

DESCRIPTION

TITLE OF INVENTION: ROTOR CORE, ROTOR, AND ROTARY ELECTRIC MACHINE

TECHNICAL FIELD

[0001] The present invention relates to a rotor core, a rotor, and a rotary electric machine. This application is based upon and claims the benefit of priority of the prior Japanese Patent Application No. 2021-185697 filed on November 15, 2021, the entire contents of which are incorporated herein by reference.

BACKGROUND ART

[0002] In a permanent magnet-embedded rotary electric machine such as an IPMSM (Interior Permanent Magnet Synchronous Motor), permanent magnets are embedded in a rotor core, and flux barriers are formed near the permanent magnets. The flux barrier is formed to control a flow of a magnetic flux in the rotary electric machine. The flux barrier allows improvement in characteristics of the rotary electric machine. Patent Literature 1 describes that magnet holes through which permanent magnets are installed are each provided with flux barriers. This flux barrier is provided on each of an outer peripheral side and an inner peripheral side further than the permanent magnet. Further, Patent Literature 1 describes that the flux barrier on the outer peripheral side is opened in an outer peripheral side of a rotor core. In addition, Patent Literature 1

describes that a curvature of the flux barrier on the inner peripheral side is defined to reduce stress of an inter-magnet bridge portion between the flux barriers on the inner peripheral side.

CITATION LIST

PATENT LITERATURE

[0003] Patent Literature 1: Japanese Laid-open Patent Publication No. 2019-57984

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0004] However, the technique described in Patent Literature 1 defines the configuration of the flux barrier on the outer peripheral side only from the viewpoint of suppressing a short circuit of a magnetic flux via the outer peripheral side of the rotor core. This prevents a sufficient improvement in torque of a rotor.

[0005] The present invention has been made in view of the problems as described above, and an object thereof is to increase the torque of the rotor.

SOLUTION TO PROBLEM

[0006] A rotor core of the present invention includes a soft magnetic material portion formed using a soft magnetic material, and having at least one magnet hole per one pole, wherein: the magnet hole has, relative to a permanent magnet installed through the magnet hole, a space serving as a front-side flux barrier and a space serving as a rear-side flux barrier on both sides in a left-right direction

perpendicular to a magnetization direction of the permanent magnet and a direction parallel to a rotation axis line serving as a center of rotation; the space serving as at least one flux barrier, of the space serving as the front-side flux barrier and the space serving as the rear-side flux barrier, has an open end portion opened in an outer peripheral surface of the rotor core; in a cross section perpendicular to the rotation axis line, a position of an open-end front-side corner portion of at least one of the open end portions provided in a same pole of a rotor is on a rear side in a rotation direction of the rotor core further than a reference position relative to the magnet hole having the open end portion; in the cross section, the open-end front-side corner portion is a corner portion on a front side in the rotation direction of the rotor core, of two corner portions in a circumferential direction of the rotor core, of at least one of the open end portions installed in the same pole of the rotor; in the cross section, the reference position relative to the magnet hole having the open end portion is a position at an intersection point of a straight line passing through a permanent-magnet reference end portion which is one of end portions of the permanent magnet at a position closest to the open end portion, in the permanent magnet installed through the magnet hole, and the rotation axis line, and, the outer peripheral surface of the rotor core; and in the

cross section, the permanent-magnet reference end portion of the permanent magnet at the position closest to the open end portion is, of end portions of the permanent magnet, an end portion at a position at the farthest distance in the circumferential direction from a straight line passing through a central position in the circumferential direction of a region of one pole including the permanent magnet, and the rotation axis line, and the distance in the circumferential direction from a straight line passing through the central position in the circumferential direction of the region of one pole including the permanent magnet, at the position closest to the open end portion, and the rotation axis line is a distance defined on a side, of the front side and the rear side in the rotation direction of the rotor core, in which the open end portion is present.

A rotor of the present invention includes the rotor core, and a plurality of permanent magnets installed in the rotor core.

A rotary electric machine of the present invention includes the rotor, and the stator.

BRIEF DESCRIPTION OF DRAWINGS

[0007] [Fig. 1] Fig. 1 is a view illustrating one example of a basic shape of an IPMSM.

[Fig. 2] Fig. 2 is a view illustrating a rotor cross section of the IPMSM illustrated in Fig. 1.

[Fig. 3] Fig. 3 is a view illustrating one example of an optimum shape of the IPMSM.

[Fig. 4A] Fig. 4A is a view illustrating a first analysis result of a magnetic flux density vector in the IPMSM in the optimum shape.

[Fig. 4B] Fig. 4B is a view for explaining one example of an outline of flows of magnetic fluxes in the first analysis result.

[Fig. 5A] Fig. 5A is a view illustrating a second analysis result of a magnetic flux density vector in the IPMSM in the optimum shape.

[Fig. 5B] Fig. 5B is a view for explaining one example of an outline of flows of magnetic fluxes in the second analysis result.

[Fig. 6A] Fig. 6A is a view illustrating one example of a magnetic flux density vector in the IPMSM in the basic shape when a residual magnetic flux density of permanent magnets is 0.4 T.

[Fig. 6B] Fig. 6B is a view for explaining one example of an outline of flows of magnetic fluxes in the IPMSM in the basic shape when the residual magnetic flux density of the permanent magnets is 0.4 T.

[Fig. 7A] Fig. 7A is a view illustrating one example of a magnetic flux density vector in the IPMSM in the basic shape when a residual magnetic flux density of the permanent magnets is 1.0 T.

[Fig. 7B] Fig. 7B is a view for explaining one example of an outline of flows of magnetic fluxes

in the IPMSM in the basic shape when the residual magnetic flux density of the permanent magnets is 1.0 T.

[Fig. 8] Fig. 8 is a view illustrating one example of a configuration of an IPMSM of an embodiment.

[Fig. 9] Fig. 9 is a view illustrating one example of a rotor cross section in the embodiment.

[Fig. 10] Fig. 10 is a view illustrating one example of a configuration of a rotor core of the embodiment.

[Fig. 11A] Fig. 11A is a view enlarging and illustrating a part of the rotor core illustrated in Fig. 10.

[Fig. 11B] Fig. 11B is a view illustrating a first modified example of the configuration of the rotor core.

[Fig. 11C] Fig. 11C is a view illustrating a second modified example of the configuration of the rotor core.

[Fig. 12A] Fig. 12A is a view illustrating a first example of a configuration of a rotor targeted for being analyzed.

[Fig. 12B] Fig. 12B is a view illustrating a second example of a configuration of a rotor targeted for being analyzed.

[Fig. 12C] Fig. 12C is a view illustrating a third example of a configuration of a rotor targeted for being analyzed.

[Fig. 12D] Fig. 12D is a view illustrating a fourth example of a configuration of a rotor targeted for being analyzed.

[Fig. 12E] Fig. 12E is a view illustrating a fifth example of a configuration of a rotor targeted for being analyzed.

[Fig. 12F] Fig. 12F is a view illustrating a sixth example of a configuration of a rotor targeted for being analyzed.

[Fig. 12G] Fig. 12G is a view illustrating a seventh example of a configuration of a rotor targeted for being analyzed.

[Fig. 12H] Fig. 12H is a view illustrating an eighth example of a configuration of a rotor targeted for being analyzed.

[Fig. 12I] Fig. 12I is a view illustrating a ninth example of a configuration of a rotor targeted for being analyzed.

DESCRIPTION OF EMBODIMENTS

[0008] Hereinafter, one embodiment of the present invention will be explained while referring to the drawings.

Note that a thing that comparison objects such as a length, a position, a size, and an interval are the same includes not only a thing that the comparison objects are strictly the same but also a thing that the comparison objects differ within a range that does not depart from the gist of the invention. For example, the thing that the comparison objects are

the same also includes a thing that the comparison objects differ within a tolerance range defined when designed. Further, in each drawing, x-y-z coordinates indicate a relation of directions in the drawing. In the x-y-z coordinates, a symbol of white circle (○) with black circle (●) given therein indicates an arrow having a direction from a far side toward a near side of the paper sheet as a positive direction. Further, in each drawing, for the convenience of notation, for a plurality of the same components, the illustration of a reference sign of a partial component of the plurality of components will be omitted. In addition, in the following, the plurality of components are explained using the component given a reference sign thereto of the plurality of components as necessary.

[0009] (Circumstances)

The present inventors proposed a technique of designing shapes of various cores including a rotor core of an IPMSM in Japanese Laid-open Patent Publication No. 2021-114099. Thus, the present inventors found a shape contributing to improvement in torque as a shape of the rotor core by using the technique. The later-described embodiment of the present invention has been made based on the result. The following will explain the result, and explain the circumstances that have led to the later-described embodiment of the present invention.

[0010] The technique described in the specification

of Japanese Laid-open Patent Publication No. 2021-114099 requires setting of a basic shape of elements targeted for design. This section exemplifies a case of setting shapes of flux barriers 113a to 113b, 114a to 114b in a rotor 110 included in an IPMSM 100 illustrated in Fig. 1 as the basic shape of the elements targeted for design. Thus, first, the IPMSM 100 illustrated in Fig. 1 will be explained.

[0011] Fig. 1 exemplifies a case where the number of poles of the IPMSM 100 are eight. In Fig. 1, a range of a double arrow indicated as "one pole" is a section forming one pole of the IPMSM 100. Note that when the number of poles of the IPMSM 100 are n , the IPMSM 100 has, on the whole, a relation of rotational symmetry of n -time symmetry in which a rotation axis line 0 of the IPMSM 100 is set as a rotation symmetry axis. n is an integer of two or more, and n is eight in the example illustrated in Fig. 1 ($n = \text{eight}$).

Fig. 1 illustrates one of four regions obtained by dividing a cross section cut perpendicularly to the rotation axis line 0 of the IPMSM 100 into quarters, and illustrates a region forming two poles of the rotor 110 in a region of the IPMSM 100. These four regions have, on the whole, a relation of four (= eight poles $\div$ two)-time symmetry in which the rotation axis line 0 of the IPMSM 100 is set as the rotation symmetry axis. Accordingly, in Fig. 1, rotating the region illustrated in Fig. 1 by 90° with a center line of the IPMSM 100 set as the rotation

axis line 0 provides the entire configuration of the cross section of the IPMSM 100 when the IPMSM 100 is cut perpendicularly to the rotation axis line 0.

