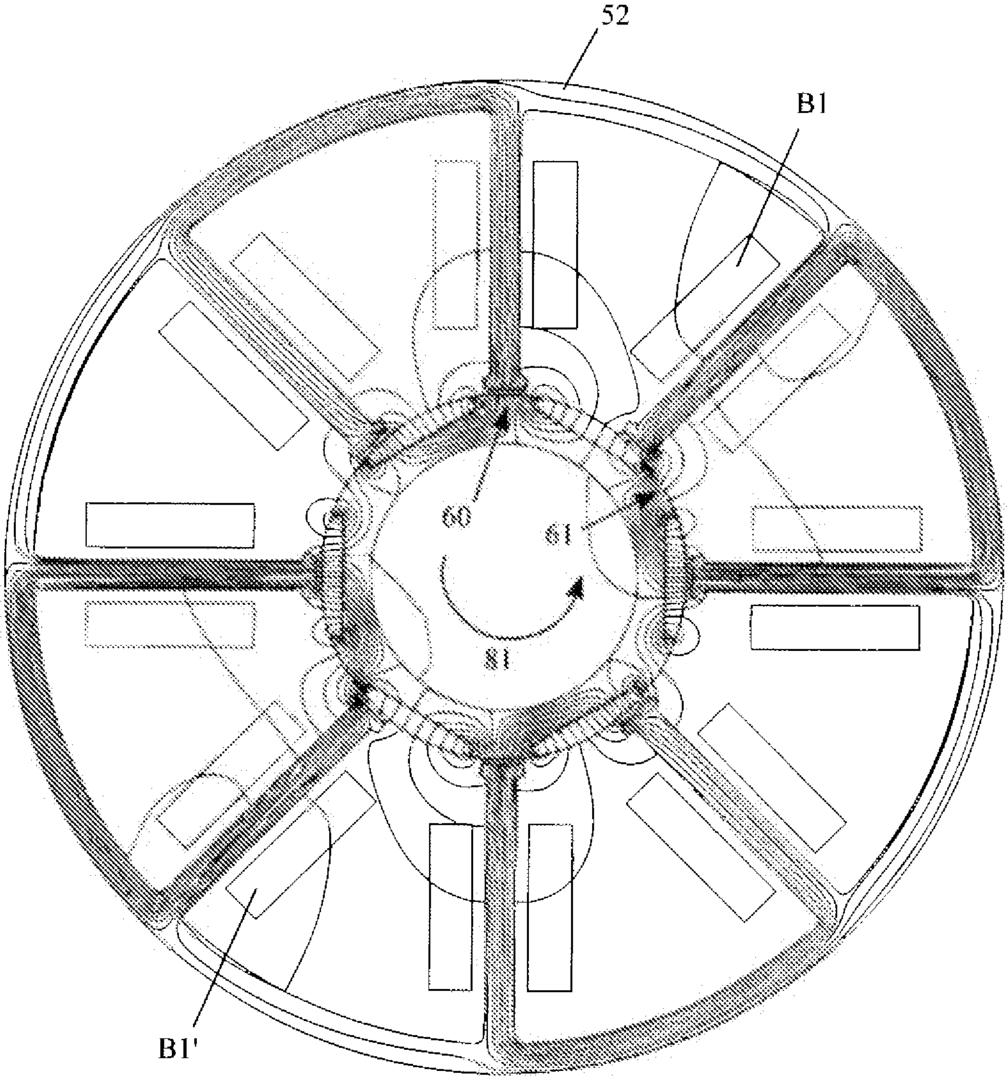

FIG. 3

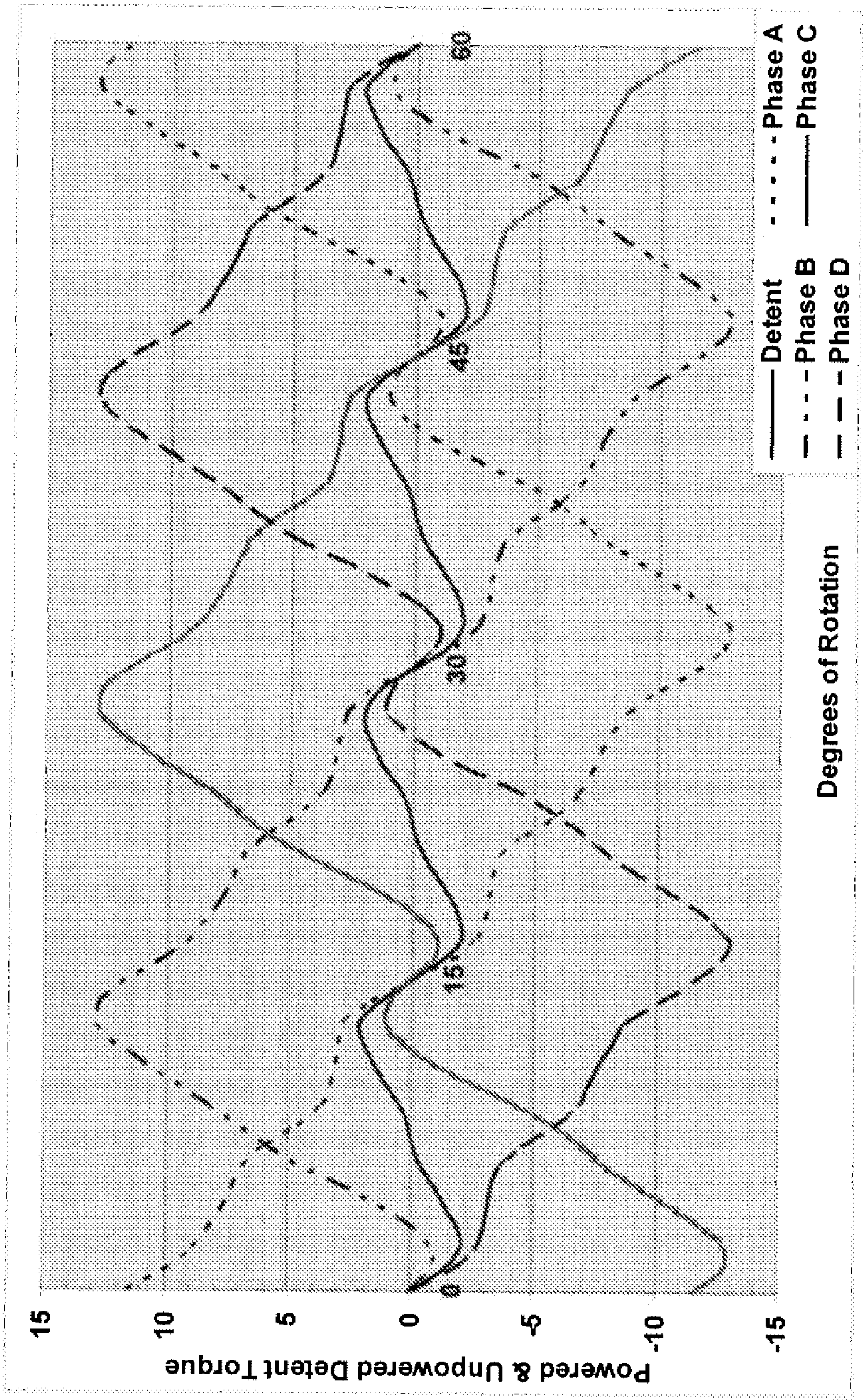
Powered & Unpowered Detent Torque
15
10
5
0
-5
-10
-15
0
15
30
45
60
Degrees of Rotation
Detent
Phase A
Phase B
Phase C
Phase D