[0012] As illustrated in Fig. 1, the IPMSM 100 includes the rotor 110 and a stator 120.

The stator 120 includes a stator core 121 and a not-illustrated stator coil, and aims to generate a rotating magnetic field. Note that in Fig. 1, the illustration of the stator coil included in the stator 120 is omitted. However, the non-illustrated stator coil is disposed in each of slots 122 of the stator core 121 (as described previously, for the convenience of notation, a reference sign is given to only one slot in Fig. 1).

[0013] The rotor 110 rotates with the rotation axis line 0 of the IPMSM 100 set as a rotation axis line. In this section, Fig. 1 exemplifies a case where the rotor 110 rotates in a direction of an arrow given on the side of "rotation direction" (a counterclockwise direction opposite to the paper sheet). Note that the rotation axis line 0 of the rotor 110 and the rotation axis line 0 of the IPMSM 100 coincide.

The rotor 110 includes a rotor core 111 and a plurality of permanent magnets per one pole (two permanent magnets 112a to 112b in the example illustrated in Fig. 1). The rotor core 111 is formed using a soft magnetic material.

[0014] Here, the case of installing the plurality of permanent magnets 112 per one pole in the rotor core

111 is exemplified. Accordingly, in the rotor core 111, along a direction parallel to the rotation axis line 0 of the rotor core 111, a plurality of magnet holes are formed per one pole (in the following explanation, the direction parallel to the rotation axis line 0 is referred to as a z-axis direction as necessary). The magnet hole is a through hole penetrating in the z-axis direction. A plurality of the permanent magnets 112a to 112b are each inserted into the magnet hole formed in the rotor core 111, thereby being installed (embedded) in the rotor core 111. Fig. 1 illustrates the region forming the two poles of the rotor 110 in the region of the IPMSM 100 as previously described. In Fig. 1, the two permanent magnets 112a to 112b are embedded per one pole. Consequently, a total of 16 permanent magnets are embedded in the rotor core 111. Note that as previously described, in Fig. 1, for the convenience of notation, reference signs are given to only the section forming one pole of the rotor 110, and reference signs in sections forming the other seven poles of the rotor 110 are omitted.

[0015] In the magnet holes formed in the rotor core 111, spaces in the absence of the permanent magnets 112a to 112b serve as the flux barriers 113a to 113b, 114a to 114b. The flux barriers 113a to 113b, 114a to 114b are regions through which no magnetic flux passes, or regions which make it more difficult for the magnetic flux to pass through than regions around

the flux barriers 113a to 113b, 114a to 114b. Here, a case of the absence of a material object in the flux barriers 113a to 113b, 114a to 114b is exemplified (that is, a case where the flux barriers 113a to 113b, 114a to 114b are gap portions (regions of air) is exemplified). However, even the installation of a nonmagnetic material in the flux barriers 113a to 113b, 114a to 114b yields results similar to later-described results illustrated in Fig. 4A to Fig. 7B.

[0016] In the following explanation, a cross section of the rotor 110 when cut perpendicularly to the rotation axis line 0 of the IPMSM 100 (rotor 110) is referred to as a rotor cross section as necessary. Fig. 2 is a view illustrating the rotor cross section corresponding to one pole of the IPMSM 100 illustrated in Fig. 1. Incidentally, in Fig. 2, to avoid making positions pointed by reference signs unclear, hatching indicating the cross section is omitted.

[0017] In Fig. 2, the magnetic flux flows in and out from pole faces 201a to 201b, 201c to 201d of the permanent magnets 112a to 112b. Further, in Fig. 2, directions orthogonal to the pole faces 201a to 201b, 201c to 201d are magnetization directions D_m of the permanent magnets 112a to 112b. In the following explanation, in the rotor cross section, both left and right directions relative to the magnetization direction D_m of the permanent magnet 112 at the

center of each of the permanent magnets 112a to 112b are referred to as a left-right direction D_s as necessary. The left-right direction D_s is a direction perpendicular to the magnetization direction D_m of the permanent magnet 112 and a direction parallel to the rotation axis line 0 of the IPMSM 100. The flux barriers 113a and 114a are formed on both sides of the left-right direction D_s of the permanent magnet 112a, and the flux barriers 113b and 114b are formed on both sides of the left-right direction D_s of the permanent magnet 112b.

[0018] In the following explanation, of the flux barriers 113a to 113b, 114a to 114b, the flux barriers positioned on an outer peripheral side in the left-right direction D_s further than the permanent magnets 112a to 112b are referred to as the outer-peripheral-side flux barriers 113a to 113b as necessary. Further, of the flux barriers 113a to 113b, 114a to 114b, the flux barriers positioned on an inner peripheral side in the left-right direction D_s further than the permanent magnets 112a to 112b are referred to as the inter-magnet flux barriers 114a to 114b as necessary.

[0019] Bridge portions 116a to 116b are (small) regions connecting a region of the soft magnetic material of the rotor core 111 in a circumferential direction. The circumferential direction is a direction going around an outer peripheral surface 115 of the rotor 110 (rotor core 111) (a direction

parallel to and a direction antiparallel to the rotation direction of the rotor 110 (rotor core 111)). A bridge portion 117a is a (small) region connecting the region of the soft magnetic material of the rotor core 111 in a radial direction of the IPMSM 100. In the following explanation, of the bridge portions 116a to 116b, 117a, the bridge portions 116a to 116b positioned on the outer peripheral side (the outer peripheral side in the radial direction of the IPMSM 100) in the left-right direction Ds further than the permanent magnets 112a to 112b are referred to as the outer-peripheral-side bridge portions as necessary. Further, of the bridge portions 116a to 116b, 117a, the bridge portion 117a positioned on the inner peripheral side (the inner peripheral side in the radial direction of the IPMSM 100) in the left-right direction Ds further than the permanent magnets 112a to 112b is referred to as the inter-magnet bridge portion 117a as necessary. In the example illustrated in Fig. 2, the outer-peripheral-side bridge portions 116a to 116b are the regions of the soft magnetic material positioned between the outer-peripheral-side flux barriers 113a to 113b and the outer peripheral surface 115 of the rotor core 111. Further, the inter-magnet bridge portion 117a is the region of the soft magnetic material positioned between the inter-magnet flux barriers 114a and 114b.

[0020] The bridge portions 116a to 116b, 117a are ones for suppressing a return of the magnetic flux

flowing out from the permanent magnets 112a to 112b to the permanent magnets 112. In the bridge portions 116a to 116b, 117a, an area of a cross section perpendicular to a traveling direction of the magnetic flux is smaller than that of the other region. Accordingly, magnetic resistances of the bridge portions 116a to 116b, 117a are larger than a magnetic resistance of the other region of the soft magnetic material forming the rotor core 111. Thus, providing the bridge portions 116a to 116b, 117a allows the suppression of the return of the magnetic flux flowing out from the permanent magnets 112a to 112b to the permanent magnets 112. The bridge portions 116a to 116b, 117a are present for securing mechanical strength of the rotor core 111. The magnetic flux passing through the bridge portions 116a to 116b, 117a flows back to the permanent magnets 112a to 112b, which has given a common general technical knowledge of hardly contributing to torque of the rotor 110 to a person skilled in the art so far. In the following explanation, a magnetic flux flowing out from one pole face of the permanent magnet, passing through the bridge portion, and returning (flowing back) to the other pole face of the permanent magnetic flux is referred to as a reflux magnetic flux as necessary.

[0021] The present inventors designed a shape of the rotor core 111 according to the technique described in the specification of Japanese Laid-open Patent

Publication No. 2021-114099. At that time, the flux barriers 113a to 113b, 114a to 114b illustrated in Fig. 1 and Fig. 2 were set as the elements targeted for design (elements whose shapes were changed from the basic shape). Further, the permanent magnet 112 was set as a predetermined core element (an element whose shape was not changed) except for the elements targeted for design. Further, a residual magnetic flux density of the permanent magnet 112 was set to 0.4 T. Note that the residual magnetic flux density of the permanent magnet 112 is defined in advance by specifications of the permanent magnet 112, for example. Further, an exciting current flowing through the non-illustrated stator coil was set as a three-phase alternating current having a peak value of 20 A and a frequency of 50 Hz. Further, a lead angle was set to 30° . In addition, with a stress produced in the rotor core 111 by centrifugal force applied to the rotor 110 with rotation of the rotor 110 ignored, the maximization of a value of the average torque of the rotor 110 was set as an optimization condition in an algorithm for an optimization problem. That is, a shape illustrated in Fig. 3 is an optimum shape in a case of permitting the stress produced in the rotor core 111 to become excessive. Accordingly, as long as the optimization condition is satisfied, the shape illustrated in Fig. 3 is a shape in no consideration of whether or not a shape of the rotor core 111 is feasible. In the

following explanation, to be distinguished from an IPMSM in the shape designed in this manner, the IPMSM 100 illustrated in Fig. 1 is referred to as the IPMSM 100 in the basic shape as necessary. Fig. 3 is a view illustrating one example of a configuration of the IPMSM 100 optimized to maximize the value of the average torque of the rotor 110 according to the technique described in the specification of Japanese Laid-open Patent Publication No. 2021-114099 from the IPMSM 100 in the basic shape. In the following explanation, the IPMSM 100 illustrated in Fig. 3 is referred to as the IPMSM 100 in the optimum shape as necessary. Hereinafter, the findings in which the IPMSM 100 illustrated in Fig. 3 has been obtained from the IPMSM 100 in the optimum shape by the present inventors will be explained.

[0022] ((First finding))

As previously described, the optimum shape illustrated in Fig. 3 is the shape in the case of permitting the stress produced in the rotor core 111 to become excessive. The outer-peripheral-side bridge portions 116a to 116b are composed of the soft magnetic material. Accordingly, air is smaller in magnetic permeability than the outer-peripheral-side bridge portions 116a to 116b, and thus air is larger in magnetic resistance than the outer-peripheral-side bridge portions 116a to 116b. Thus, in the IPMSM 100 in the optimum shape illustrated in Fig. 3, outer-peripheral-side flux barriers 113c to 113d are formed

in such a manner that (a part of) the outer-peripheral-side flux barriers 113a to 113b illustrated in Fig. 1 and Fig. 2 reach (reaches) the outer peripheral surface 115 of the rotor core 111 to be open to (communicate with) an outer portion. In other words, in the outer peripheral surface 115 of the rotor core 111 (soft magnetic material portion), open end portions are formed by the outer-peripheral-side flux barriers 113c to 113d. A long side direction of the open end portions is a direction parallel to the z-axis direction, a short side direction of the open end portions is the circumferential direction, and the open end portions communicate with the outer portion. Note that the open end portion is an opened end portion, and is not an actual surface but a virtual surface. In the IPMSM 100 in the basic shape illustrated in Fig. 2, the outer-peripheral-side bridge portions 116a to 116b are present. Accordingly, the outer-peripheral-side flux barriers 113a to 113b do not reach the outer peripheral surface 115, and are closed. Fig. 2 and Fig. 3 are different in this point. On the other hand, in the IPMSM 100 in the optimum shape illustrated in Fig. 3, the outer-peripheral-side flux barriers 113c to 113d reach the outer peripheral surface 115 of the rotor core 111 to be open. Therefore, most of the magnetic flux passing through the bridge portions 116a to 116b illustrated in Fig. 1 and Fig. 2 can be said to be a reflux magnetic flux.

[0023] The outer-peripheral-side flux barriers 113c to 113d illustrated in Fig. 3 reduce the reflux magnetic flux. In addition to this, the present inventors gave attention to a displacement of open end portions 310c to 310d of the outer-peripheral-side flux barriers 113c to 113d to a rear side in the rotation direction of the rotor core 111 (a side opposite to the rotation direction) as illustrated in Fig. 3. Then, the present inventors considered that the outer-peripheral-side flux barriers 113d to 113d play a role other than the reduction in reflux magnetic flux known as the common general technical knowledge so far.

[0024] Thus, the present inventors reviewed, of results of electromagnetic field analysis (magnetic flux density vector) in the IPMSM 100 in the optimum shape illustrated in Fig. 3, the result near the outer-peripheral-side flux barriers 113c to 113d. Note that in Fig. 3, r , θ represent a moving radius and an argument in polar coordinates (circular coordinates), respectively. In Fig. 3, a position of the rotation axis line 0 in a cross section of the rotor core 111 when cut perpendicularly to the rotation axis line 0 of the rotor core 111 is set as the origin 0 of the polar coordinates. Further, a direction from the origin 0 toward an outer side is a positive direction of a moving radius direction (a radial direction of the IPMSM 100), and a counterclockwise direction opposite to the sheet

paper (rotation direction) is set as a positive direction of the argument. Incidentally, the outer side is a side where the outer peripheral surface 818 of the rotor core 811 is present.

[0025] Fig. 4A to Fig. 4B are views for explaining a first result of the electromagnetic field analysis in the IPMSM 100 in the optimum shape. Fig. 4A is the view illustrating one example of the magnetic flux density vector in the IPMSM 100 in the optimum shape. Fig. 4B is the view for explaining one example of an outline of flows, of magnetic fluxes in the IPMSM 100 in the optimum shape, of magnetic fluxes near the outer peripheral surface 115 of the rotor core 111.

In Fig. 4A, the magnetic flux density vector is represented by arrows each having a density corresponding to the magnitude thereof. However, for the convenience of notation, Fig. 4A cannot clearly illustrate characteristics of the magnetic flux density vector. Thus, for the convenience of explanation, Fig. 4B illustrates the outline of the flows, of the magnetic fluxes in the IPMSM 100 in the optimum shape, of magnetic fluxes necessary for the explanation. In Fig. 4B, "N" and "S" indicated in the permanent magnets 112a to 112b indicate magnetic poles (N pole and S pole) of the rotor 110.

Accordingly, the pole faces 201a, 201c of the permanent magnets 112a, 112b are the pole faces of N pole, and the pole face 201b, 201d thereof are the pole faces of S pole.

[0026] Further, in Fig. 4B, arrows illustrated in teeth 123a to 123d of the stator core 121 indicate magnetic fluxes generated in the teeth 123a to 123d of the stator core 121 at the time when a positional relationship between the rotor 110 and the stator 120 is a positional relationship illustrated in Fig. 4A and Fig. 4B. Specifically, the arrows illustrated in the teeth 123a to 123b of the stator core 121 indicate that the magnetic fluxes in a direction from the rotation axis line 0 of the IPMSM 100 toward the outer side along the radial direction of the IPMSM 100 are generated in the teeth 123a to 123b of the stator core 121. On the other hand, the arrows illustrated in the teeth 123c to 123d of the stator core 121 indicate that the magnetic fluxes in a direction toward the rotation axis line 0 of the IPMSM 100 along the radial direction of the IPMSM 100 are generated in the teeth 123c to 123d of the stator core 121. Further, the number of arrows represents a relative magnitude relation of magnetic flux quanta (magnetic flux densities) in the teeth 123c to 123d of the stator core 121. Note that a larger number of arrows indicates a larger flux quantum (an increase in magnetic flux density). However, a ratio of the magnetic flux quanta (magnetic flux densities) does not necessarily correspond to a ratio of the numbers of arrows. Further, an instantaneous value of torque of the rotor 110 varies while the rotor 110 is rotating once. The time when the positional

relationship between the rotor 110 and the stator 120 is the positional relationship illustrated in Fig. 4A and Fig. 4B is the time when the instantaneous value of the torque of the rotor 110 is maximum.

[0027] Further, in Fig. 4B, an arrow extending from the rotor 110 (rotor core 111) toward the stator 120 (stator core 121) indicates a direction of a magnetic flux flowing from the rotor 110 (rotor core 111) toward the stator 120 (stator core 121). Further, an arrow extending from the stator 120 (stator core 121) toward the rotor 110 (rotor core 111) indicates a direction of a magnetic flux flowing from the stator 120 (stator core 121) toward the rotor 110 (rotor core 111). In Fig. 4B, for the convenience of notation, any of magnetic fluxes ϕ_1 , ϕ_2 , ϕ_3 represented by these arrows is represented by one arrow. However, magnetic flux quanta of the magnetic fluxes ϕ_1 , ϕ_2 , ϕ_3 are not necessarily the same.

[0028] The result illustrated in Fig. 4A to Fig. 4B is a result when the rotor core 111 rotates in the counterclockwise direction opposite to the paper sheet. Accordingly, of the two permanent magnets 112a to 112b in the same pole, the permanent magnet positioned on a front side in the rotation direction (rotation direction side) is the permanent magnet 112a, and the permanent magnet positioned on the rear side is the permanent magnet 112b (refer to the arrows marked on sides of "front side" and "rear side" in Fig. 4B). In the following explanation, the

permanent magnet 112a positioned on the front side in the rotation direction is referred to as the permanent magnet 112a on the front side as necessary. Further, the permanent magnet 112b positioned on the rear side in the rotation rear direction is referred to as the permanent magnet 112b on the rear side as necessary.

[0029] The outer-peripheral-side flux barrier 113c reduces the reflux magnetic flux flowing back from one pole face (for example, N pole) of the permanent magnet 112a on the front side via the outer-peripheral-side bridge portion 116a illustrated in Fig. 2 to the other pole face (for example, S pole). Similarly, the outer-peripheral-side flux barrier 113b reduces the reflux magnetic flux flowing back from one pole face (for example, N pole) of the permanent magnet 112b on the rear side via the outer-peripheral-side bridge portion 116b illustrated in Fig. 2 to the other pole face (for example, S pole).

[0030] Meanwhile, the torque of the rotor 110 is proportional to the inner product of a moving radius direction (the radial direction of the IPMSM 100) component B_r and a circumferential direction component B_θ of the magnetic flux density vector in a gap G between the rotor 110 (rotor core 111) and the stator 120 (stator core 121). In the following explanation, the moving radius direction (the radial direction of the IPMSM 100) component is referred to as a radial direction component as necessary. Accordingly, when

a polar coordinate system is defined as illustrated in Fig. 3, in a case where both the radial direction component B_r and the circumferential direction component B_θ of the magnetic flux density vector in a direction from the rotor 110 toward the stator 120 are positive, and a direction of this magnetic flux density vector is a direction greatly inclining to the radial direction of the IPMSM 100, the torque of the rotor 110 increases.

[0031] In Fig. 4B, the magnetic flux ϕ_1 from a region on the rear side in the rotation direction of the IPMSM 100 further than the outer-peripheral-side flux barrier 113c in a region of the outer peripheral surface 115 of the rotor core 111 toward the teeth 123a of the stator core 121 greatly inclines to the radial direction of the IPMSM 100. This is considered because the open end portion 310c of the outer-peripheral-side flux barrier 113c is displaced to the rear side in the rotation direction (the side opposite to the rotation direction) of the rotor core 111.

[0032] From the above, the present inventors obtained the first finding that displacing the open end portion 310 of the outer-peripheral-side flux barrier 113 to the rear side in the rotation direction (the side opposite to the rotation direction) of the rotor core 111 allows an increase in the torque of the rotor 110. In the following explanation, the magnetic flux ϕ_1 from the region on

the rear side in the rotation direction of the IPMSM 100 further than the outer-peripheral-side flux barrier 113c in the region of the outer peripheral surface 115 of the rotor core 111 toward the teeth 123a of the stator core 121 is referred to as the magnetic flux ϕ_1 on the rear side of the outer-peripheral-side flux barrier 113c as necessary.

[0033] Note that in Fig. 4B, a magnetic flux in a direction opposite to the magnetic flux ϕ_1 on the rear side of the outer-peripheral-side flux barrier 113c also contributes to the increase in the torque of the rotor 110. This is because both the radial direction component B_r and the circumferential direction component B_θ of the magnetic flux density vector become negative.

[0034] ((Second finding))

Further, the present inventors gave attention to the formation of recess portions 118a, 119a in positions different from those of the outer-peripheral-side flux barriers 113c to 113d in the IPMSM 100 in the optimum shape illustrated in Fig. 3. Thus, the present inventors reviewed, of the results of the electromagnetic field analysis (magnetic flux density vector) in the IPMSM 100 in the optimum shape illustrated in Fig. 3, the result near the recess portions 118a, 119a.