FIG. 4

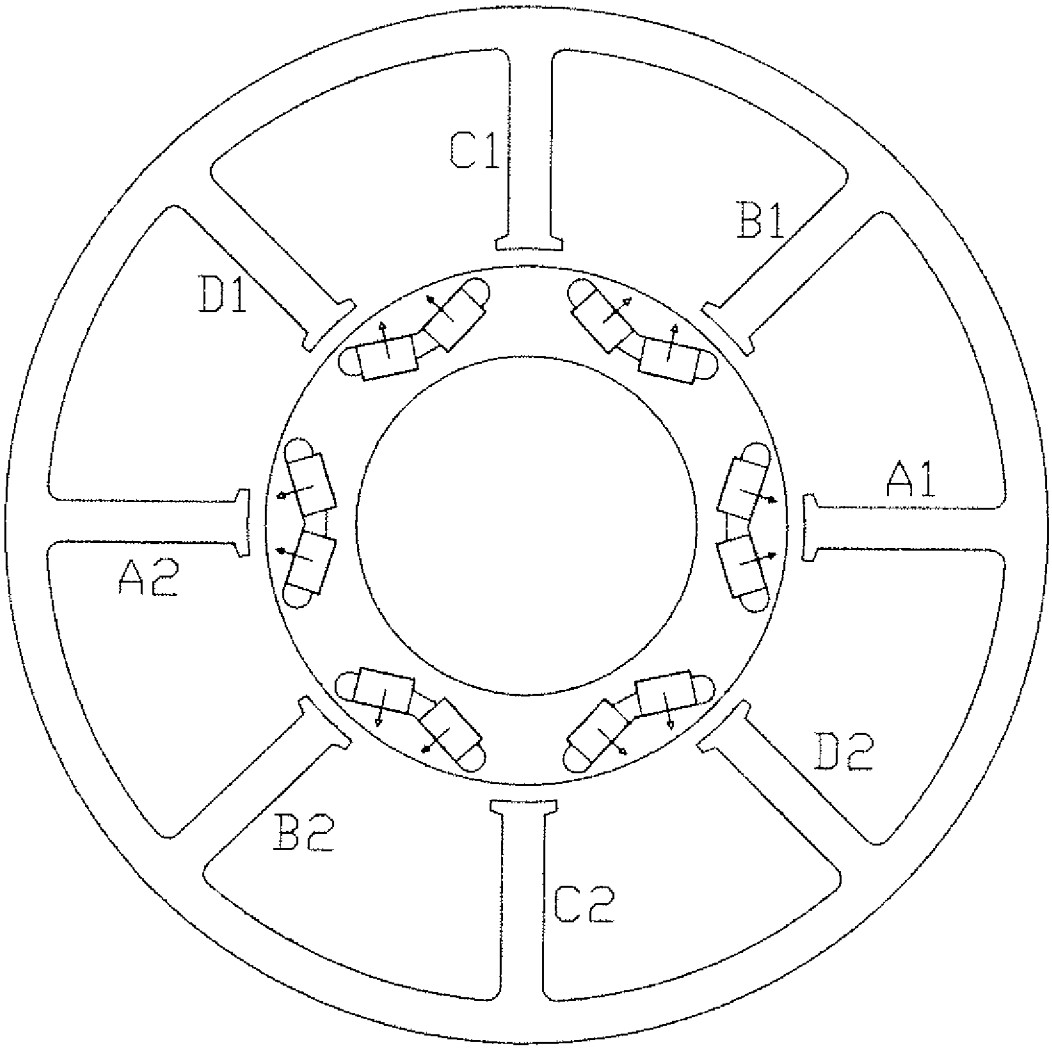

FIG. 5

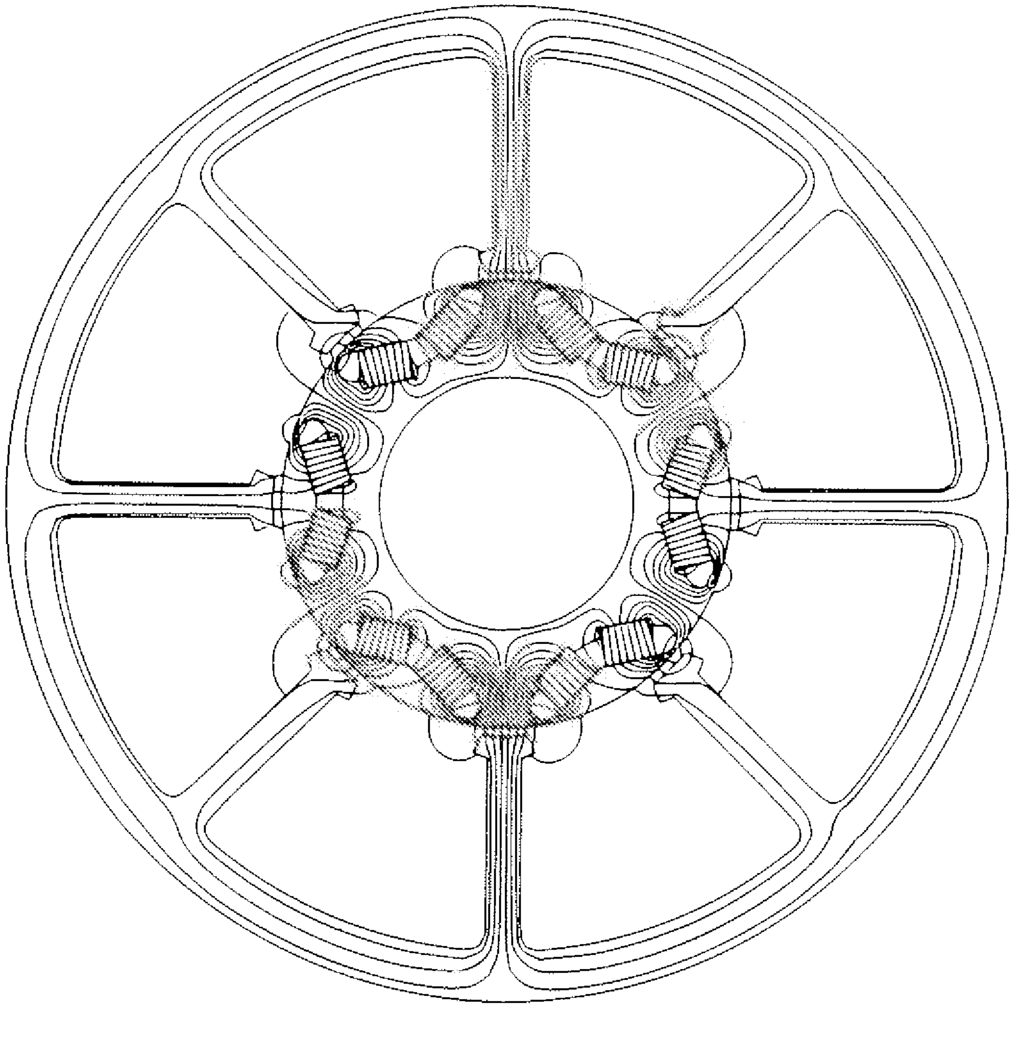

FIG. 6

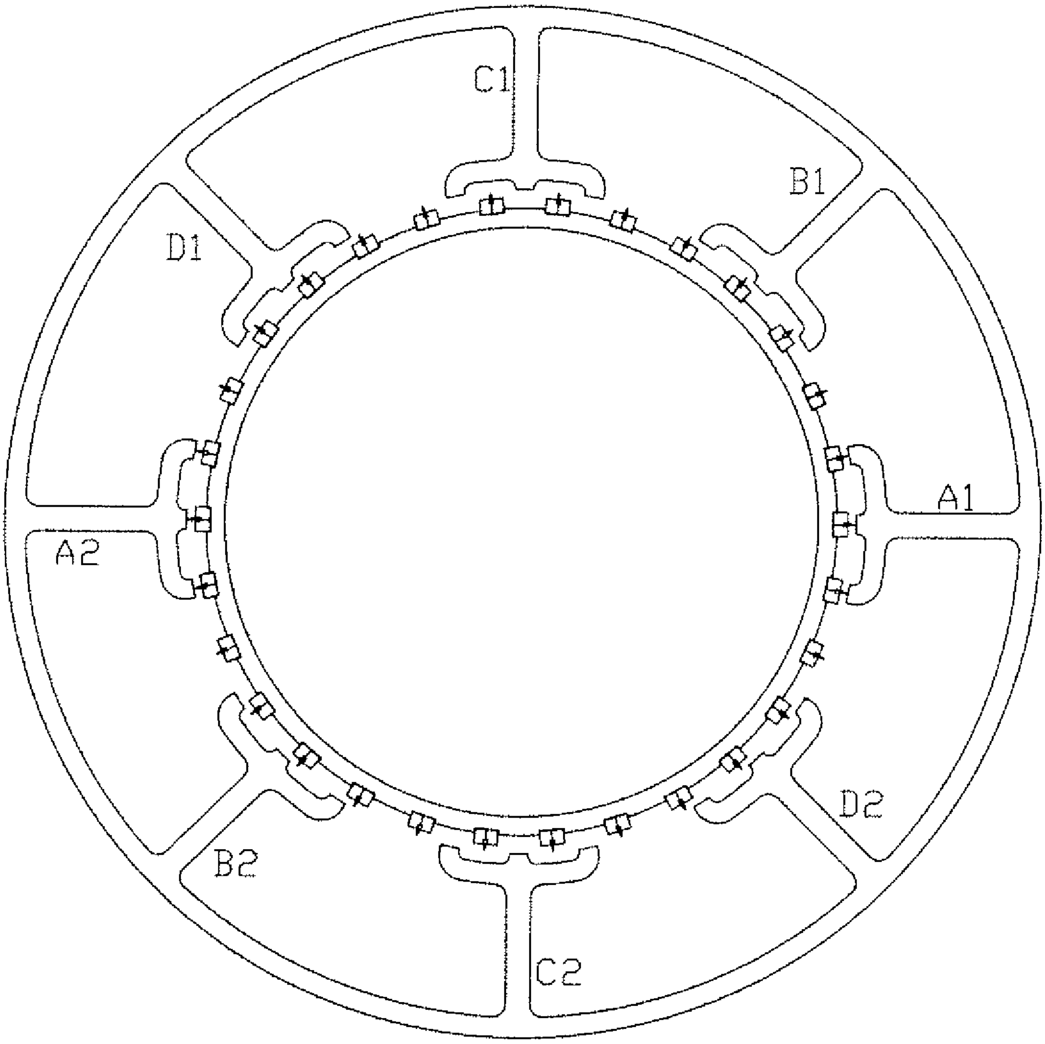