[0035] When the polar coordinate system is defined as illustrated in Fig. 3, in a case where both the radial direction component B_r and the circumferential

direction component B_θ of the magnetic flux density vector from the stator 120 toward the rotor 110 are negative, and a direction of this magnetic flux density vector is a direction greatly inclining to the radial direction of the IPMSM 100, the torque of the rotor 110 increases.

[0036] Further, as previously described, the result of the electromagnetic field analysis illustrated in Fig. 4A is the result when the exciting current flowing through the non-illustrated stator coil is the three-phase alternating current. Accordingly, the rotating magnetic field is generated in the IPMSM 100. A rotation period of the rotor core 110 (rotor core 111) and a rotation period of the rotating magnetic field generated in the stator core 121 (teeth 123) are the same. Thus, a positional relationship between the rotor core 111 and the rotating magnetic field has no change even though the rotor core 111 rotates. Incidentally, the exciting current used in the present application is not limited to the three-phase alternating current.

[0037] Thus, in Fig. 4B, the recess portion 118a faces the teeth 123a, 123c with a high magnetic flux density (the teeth 123a, 123c in each of which the number of arrows are two) even though the rotor core 111 rotates. The magnetic flux ϕ_2 from the teeth 123c of the stator core 121 toward the region on the rear side in the rotation direction of the IPMSM 100 further than the recess portion 118a in the region of

the outer peripheral surface 115 of the rotor core 111 inclines to the radial direction of the IPMSM 100, and both the radial direction component B_r and the circumferential direction component B_θ of the magnetic flux density vector caused by the magnetic flux ϕ_2 are negative.

[0038] Accordingly, the magnetic flux ϕ_2 from the teeth 123c of the stator core 121 toward the region on the rear side in the rotation direction of the IPMSM 100 further than the recess portion 118a in the region of the outer peripheral surface 115 of the rotor core 111 contributes to the increase in the torque of the rotor 110. In the following explanation, the magnetic flux ϕ_2 from the teeth 123c of the stator core 121 toward the region on the rear side in the rotation direction of the IPMSM 100 further than the recess portion 118a in the region of the outer peripheral surface 115 of the rotor core 111 is referred to as the magnetic flux ϕ_2 on the rear side of the recess portion 118a as necessary.

[0039] On the other hand, the magnetic flux ϕ_3 from the teeth 123c of the stator core 121 toward a region on the front side in the rotation direction of the IPMSM 100 further than the recess portion 118a in the region of the outer peripheral surface 115 of the rotor core 111 inclines to the radial direction of the IPMSM 100, and the radial direction component B_r and the circumferential direction component B_θ of the magnetic flux density vector caused by the magnetic

flux ϕ_3 are negative and positive, respectively. Accordingly, the magnetic flux ϕ_3 from the teeth 123c of the stator core 121 toward the region on the front side in the rotation direction of the IPMSM 100 further than the recess portion 118a in the region of the outer peripheral surface 115 of the rotor core 111 does not contribute to the increase in the torque of the rotor 110. In the following explanation, the magnetic flux ϕ_3 from the teeth 123c of the stator core 121 toward the region on the front side in the rotation direction of the IPMSM 100 further than the recess portion 118a in the region of the outer peripheral surface 115 of the rotor core 111 is referred to as the magnetic flux ϕ_3 on the front side of the recess portion 118a as necessary.

[0040] Consequently, defining a size and a position of the recess portion 118a in such a manner that the magnetic flux ϕ_2 on the rear side of the recess portion 118a is larger than the magnetic flux ϕ_3 on the front side of the recess portion 118a allows the increase in the torque of the rotor 110.

[0041] Meanwhile, in Fig. 4B, the recess portion 119a faces the teeth 123a, 123b with a low magnetic flux density (the teeth 123a, 123b in each of which the number of arrows are two) even though the rotor core 111 rotates. Accordingly, the recess portion 119a contributes less to the increase in the torque of the rotor 110 than the recess portion 118a.

Further, a larger number of recess portions causes

the possibility of a decrease in mechanical strength of the rotor 110 (rotor core 111).

[0042] From the above, the present inventors obtained the second finding that providing the recess portion 118a in the position facing the teeth 123a, 123b with a higher magnetic flux density than the lowest magnetic flux density in the region of the outer peripheral surface 115 of the rotor core 111 allows the increase in the torque of the rotor 110.

[0043] Note that which piece of teeth of the teeth 123a to 123d of the stator core 121 has the lowest magnetic flux density is specified from such a result of the electromagnetic field analysis as exemplified in Fig. 4A, for example.

[0044] Further, in Fig. 4B, similarly to the magnetic flux ϕ_2 on the rear side of the recess portion 118a, a magnetic flux in a direction opposite to the magnetic flux ϕ_2 on the rear side of the recess portion 118a also contributes to the increase in the torque of the rotor 110. This is because both the radial direction component B_r and the circumferential direction component B_θ of the magnetic flux density vector become positive. Further, similarly to the magnetic flux ϕ_3 on the front side of the recess portion 118a, a magnetic flux in a direction opposite to the magnetic flux ϕ_3 on the front side of the recess portion 118a does not contribute to the increase in the torque of the rotor 110 either. This is because the radial direction

component B_r and the circumferential direction component B_θ of the magnetic flux density vector become negative and positive, respectively.

[0045] ((Third finding))

In Fig. 1 and Fig. 2, the inter-magnet bridge portion 117 is composed of the soft magnetic material. Accordingly, air is smaller in magnetic permeability than the inter-magnet bridge portion 117. Thus, air is larger in magnetic resistance than the inter-magnet bridge portion 117. Accordingly, if all inter-magnetic pole bridge portions including the inter-magnet bridge portion 117a illustrated in Fig. 1 and Fig. 2 are flux barriers (gap portions), the region of the magnetic substance material composing the inter-magnet bridge portions is replaced with the gap portion. This replacement reduces the magnetic permeability in this region. Accordingly, the magnetic resistance in this region increases. According to the previously-described common general technical knowledge, the reflux magnetic flux is considered to be reduced. Therefore, the present inventors predicted that not only the outer-peripheral-side bridge portions 116a to 116b illustrated in Fig. 1 and Fig. 2 but also the inter-magnet bridge portion 117a becomes the flux barrier (gap portion). However, as a result, the IPMSM 100 in the optimum shape illustrated in Fig. 3 is different from this prediction. However, in the IPMSM 100 in the optimum shape illustrated in Fig. 3,

as illustrated by the inter-magnet flux barriers 114c to 114d, the inter-magnet flux barriers 114a to 114b illustrated in Fig. 1 and Fig. 2 are not coupled. That is, in the IPMSM 100 in the optimum shape illustrated in Fig. 3, as illustrated by the inter-magnet bridge portion 117b, a part of the inter-magnet bridge portion 117a illustrated in Fig. 1 and Fig. 2 remains. The IPMSM 100 in the optimum shape illustrated in Fig. 3 thus results in having the shape different from the previously-described prediction.

[0046] Further, in Fig. 1 and Fig. 2, the outer-peripheral-side bridge portions 116a to 116b are in positions closer to the stator 120 than the inter-magnet bridge portion 117a. Accordingly, the magnetic flux passing through the outer-peripheral-side bridge portions 116a to 116b heads for the stator 120 side more easily than the magnetic flux passing through the inter-magnet bridge portion 117a. Thus, the magnetic flux passing through the periphery-side bridge portions 116a to 116b is considered to be less likely to become the reflux magnetic flux than the magnetic flux passing through the inter-magnet bridge portion 117a. Therefore, the coupled inter-magnet flux barriers 114a to 114b are considered to allow the magnetic flux heading for the stator 120 side to be increased more than the outer-peripheral-side flux barriers 113a to 113b reaching the outer peripheral surface 115 of the rotor core

111. However, as previously described, the IPMSM 100 in the optimum shape illustrated in Fig. 3 has a shape yielding the result opposite to this.

[0047] Thus, the present inventors reviewed, of the results of the electromagnetic field analysis (magnetic flux density vector) in the IPMSM 100 in the optimum shape illustrated in Fig. 3, the result near the permanent magnets 112a to 112b.

Fig. 5A to Fig. 5B are views for explaining a second result of the electromagnetic field analysis in the IPMSM 100 in the optimum shape. Fig. 5A is the view illustrating one example of the magnetic flux density vector in the IPMSM 100 in the optimum shape, and is the same as Fig. 4A. Fig. 5B is the view for explaining one example of an outline of flows, of magnetic fluxes in the IPMSM 100 in the optimum shape, of magnetic fluxes near the permanent magnets 112a to 112b.

[0048] The notation in Fig. 5B is the same as the notation in Fig. 4B. Fig. 5B illustrates directions of the magnetic fluxes flowing out from the permanent magnets 112a to 112b. Arrows extending from the permanent magnets 112a to 112b have a similar meaning to the arrows indicated in the teeth 123c to 123d of the stator core 121. That is, the number of arrows extending from the permanent magnets 112a to 112b represents a relative magnitude relation of magnetic flux quanta (magnetic flux densities) flowing out from the permanent magnets 112a to 112b. Note that

lengths of the arrows extending from the permanent magnets 112a to 112b have nothing to do with the magnitude of the magnetic fluxes.

[0049] In Fig. 5B, most of the magnetic flux flowing out from the permanent magnet 112a on the front side does not head for the inter-magnet bridge portion 117b (the region which is not replaced with the flux barrier in the inter-magnet bridge portion 117a illustrated in Fig. 2) between the permanent magnets 112a and 112b, but heads for the stator 120 side (refer to a magnetic flux ϕ_{11}). On the other hand, the magnetic fluxes flowing out from the permanent magnet 112b on the rear side include magnetic fluxes passing through the inter-magnet bridge portion between the permanent magnets 112a and 112b (refer to magnetic fluxes ϕ_{13} , ϕ_{14}) other than a magnetic flux heading for the stator 120 side (refer to a magnetic flux ϕ_{12}). However, the magnetic fluxes flowing out from the permanent magnet 112b on the rear side and passing through the bridge portion between the permanent magnets 112a and 112b do not return to the permanent magnet 112b on the rear side, but one of them heads for the permanent magnet 112a on the front side (refer to the magnetic flux ϕ_{13}), and the other passes through a region on the inner peripheral side of the IPMSM 100 further than the permanent magnet 112a on the front side and heads for the stator 120 (refer to the magnetic flux ϕ_{14}).