FIG. 7

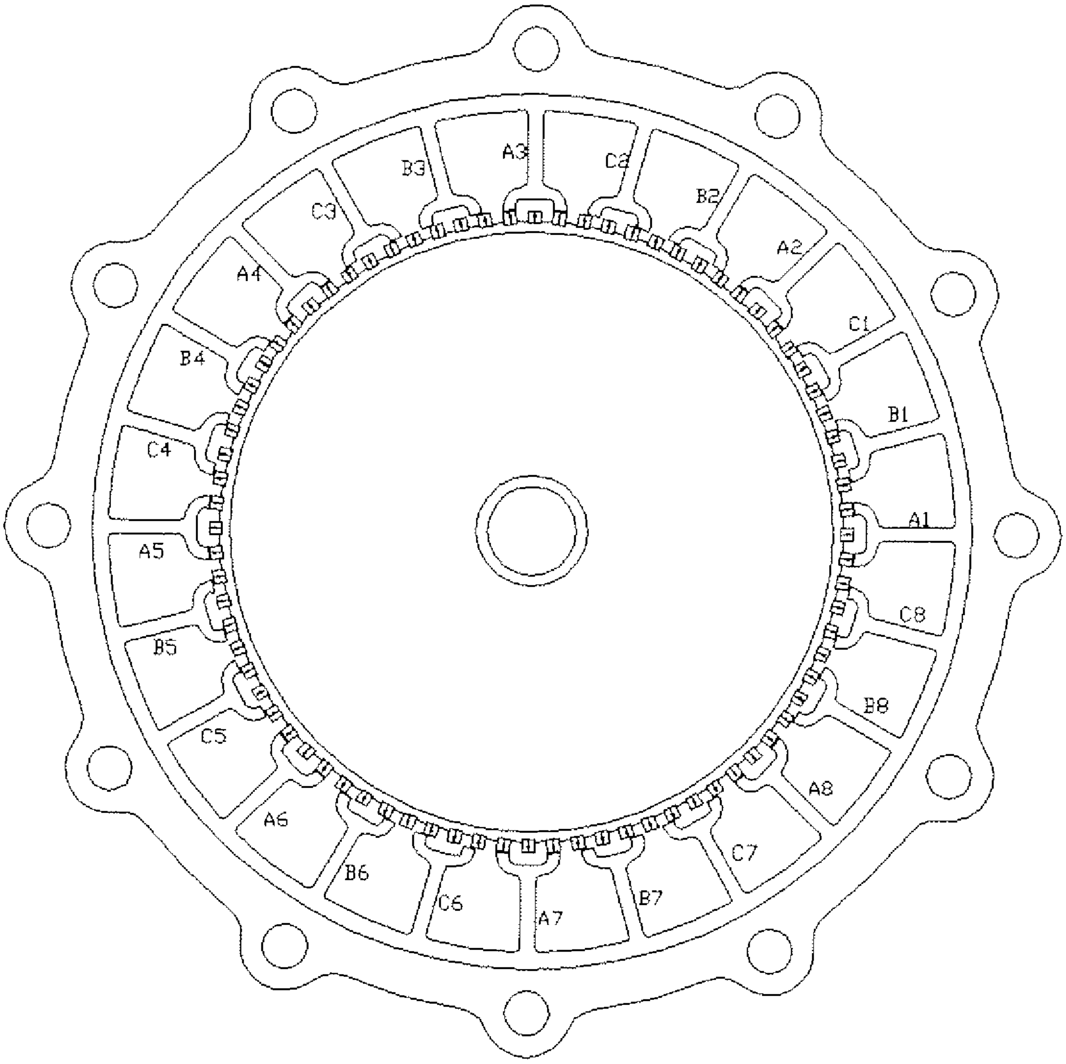

FIG. 8

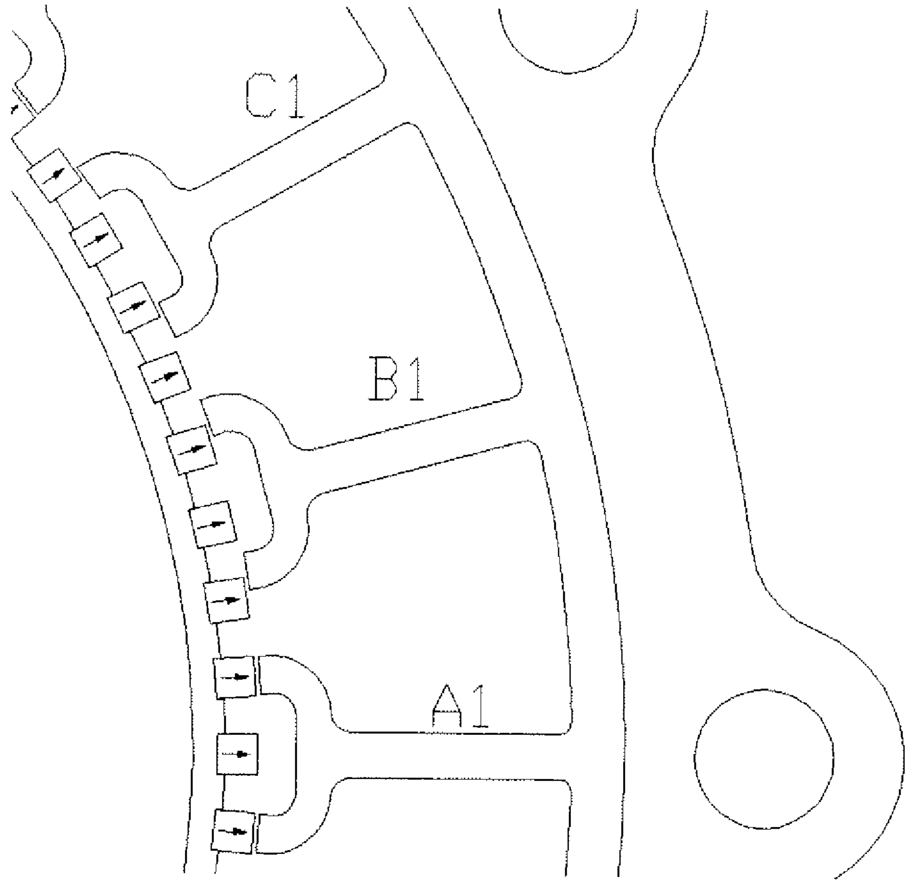

FIG. 9

	Terminal				