[0050] Thus, when the inter-magnet flux barriers

114c to 114d are provided between the permanent magnets 112a and 112b, of the magnetic fluxes passing through the inter-magnet bridge portion between the permanent magnets 112a and 112b, the magnetic fluxes ϕ_{13} , ϕ_{14} contributing to the torque of the rotor 110 without becoming the reflux magnetic flux are present. Accordingly, providing the inter-magnet bridge portion 117a allows the magnetic flux contributing to the torque of the rotor 110 to be generated (refer to the magnetic flux ϕ_{13} illustrated in Fig. 5B). Further, the outer-peripheral-side bridge portions 116a to 116b reach the outer peripheral surface 115 to be opened, thereby allowing a decrease in the reflux magnetic flux and an increase in the magnetic flux heading for the stator 120 side (refer to the magnetic flux ϕ_{11} illustrated in Fig. 5B). That is, the present inventors obtained the third finding that actively providing the inter-magnet bridge portion 117a and extending the outer-peripheral-side flux barriers 113a to 113b to the outer peripheral surface 115 of the rotor core 111 to be opened allow the increase in the torque of the IPMSM 100 without dividing the rotor core 111.

[0051] Note that here, a case where the cross section of the rotor 110 in a direction perpendicular to the z-axis direction (the direction in which the rotation axis line extends) (x-y cross section) is the same in any position in the z-axis direction is exemplified. However, this need not necessarily be

adopted. For example, a so-called skew may be performed on the rotor core 111. Specifically, the skew is achieved by stacking a plurality of soft magnetic material blocks in the z-axis direction in a state of rotating them by a predetermined angle in the same direction with the z axis set as an axis. For this manner, the permanent magnets are installed in each soft magnetic material block. Accordingly, for example, as many permanent magnets as the product of the number of magnet holes of each soft magnetic material block and the number of the soft magnetic material blocks are required. Performing such a skew allows suppression of vibrations of a rotary electric machine.

[0052] Here, the soft magnetic block is produced by stacking a plurality of soft magnetic material plates having the same size and shape in such a manner that their contours (an inner edge and an outer edge) coincide, for example. The soft magnetic material plates used for each soft magnetic material block may have the same shape and size or different shapes and sizes. However, when the plurality of soft magnetic material blocks are stacked, outer edges of the soft magnetic material blocks coincide. Further, the soft magnetic material blocks may have the same predetermined angle or different predetermined angles. Further, the soft magnetic material block may be formed without using the plate-shaped soft magnetic material.

[0053] ((Fourth finding))

Moreover, the present inventors considered that a low residual magnetic flux density of the permanent magnets 112a to 112b reduces a flux quantum generated in the permanent magnets 112a to 112b (the magnetic flux density becomes low), which makes the magnetic flux less likely to flow back. Thus, the electromagnetic field analysis in each of a case of setting a residual magnetic flux density of the permanent magnets 112a to 112b to 0.4 T and a case of setting a residual magnetic flux density thereof to 1.0 T was performed on the IPMSM 100 in the basic shape illustrated in Fig. 1. Fig. 6A to Fig. 6B are views illustrating one example of the result of the electromagnetic field analysis in the IPMSM 100 in the basic shape when the residual magnetic flux density of the permanent magnets 112a to 112b is 0.4 T. Fig. 7A to Fig. 7B are views illustrating one example of the result of the electromagnetic field analysis in the IPMSM 100 in the basic shape when the residual magnetic flux density of the permanent magnets 112a to 112b is 1.0 T. Note that in Fig. 4A to Fig. 7B, conditions except for the residual magnetic flux densities of the permanent magnets 112a to 112b and the shapes of the rotor core 111 are the same.

[0054] Fig. 6A, Fig. 7A are the views illustrating examples of magnetic flux density vectors in the IPMSM 100 in the basic shape when the residual

magnetic flux densities of the permanent magnets 112a to 112b are 0.4 T, 1.0 T, respectively. Fig. 6B, Fig. 7B are the views for explaining examples of outlines of flows of magnetic fluxes in the IPMSM 100 in the basic shape when the residual magnetic flux densities of the permanent magnets 112a to 112b are 0.4 T, 1.0 T, respectively. Fig. 6B and Fig. 7B illustrate the outlines of the flows of the magnetic fluxes necessary for the explanation of magnetic fluxes in the IPMSM 100 in the basic shape, for convenience of the explanation, similarly to Fig. 4B and Fig. 5B. Incidentally, the meaning of arrows in Fig. 6B and Fig. 7B is the same as the meaning of the arrows in Fig. 5B.

[0055] In Fig. 6B, when the residual magnetic flux density of the permanent magnets 112a to 112b is 0.4 T, most of the magnetic fluxes flowing out from the permanent magnets 112a to 112b are reflux magnetic fluxes passing through the outer-peripheral-side bridge portions 116a to 116b (refer to magnetic fluxes $\phi 25$, $\phi 26$). This corresponds to the fact that in the IPMSM 100 in the optimum shape illustrated in Fig. 3, the result that (a part of) the outer-peripheral-side flux barriers 113a to 113b illustrated in Fig. 1 and Fig. 2 reach (reaches) the outer peripheral surface 115 of the rotor core 111 to be open can be obtained. Further, in Fig. 6B, most of the magnetic fluxes passing through the inter-magnet bridge portion 117a are magnetic fluxes

becoming no reflux magnetic flux similarly to the magnetic fluxes ϕ_{13} to ϕ_{14} illustrated in Fig. 5B (refer to the magnetic fluxes ϕ_{13} to ϕ_{14} illustrated in Fig. 5B and magnetic fluxes ϕ_{23} to ϕ_{24} illustrated in Fig. 6B).

[0056] On the other hand, in Fig. 7B, when the residual magnetic flux density of the permanent magnets 112a to 112b is 1.0 T, most of the magnetic fluxes flowing out from the permanent magnets 112a to 112b and passing through the inter-magnet bridge portion 117a become reflux magnetic fluxes (refer to magnetic fluxes ϕ_{33} , ϕ_{34}). As a result illustrated in Fig. 7A, the reflux magnetic flux is dominant in the magnetic flux passing through the inter-magnet bridge portion 117a. This demonstrates that a high residual magnetic flux density of the permanent magnets 112a to 112b reduces the magnetic fluxes ϕ_{13} to ϕ_{14} , ϕ_{23} to ϕ_{24} becoming no reflux magnetic flux illustrated in Fig. 5B and Fig. 6B. Note that also in Fig. 7B, similarly to Fig. 6B, reflux magnetic fluxes flowing out from the permanent magnets 112a to 112b and passing through the outer-peripheral-side bridge portions 116a to 116b are present (refer to magnetic fluxes ϕ_{35} , ϕ_{36}). Further, also in Fig. 7B, similarly to Fig. 6B, magnetic fluxes heading for the stator 120 side from the permanent magnets 112a to 112b are present (refer to magnetic fluxes ϕ_{31} , ϕ_{32}).

[0057] As described above, the present inventors obtained the fourth finding that by using the

permanent magnets 112a to 112b having a low residual magnetic flux density, the magnetic flux passing through the inter-magnet bridge portion 117a includes a lot of magnetic flux becoming no reflux magnetic flux and contributing to the torque of the rotor 110. This causes the consideration that under the same conditions except for the residual magnetic flux density of the permanent magnets 112a to 112b, the use of the permanent magnets 112a to 112b having a low residual magnetic flux density increases an improvement effect of the torque of the rotor 110 caused by providing the inter-magnet bridge portion 117a more than the use of the permanent magnets 112a to 112b having a high residual magnetic flux density. Accordingly, installing the permanent magnets 112a to 112b having a low residual magnetic flux density in the rotor core 111 allows the increase in the improvement effect of the torque of the rotor 110. Thus, for example, the torque of the rotor 110 can be improved even without using a permanent magnet containing rare earth. For example, even the use of a ferrite magnet or the like as a permanent magnet containing no rare earth allows the improvement in the torque of the rotor 110.

An embodiment of the present invention explained below has been made based on the above circumstances.

[0058] Note that as previously described, in this section, Fig. 1 exemplifies the case where the rotor 110 rotates in the direction of the arrow given on

the side of "rotation direction" (the counterclockwise direction opposite to the paper sheet). However, the explanation in this section does not change depending on the direction in which the rotor 110 rotates. Note that when the rotor 110 rotates in a direction opposite to the direction of this arrow illustrated in Fig. 1, the permanent magnet 112 on the front side and the permanent magnet 112 on the rear side are the permanent magnets 112b, 112a, respectively, in the explanation in this section. Further, directions of magnetic fluxes and a magnitude relation between magnetic flux quanta (magnetic flux densities) in the teeth 123a to 123d of the stator core 121 are replaced with ones illustrated in Fig. 4A to Fig. 7B. That is, in Fig. 4B, Fig. 5B, Fig. 6B, and Fig. 7B, the arrows pointing outward and the arrows pointing inward indicated in the teeth 123a to 123d of the stator core 121 point inward and outward, respectively. Further, in Fig. 4B, Fig. 5B, Fig. 6B, and Fig. 7B, the two arrows and the one arrow change into one arrow and two arrows, respectively.

[0059] (Embodiment)

Hereinafter, one embodiment of the present invention will be explained. This embodiment exemplifies a case where the rotary electric machine is an inner rotor-type IPMSM. Fig. 8 is a view illustrating one example of a configuration of an IPMSM 800. Fig. 8 is a sectional view of the IPMSM

800 when cut perpendicularly to a rotation axis line 0) of the IPMSM 800 (rotor 810). Similarly to Fig. 1, in Fig. 8, a range of a double arrow indicated as "one pole" is a section forming one pole of the IPMSM 800. This embodiment exemplifies a case where the IPMSM 800 has eight poles. However, the number of poles of the IPMSM 800 is not limited to eight. As previously described, when the number of poles of the IPMSM 800 is n , the IPMSM 800 has, on the whole, a relation of rotational symmetry of n -time symmetry in which the rotation axis line 0 of the IPMSM 800 is set as a rotation symmetry axis. n is an integer of two or more, and n is eight in the example illustrated in Fig. 8 ($n = \text{eight}$).

[0060] In Fig. 8, the IPMSM 800 includes a rotor 810 and the stator 120. The stator 120 is the same as the stator 120 illustrated in Fig. 1. Accordingly, here, the same reference sign as the reference sign given in Fig. 1 is given, and a detailed explanation of the stator 120 is omitted. The IPMSM 800 includes the stator 120 (the non-illustrated stator coil and the stator core 121) defined as follows, for example. The stator core 121 is formed of a yoke portion having a fixed width and 24 teeth portions, for example. The width of the yoke portion and a length of the teeth portion are each a length in a radial length of the IPMSM 800. A shape of the yoke portion is circular, for example. The 24 teeth portions are installed at regular intervals on an inner peripheral

surface of the yoke portion, for example. The width of the yoke portion is half a difference between an inside diameter and an outside diameter of the stator 120, for example. The length of the teeth portion is 0.4 times the difference between the inside diameter and the outside diameter of the stator 120, for example. A projecting portion is formed at a tip (an end on the rotation axis line 0 side) of the teeth portion. The projecting portion is formed to project to both sides in the circumferential direction. A length and a width in the circumferential direction of the projecting portion are each 0.3 times the length of the teeth portion, for example. However, as long as a configuration of the stator 120 is a configuration adopted typically as a stator of an IPMSM, the previously-described findings are not changed by the configuration of the stator 120.

[0061] This embodiment exemplifies a case where the exciting current flowing through the non-illustrated stator coil included in the stator 120 is the three-phase alternating current. Accordingly, a rotating magnetic field with a period in response to a frequency of the three-phase alternating current is generated in the stator core 121 (teeth 123). Note that as previously described, also in Fig. 8 similarly to Fig. 1, reference signs are given to only a section forming one pole of the rotor 810, and reference signs in sections forming the other seven poles of the rotor 810 are omitted.

[0062] The rotor 810 rotates with the rotation axis line 0 of the IPMSM 800 set as a rotation axis line. The rotor 810 rotates in only one direction of a counterclockwise direction and a clockwise direction opposite to the paper sheet of Fig. 8. This embodiment exemplifies a case where the rotor 810 rotates in the counterclockwise direction opposite to the paper sheet of Fig. 8 (refer to an arrow given on the side of "rotation direction" in Fig. 8). Fig. 9 is a view illustrating one example of a configuration of the rotor 810 (rotor cross section). In the following explanation, a rotation direction of the rotor 810 is abbreviated as a rotation direction as necessary. Note that as previously described, also in Fig. 9 similarly to Fig. 8, reference signs are given to only a section forming one pole of the rotor 810, and reference signs in sections forming the other seven poles of the rotor 810 are omitted.

[0063] In Fig. 8 and Fig. 9, this embodiment exemplifies a case where the rotor 810 includes a rotor core 811 and a plurality of permanent magnets 812a to 812b per one pole. Specifically, this embodiment exemplifies a case where the rotor 810 includes a rotor core 811 and the two permanent magnets 812a to 812b per one pole. The rotor core 811 is formed using a soft magnetic material. The rotor core 811 is produced using a plurality of electromagnetic steel sheets stacked along the rotation axis line 0 of the rotor 810, for example.

However, the rotor core 811 need not necessarily be produced using the electromagnetic steel sheets stacked in plurality. The rotor core 811 may be, for example, a powder magnetic core, an amorphous core, and a nanocrystal core. Note that when the rotor core 811 is the powder magnetic core, the amorphous core, and the nanocrystal core, each soft magnetic material forming the rotor core 811 is produced using insulator-coated soft magnetic particles, an amorphous alloy, and a nanocrystalline alloy.

[0064] Fig. 10 is a view illustrating one example of a configuration of the rotor core 811. Similarly to Fig. 8 and Fig. 9, Fig. 10 is also a sectional view of the rotor core 811 when cut perpendicularly to a rotation axis line 0 of the rotor core 811. In the following explanation, the cross section of the rotor core 811 when cut perpendicularly to the rotation axis line 0 of the rotor core 811 is referred to as a rotor core cross section as necessary. Note that the rotation axis line 0 of the rotor core 811 coincides with the rotation axis line 0 of the IPMSM 800 and the rotation axis line 0 of the rotor 810. Further, as previously described, also in Fig. 10, similarly to Fig. 8 and Fig. 9, reference signs are given to only a section forming one pole of the rotor core 811, and reference signs in sections forming the other seven poles of the rotor core 811 are omitted.

[0065] As illustrated in Fig. 10, this embodiment exemplifies a case where a plurality of magnet holes

817a to 817b are formed per one pole in the rotor core 811. Specifically, this embodiment exemplifies a case where the two magnet holes 817a to 817b are formed per one pole in the rotor core 811. Further, this embodiment exemplifies a case where the plurality of magnet holes 817a to 817b are each a through hole penetrating in the z-axis direction. In Fig. 8 to Fig. 10, the plurality of permanent magnets 812a, 812b are respectively inserted into the magnet holes 817a, 817b formed through the rotor core 811, thereby being installed (embedded) in the rotor core 811. In this manner, in this embodiment, the rotor core 811 includes the plurality of magnet holes 817a to 817b per one pole as the magnet holes through which the permanent magnets 812a to 812b are installed. Accordingly, in the example illustrated in Fig. 10, the magnet hole 817a is, of the plurality of magnet holes installed in the same pole, the magnet hole on the front side in the rotation direction. Further, in the example illustrated in Fig. 10, the magnet hole 817b is the magnet hole on the rear side in the rotation direction of the rotor 810 (the rotor core 811). In the following explanation, the magnet hole 817a on the front side in the rotation direction of the rotor 810 (the rotor core 811) is referred to as the front-side magnet hole 817a as necessary. Further, in the following explanation, the magnet hole 817b on the rear side in the rotation direction of the rotor 810 (the rotor

core 811) is referred to as the rear-side magnet hole 817b as necessary.

[0066] Further, through the rotor core 811, a hole 816 through which the permanent magnets 812a to 812b are not installed is formed. The hole 816 is a through hole penetrating in the z-axis direction, and a non-illustrated shaft or the like is installed therethrough. Note that holes other than the hole 816 and the magnet holes 817a to 817b may be formed through the rotor core 811. Through these holes, the permanent magnets 812a to 812b may be installed or need not be installed.

[0067] In Fig. 9, this embodiment exemplifies a case where a magnetic flux flows in and out from pole faces 901a to 901d of the permanent magnets 812a to 812b. Directions orthogonal to the pole faces 901a to 901d are magnetization directions D_m of the permanent magnets 812a to 812b. As illustrated in Fig. 9, the magnetization directions D_m of the permanent magnets 812a to 812b are directions of double arrows indicated to run across the permanent magnets 812a to 812b. In Fig. 8 to Fig. 10, the magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed are formed in such a manner that the pole faces 901a to 901d of the permanent magnets 812a to 812b installed through the magnet holes 817a to 817b are inclined to an outer peripheral surface 818 of the rotor core 811. As illustrated in Fig. 8 to Fig. 10, this embodiment

exemplifies a case where the magnet holes 817a to 817b are formed in such a manner that the closer to the outer peripheral surface 818 of the rotor core 811 the magnet holes 817a to 817b are, the wider an interval in a circumferential direction between the permanent magnets 812a and 812b installed through the magnet holes 817a to 817b is. Thus, this embodiment exemplifies a case where the permanent magnets 812a to 812b are disposed in a so-called V-shape.

[0068] As explained in the section of ((Fourth finding)) in the section of (Circumstances), from the viewpoint of reducing a reflux magnetic flux due to the permanent magnets 812a to 812b, a residual magnetic flux density of the permanent magnets 812a to 812b is preferably lower in a range of exhibiting a function as the permanent magnet in the IPMSM 800. Note that exhibiting the function as the permanent magnet in the IPMSM 800 means that at least a part of the magnetic flux generated by the permanent magnet reaches the stator 120, thereby becoming a magnetic flux contributing to torque of the rotor. When the residual magnetic flux density at room temperature of the permanent magnets 812a to 812b exceeds 0.4 T, an increase in a flux quantum generated by the permanent magnets 812a to 812b increases the reflux magnetic flux included in the magnetic flux passing through an inter-magnet bridge portion 821a. Thus, an effect of an increase in torque of the rotor 810 caused by the magnetic fluxes becoming no reflux magnetic flux

(refer to the magnetic fluxes ϕ_{13} , ϕ_{14} illustrated in Fig. 5B) decreases. Moreover, when the residual magnetic flux density at room temperature of the permanent magnets 812a to 812b exceeds 0.8 T, such a decrease in the effect of the increase in the torque of the rotor 810 is significant. Further, the residual magnetic flux density at room temperature of the permanent magnets 812a to 812b exceeding 0.4 T causes a case of requiring the use of the permanent magnets 812a to 812b containing rare earth. Further, the residual magnetic flux density at room temperature of the permanent magnets 812a to 812b exceeding 0.8 T causes a case of requiring the use of the permanent magnets 812a to 812b containing a large amount of rare earth.

[0069] From the above viewpoint, the residual magnetic flux density at room temperature of the permanent magnets 812a to 812b is preferably 0.8 T or less, and more preferably 0.4 T or less. Further, a smaller amount of rare earth is preferably contained in the permanent magnets 812a to 812b, and no rare earth is more preferably contained in the permanent magnets 812a to 812b. However, the residual magnetic flux density at room temperature of the permanent magnets 812a to 812b need not be in the previously-described range as long as the function as the permanent magnet in the IPMSM can be exhibited.