State	A1	B1	C1	D1	CT
1	-				+
2		-			+
3			-		+
4				-	+

FIG. 10

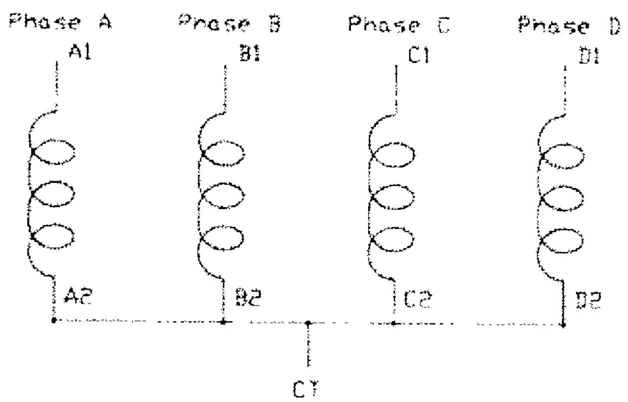

FIG. 11

State \ Terminal	A1	B1	A2	B2
1	+	-	-	+
2	-	-	+	+
3	-	+	+	+
4	+	+	-	-

FIG. 12

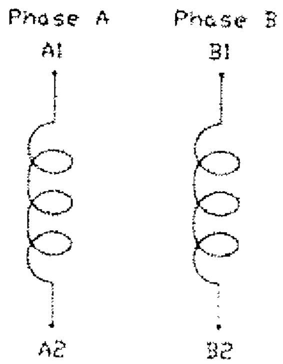

FIG. 13

State \ Terminal	A1	B1	C1