[0070] In Fig. 9, flux barriers 813a to 813b, 814a to 814b are, in the magnet holes 817a to 817b

illustrated in Fig. 10 through which the permanent magnets 812a to 812b are installed, spaces where the permanent magnets 812a to 812b are absent. A material object is absent in the flux barriers 813a to 813b, 814a to 814b. That is, the flux barriers 813a to 813b, 814a to 814b are gap portions (regions of air). The flux barriers 813a to 813b, 814a to 814b are each a region through which no magnetic flux passes, or a region which makes it more difficult for the magnetic flux to pass through than a region around the flux barriers 813a to 813b, 814a to 814b. This embodiment exemplifies a case where the material object is absent in the flux barriers 813a to 813b, 814a to 814b as described above. However, this need not necessarily be adopted. For example, the flux barriers 813a to 813b, 814a to 814b may be formed by installing a nonmagnetic material in, in the magnet holes 817a to 817b illustrated in Fig. 10 through which the permanent magnets 812a to 812b are installed, the spaces where the permanent magnets 812a to 812b are absent.

[0071] In Fig. 9, the flux barriers 813a to 813b positioned on the outer peripheral side in the left-right direction Ds further than the permanent magnets 812a to 812b are outer-peripheral-side flux barriers. The outer-peripheral-side flux barriers 813a to 813b reach the outer peripheral surface 818 of the rotor 810 (the rotor core 811) to be open in the rotor cross section. On the other hand, the flux barriers

814a to 814b positioned on the inner peripheral side in the left-right direction Ds further than the permanent magnets 812a to 812b are inter-magnet flux barriers. The inter-magnet flux barriers 814a to 814b are not each open except for end portions in the z-axis direction. Incidentally, the outer peripheral side indicates the outer peripheral surface 818 side of the rotor core 811, and the inner peripheral side indicates an inner peripheral surface 819 side of the rotor core 811.

[0072] As previously described, the permanent magnet 812a is the front-side permanent magnet 812a on the front side further than the permanent magnet 812b, and the permanent magnet 812b is the rear-side permanent magnet 812b. The outer-peripheral-side flux barrier 813a positioned on the outer peripheral side further than the front-side permanent magnet 812a is positioned on the front side in the rotation direction further than the front-side permanent magnet 812a. On the other hand, the outer-peripheral-side flux barrier 813b positioned on the outer peripheral side further than the rear-side permanent magnet 812b is positioned on the rear side in the rotation direction further than the rear-side permanent magnet 812b.

[0073] Further, as illustrated in Fig. 10, in the outer peripheral surface 818 of the rotor core 811, a recess portion 815a is formed. The recess portion 815a is formed in a position opposite apart from the

teeth 123a, 123b different from the teeth 123b, 123d having the lowest magnetic flux density of the teeth 123 of the stator core 121 installed in a position opposite apart from the outer peripheral surface 818 of the rotor core 811. As explained in the section of (Circumstances), a rotation period of the rotor core 811 and a rotation period of a rotating magnetic field generated in the stator core 121 (teeth 123) are the same. Accordingly, even though the rotor core 811 rotates, magnetic flux densities of the teeth 123 at the position facing the recess portion 815a are the same. This embodiment exemplifies a case where the one recess portion 815a is formed per one pole. However, the number of the recess portions 815 per one pole may be two or more. The magnetic flux density of the teeth 123a, 123c of the stator core 121 installed at the position opposite apart from the recess portion 815a is preferably high, and is more preferably the highest magnetic flux density. This is because the torque of the rotor 810 is allowed to increase.

[0074] Fig. 11A is a view enlarging and illustrating a part of the rotor core 811 illustrated in Fig. 10 (a view illustrating the rotor core cross section). Fig. 11B and Fig. 11C are modified examples with respect to Fig. 11A. One example of a configuration of the rotor core 811 of this embodiment will be explained in detail while referring to Fig. 10 and Fig. 11A to Fig. 11C. Incidentally, in Fig. 11A to

Fig. 11C, to avoid making positions pointed by reference signs unclear, the illustration of hatching indicating cross sections is omitted.

In Fig. 10, in a region occupied by the rotor core 811, a region of the soft magnetic material (a region except for the hole 816, the magnet holes 817a to 817b) is a soft magnetic material portion 820. As illustrated in Fig. 10 and Fig. 11A, in the rotor core cross section, the magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed has first end portions 1111a to 1111b, second end portions 1112a to 1112b, third end portions 1113a to 1113b, and fourth end portions 1114a to 1114b. In the following, one example of the first end portions 1111a to 1111b, the second end portions 1112a to 1112b, the third end portions 1113a to 1113b, and the fourth end portions 1114a to 1114b will be explained.

[0075] First, the first end portions 1111a to 1111b will be explained. The first end portions 1111a to 1111b are end portions positioned on an outermost periphery side in spaces serving as the outer-peripheral-side flux barriers 813a to 813b included in the magnet holes 817a to 817b. The first end portions 1111a to 1111b are open end portions open in positions on the outer peripheral surface 818 of the rotor core 811 in the rotor core cross section. In the following explanation, this sometimes causes the first end portion 1111 to be also referred to as an

open end portion 1011. In the following explanation, in the rotor core cross section, a bent or curved portion is referred to as a corner portion as necessary. However, a region different from the open end portion in the outer peripheral surface 818 of the rotor core 811 (an arc region in which a distance from the rotation axis line 0 is a radial length of the rotor 810) is set to be no corner portion.

[0076] In the rotor core cross section, when the bent portion of the magnet holes 817a to 817b is the corner portion, a position of the corner portion is set as the bent position. In the rotor core cross section, when the curved portion of the magnet holes 817a to 817b is the corner portion, a position of the corner portion is set as a position at a representative point of the curved portion (a portion having curvature). These details will be explained while referring to Fig. 11A to Fig. 11C to be described later. In the example illustrated in Fig. 11A, the first end portions 1111a and 1111b are regions along the circumferential direction from one to the other of the corner portions 1131a to 1131b and from one to the other of the corner portions 1131c to 1131d, at two positions on the outer peripheral surface 818 (outermost peripheral side) of the rotor core 811 of the 12 corner portions of each of the one magnet hole 817a and the one magnet hole 817b, in the rotor core cross section. Incidentally, the circumferential direction is a direction going

around the outer peripheral surface 818 of the rotor 810 (the rotor core 811) (a direction parallel to and a direction antiparallel to the rotation direction of the rotor 810 (the rotor core 811)).

[0077] Too short a length L1 in the circumferential direction of the first end portions 1111a to 1111b makes a magnetic resistance in the first end portions 1111a to 1111b too small. As a result, an increase in a magnetic flux going over the magnet holes 817a to 817b in the circumferential direction causes the possibility of an increase in the reflux magnetic flux. On the other hand, too long a length L1 in the circumferential direction of the first end portions 1111a to 1111b decreases outer side portions 822a to 822h, thereby causing the possibility of a decrease in the magnetic flux contributing to the torque of the rotor 810. The length L1 in the circumferential direction of the first end portions 1111a to 1111b is appropriately defined from such a viewpoint. The length L1 in the circumferential direction of the first end portions 1111a to 1111b only needs to be defined from within a range of not less than 0.1 times nor more than 1.0 times a length L2 in the magnetization direction Dm of the permanent magnets 812a to 812b, for example. Note that this embodiment exemplifies a case where the length in the magnetization direction Dm of the permanent magnets 812a to 812b is fixed. However, the length in the magnetization direction Dm of the permanent magnets

812a to 812b need not be fixed. When the length in the magnetization direction D_m of the permanent magnets 812a to 812b is not fixed, the length L_1 in the circumferential direction of the first end portions 1111a to 1111b only needs to be defined with a representative value (for example, an average value) of the length L_2 in the magnetization direction D_m of the permanent magnets 812a to 812b set as a length in the magnetization direction D_m of the permanent magnets 812a to 812b.

[0078] Further, lengths of the other regions of the magnet holes 817a to 817b in the rotor core cross section are also defined from the viewpoints of suppressing the reflux magnetic flux and securing a magnetic path and strength similarly to the length L_1 in the circumferential direction of the first end portions 1111a to 1111b. For example, a minimum value of a length between two end portions, facing each other, of the magnet holes 817a to 817b in the rotor core cross section only needs to be defined from within the range of, for example, not less than 0.1 times nor more than 1.0 times the length in the magnetization direction D_m of the permanent magnets 812a to 812b.

[0079] As explained in the section of ((First finding)) of the section of (Circumstances), displacing the first end portions 1111a to 1111b which are the open end portions of the outer-peripheral-side flux barriers 813a to 813b to the

rear side in the rotation direction (the side opposite to the rotation direction) of the rotor core 811 increases the torque of the rotor 810. In this embodiment for the purpose of achieving the above, as illustrated in Fig. 11A, in the rotor core cross section, positions of open-end front-side corner portions 1131a, 1131c of the first end portions 1111a, 1111b which are the open end portions are set to be on the rear side in the rotation direction of the rotor core 811 further than reference positions 831a, 831b relative to the magnet holes 817a, 817b having the first end portions 1111a, 1111b which are the open end portions. The open-end front-side corner portions 1131a, 1131c of the first end portions 1111a, 1111b are, of the corner portions of the first end portions 1111a, 1111b, the corner portions on the front side in the rotation direction of the rotor core 811 in the rotor core cross section.

[0080] Here, the reference positions 831a, 831b relative to the magnet holes 817a, 817b having the first end portions 1111a, 1111b which are the open end portions are at positions at intersection points of straight lines 1172, 1174 passing through permanent-magnet reference end portions 841a, 841b which are one of end portions of the permanent magnet 812a and one of end portions of the permanent magnet 812b, which are installed through the magnet holes 817a, 817b, and the rotation axis line 0, and, the outer peripheral surface 818 of the rotor core 811,

in the rotor core cross section, as illustrated in Fig. 11A. The permanent-magnet reference end portions 841a, 841b in the magnet holes 817a, 817b having the first end portions 1111a, 1111b which are the open end portions are, of the end portions of the permanent magnets 812a, 812b installed through the magnet holes 817a, 817b, each the end portion included in the one permanent magnet 812a or the one permanent magnet 812b at a position closest to each of the open end portions (the first end portion 1111a or 1111b). The permanent-magnet reference end portions 841a, 841b in the magnet holes 817a, 817b having the first end portions 1111a, 1111b which are the open end portions are each the end portion at a position at the farthest distance in the circumferential direction from a straight line 1177 passing through the central position in the circumferential direction of the region of one pole (magnetic pole) (of the rotor) including the permanent magnet 812a or 812b (region surrounded by dotted lines in Fig. 3), and the rotation axis line 0 (the origin 0), in the rotor core cross section, of the end portions of the one permanent magnet 812a or the one permanent magnet 812b at the position closest to the open end portion. Here, the distance in the circumferential direction from the straight line 1177 is a distance defined on the side, of the front side and the rear side in the rotation direction of the rotor core 811, in which this open end portion is

present. As illustrated in Fig. 11A, the permanent-magnet reference end portion 841a in the magnet hole 817a having the first end portion 1111a which is the open end portion is, of the end portions of the permanent magnet 812a, the end portion at the position at the farthest distance in the circumferential direction from the straight line 1177 on the front side on the first end portion 1111a side further than the straight line 1177. Further, the permanent-magnet reference end portion 841b of the magnet hole 817b having the first end portion 1111b which is the open end portion is, of the end portions of the permanent magnet 812b, the end portion at the position at the farthest distance in the circumferential direction from the straight line 1177 on the rear side on the first end portion 1111b side further than the straight line 1177.