1	+	+	-
2	+	-	-
3	+	-	+
4	-	-	+
5	-	+	+
6	-	+	-

FIG. 14

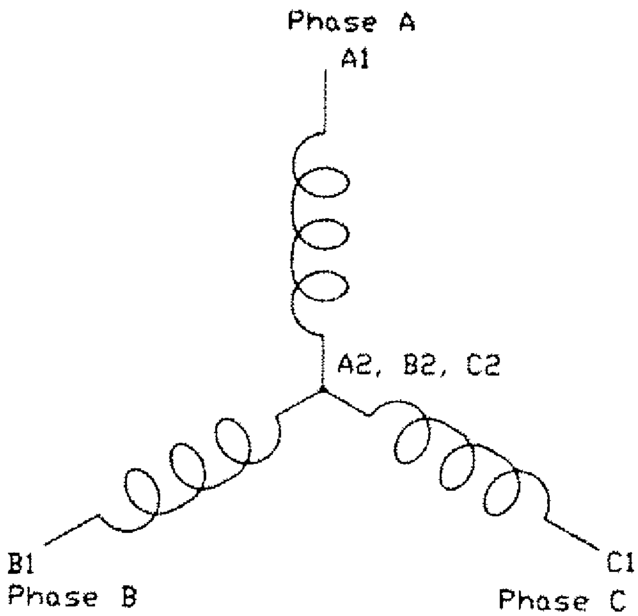

FIG. 15

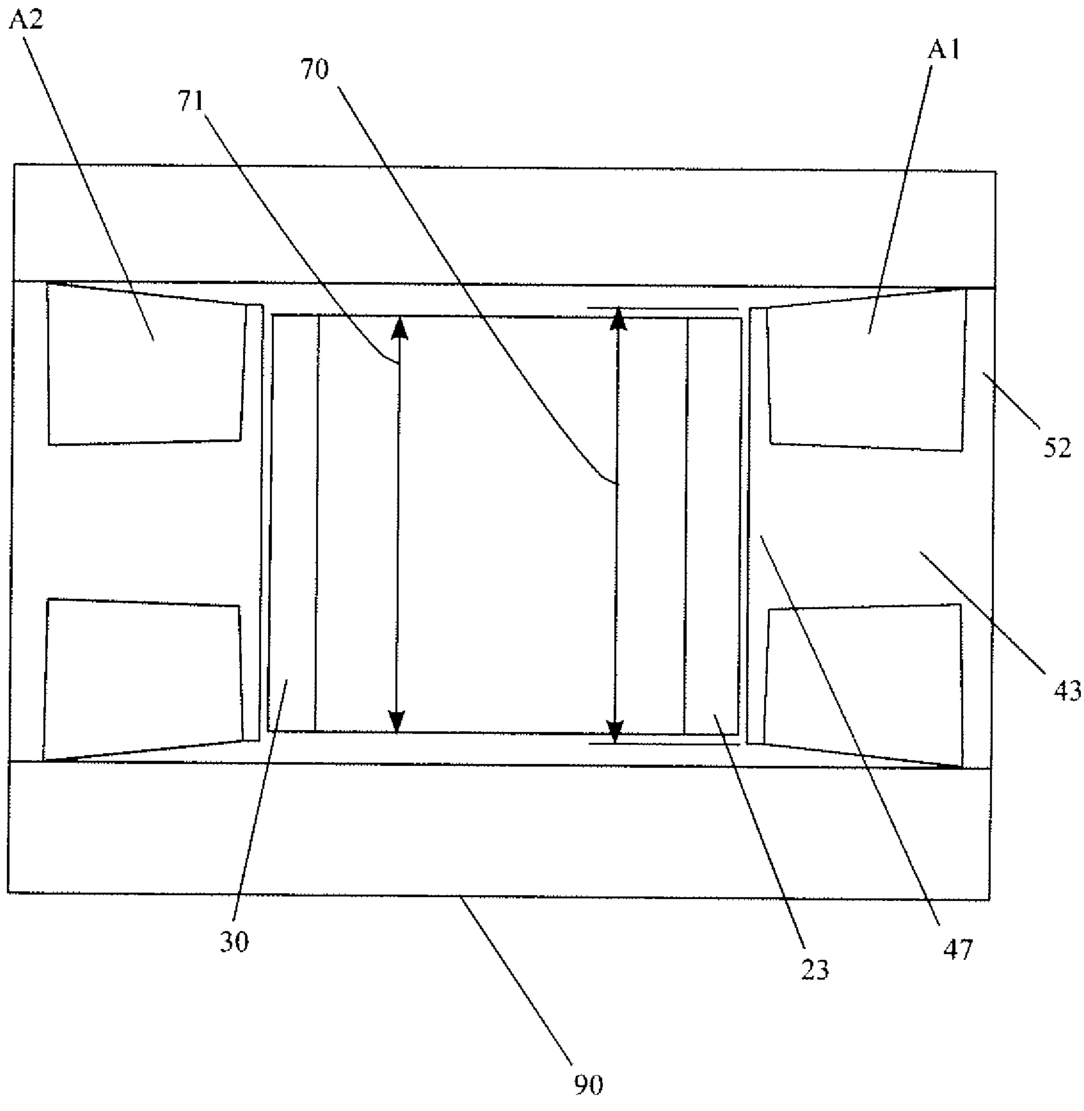

FIG. 16

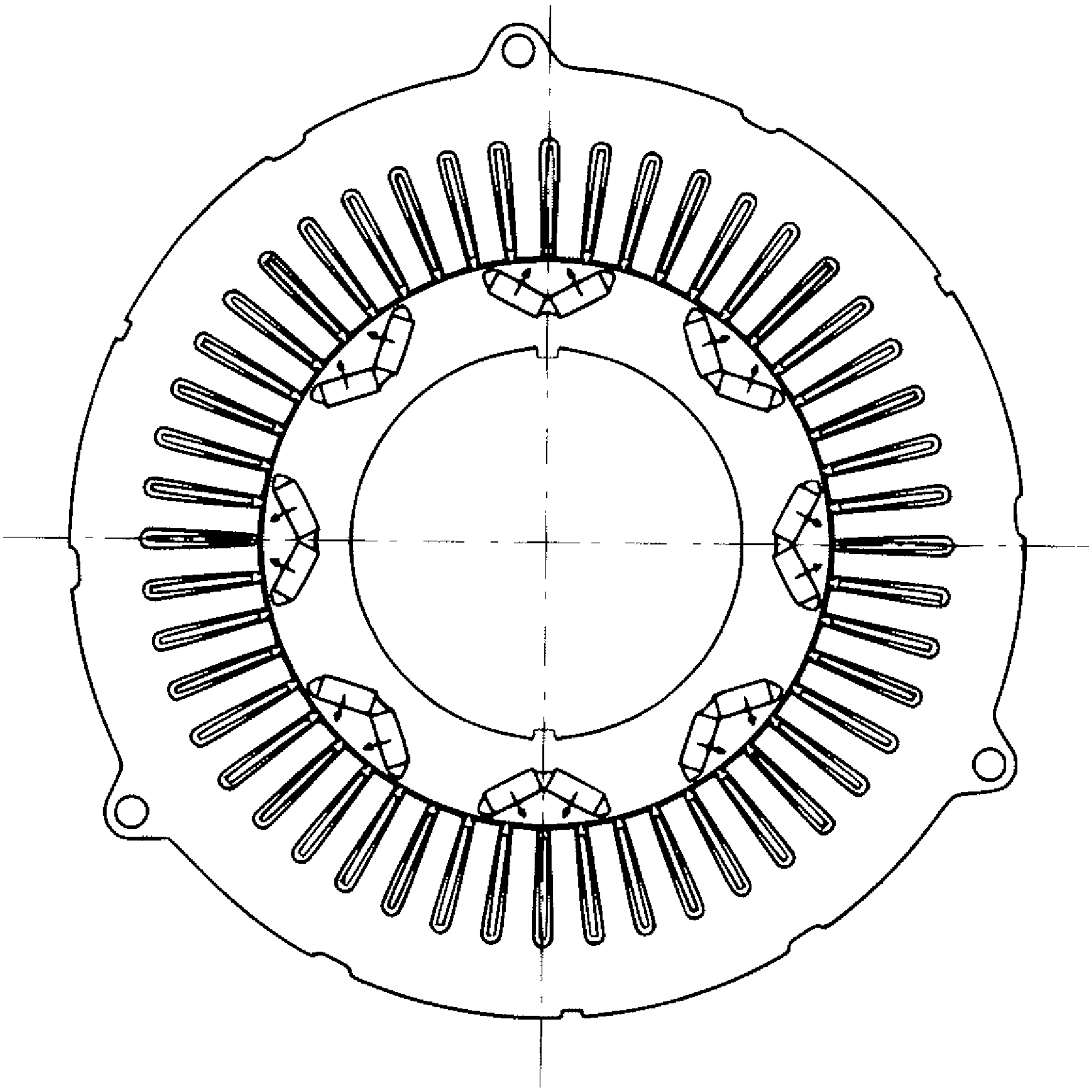

FIG. 17

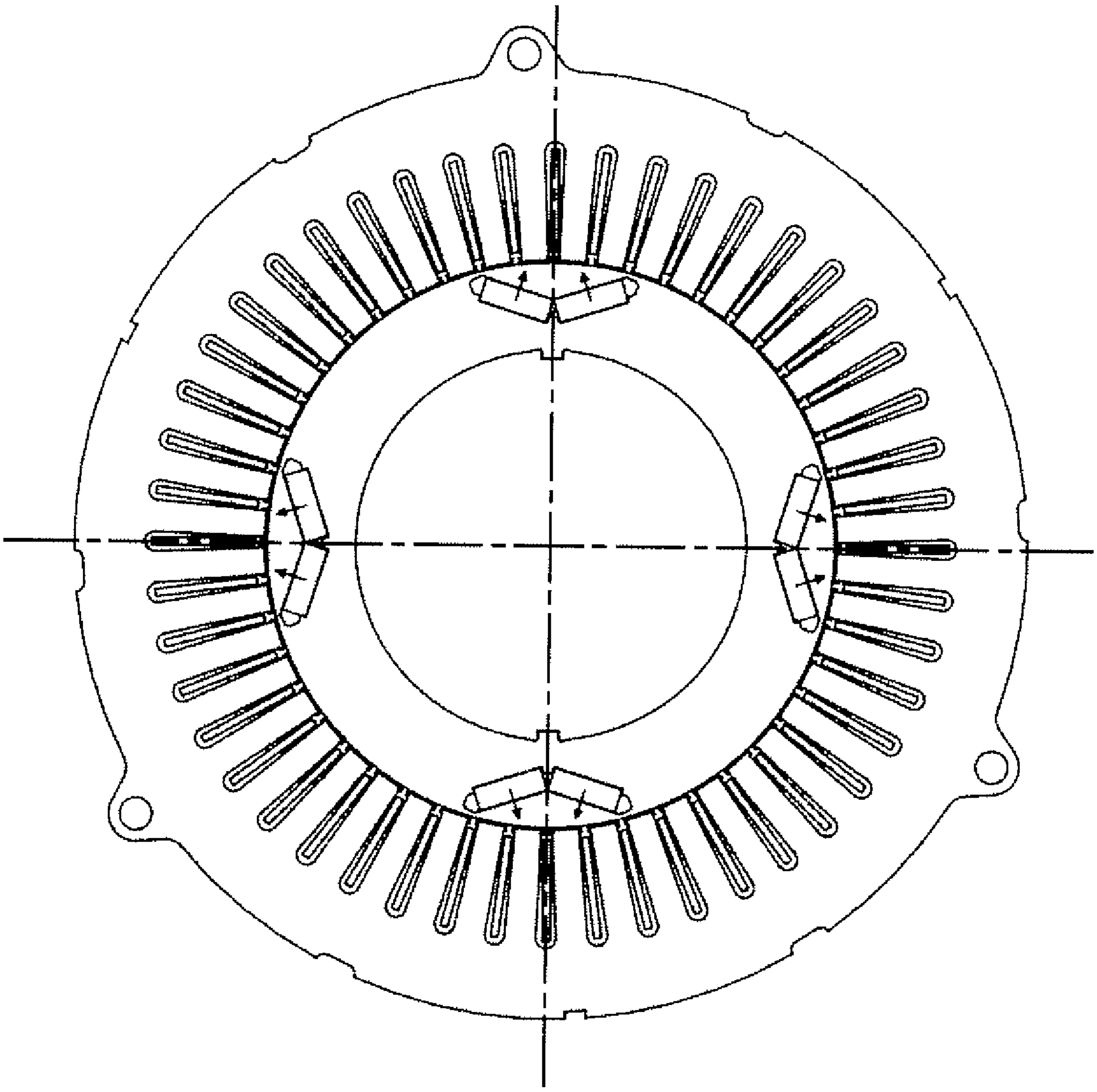

FIG. 18