[0081] Note that for the convenience of notation, although Fig. 11A illustrates a plurality of the rotation axis lines 0, the actual rotation axis line 0 is one in number as illustrated in Fig. 8 to Fig. 10 (the rotation axis lines 0 illustrated in Fig. 11A are superposed at one position). This is also the same as Fig. 11B and Fig. 11C to be described later. In this embodiment, the magnet holes 817a, 817b are respectively present on the front side and the rear side in the rotation direction of the rotor core 811 relative to the straight line 1177. Accordingly, relative to the straight line 1177, the permanent-

magnet reference end portions 841a, 841b are each present on only one of the front side and the rear side in the rotation direction of the rotor core 811. In contrast with this, for example, it is assumed that the magnet holes 817a to 817b are disposed to straddle the straight line 1177, and both the outer-peripheral-side flux barriers 113a and 114a, and, the outer-peripheral-side flux barriers 113b and 114b, each two of which are formed on both sides in the left-right direction Ds of each of the permanent magnets 812a to 812b installed through the magnet holes 817a to 817b, have the open end portions in the outer peripheral surface 818 of the rotor core 811. In this case, the permanent-magnet reference end portions 841a, 841b are each present in the rotation direction of the rotor core 811 relative to the straight line 1177 in the rotor core cross section.

[0082] In the examples illustrated in Fig. 11A to Fig. 11C, the central position in the circumferential direction of the region of one pole of the rotor is defined as a position of the midpoint of a virtual straight line connecting the permanent-magnet reference end portions 841a and 841b, for example. The straight line passing through this central position and the rotation axis line 0 (the origin 0) is set as the straight line 1177.

[0083] In the following explanation, the open-end front-side corner portions 1131a, 1131c are respectively referred to as a front-side open-end

front-side corner portion, a rear-side open-end front-side corner portion as necessary. Further, in the following explanation, the open end portion 1111a of the front-side magnet hole 817a and the open end portion 1111b of the rear-side magnet hole 817b are respectively referred to as the front-side open end portion 1111a and the rear-side open end portion 1111b as necessary.

[0084] The front-side open-end front-side corner portion 1131a is, of the two corner portions 1131a to 1131b in the circumferential direction of the rotor core 811 of the front-side open end portion 1111a which is the open end portion of a space 1123a included in the front-side magnet hole 817a and serving as the outer-peripheral-side flux barrier, the corner portion 1131a on the front side in the rotation direction of the rotor core 811.

[0085] The rear-side open-end front-side corner portion 1131c is, of the two corner portions 1131c to 1131d in the circumferential direction of the rotor core 811 of the rear-side open end portion 111b which is the open end portion of a space 1123b included in the rear-side magnet hole 817b and serving as the outer-peripheral-side flux barrier, the corner portion 1131c on the front side in the rotation direction of the rotor core 811.

[0086] Further, in the rotor core cross section, the permanent-magnet reference end portions 841a to 841b have the front-side permanent magnet end portion 841a

and the rear-side permanent magnet end portion 841b. The front-side permanent magnet end portion 841a is, of the end portions of the permanent magnets 812a to 812b installed through the front-side magnet hole 817a, the end portion at a position on the foremost side in the rotation direction. The rear-side permanent magnet end portion 841b is, of the end portions of the permanent magnet 812b installed through the rear-side magnet hole 817b, the end portion at a position on the rearmost side in the rotation direction.

[0087] Further, in the rotor core cross section, the reference positions 831a to 831b have the front-side reference position 831a. The reference positions 831a to 831b are a position at an intersection point of the straight line 1172 passing through the front-side permanent magnet end portion 841a and the rotation axis line 0, and the outer peripheral surface 818 of the rotor core 811.

[0088] Further, in the rotor core cross section, the reference positions 831a to 831b have the rear-side reference position 831b. The rear-side reference position 831b is a position at an intersection point of the straight line 1174 passing through the rear-side permanent magnet end portion 841b and the rotation axis line 0, and the outer peripheral surface 818 of the rotor core 811.

[0089] Here, from the viewpoint of certainly improving the torque of the rotor 810, positions of

the open-end front-side corner portions (the front-side open-end front-side corner portion 1131a and the rear-side open-end front-side corner portion 1131c) are preferably defined in the following manner.

The number (piece) of slots in the stator core 121 installed in the position opposite apart from the outer peripheral surface 818 of the rotor core 811 is set as N_{slot} . Further, a reference-position movement angle θ_a (rad) which is an angle around the rotation axis line 0 from the reference positions 831a to 831b is set as $2\pi/N_{slot}$. In the example illustrated in Fig. 8, N_{slot} as the number (piece) of slots in the stator core 121 is 24, and thus the reference-position movement angle θ_a is $2\pi/24$ (rad) = $15(^{\circ})$.

[0090] In the rotor core cross section, an angle θ_f formed by a straight line 1171 and the straight line 1172 is preferably set to not less than $\theta_a/24$ nor more than $15\theta_a/24$, and more preferably set within a range of $\theta_a/3 \pm \theta_a/24$. The straight line 1171 is a straight line passing through the front-side open-end front-side corner portion 1131a and the rotation axis line 0 in the rotor core cross section. The front-side open-end front-side corner portion 1131a is, of the open-end front-side corner portions 1131a, 1131c, the corner portion positioned on the front side in the rotation direction further than the center in the circumferential direction in the same pole in the rotor core cross section. The straight line 1172 is the straight line passing through the reference

position 831a relative to the magnet hole 817a having the open end portion 1111a with the front-side open-end front-side corner portion 1131a set as one of corner portions, and the rotation axis line 0, in the rotor core cross section. In the following explanation, the angle θ_f is referred to as the outer-peripheral-side flux barrier movement angle θ_f on the front side as necessary.

[0091] Further, in the rotor core cross section, an angle θ_b formed by a straight line 1173 and the straight line 1174 is preferably set to not less than $\theta_a/24$ nor more than $\theta_a/8$, and more preferably set within a range of $\theta_a/12 \pm \theta_a/24$. The straight line 1173 is a straight line passing through the rear-side open-end front-side corner portion 1131c and the rotation axis line 0 in the rotor core cross section. The rear-side open-end front-side corner portion 1131c is, of the open-end front-side corner portions 1131a, 1131c, the corner portion positioned on the rear side in the rotation direction further than the center in the circumferential direction in the same pole. The straight line 1174 is the straight line passing through the reference position 831b relative to the magnet hole 817b having the open end portion 1111b with the rear-side open-end front-side corner portion 1131c set as one of corner portions, and the rotation axis line 0, in the rotor core cross section. In the following explanation, the angle θ_b is referred to as the movement angle θ_b of the outer-

peripheral-side flux barrier on the rear side as necessary.

[0092] Further, as explained in the section of ((Second finding)) in the section of (Circumstances), providing the recess portion 815a in the position facing the teeth 123a, 123b with a higher magnetic flux density than the lowest magnetic flux density in the region of the outer peripheral surface 818 of the rotor core 811 increases the torque of the rotor 810. To further enhance the effect of increasing the torque of the rotor 810, the entire region of the recess portion 815a preferably faces the teeth 123a, 123b with this magnetic flux density. However, a partial region of the recess portion 815a may be face the teeth 123a, 123b with this magnetic flux density. Further, from the viewpoint of certainly improving the torque of the rotor 810, the recess portion 815a is preferably defined as follows.

[0093] As illustrated in Fig. 11A, in the rotor core cross section, the reference-position movement angle θ_a (rad) which is the angle around the rotation axis line 0 from the rear-side reference positions 831b is set as $2\pi/N_{slot}$. The rear-side reference position 831b is a position at an intersection point of the straight line 1174 passing through the rear-side permanent magnet end portion 841b and the rotation axis line 0, and the outer peripheral surface 818 of the rotor core 811 in the rotor core cross section. The rear-side permanent magnet end portion 841b is,

of the end portions of the permanent magnets 812a to 812b installed in the same pole, the end portion positioned on the rearmost side in the circumferential direction. In the example illustrated in Fig. 8 as previously described, N_{slot} as the number (piece) of slots in the stator core 121 is 24. Accordingly, the reference-position movement angle θ_a is $2\pi/24$ (rad) = $15(^{\circ})$.

[0094] First, in the rotor core cross section, an angle formed by a straight line 1175 and the straight line 1173 is preferably set as θ_a . The straight line 1175 is a straight line passing through a recess rear-side corner portion 1161a and the rotation axis line 0 in the rotor core cross section. The recess rear-side corner portion 1161a is, of two corner portions 1161a to 1161b in an open end portion 1151a of the recess portion 815a, a corner portion positioned on the rear side in the rotation direction, in the rotor core cross section. The straight line 1173 is the straight line passing through the rear-side open-end front-side corner portion 1131c and the rotation axis line 0 in the rotor core cross section. The rear-side open-end front-side corner portion 1131c is positioned on the rear side in the rotation direction further than the recess portion 815a in the same pole as a pole in which the recess portion 815a is installed.

[0095] Further, in the rotor core cross section, an angle θ_c formed by a straight line 1176 and the

straight line 1175 is preferably set to not less than $\theta a/8$ nor more than $25\theta a/24\theta a$, and more preferably set within a range of $3\theta a/4 \pm \theta a/12$. The straight line 1176 is a straight line passing through a recess front-side corner portion 1161b and the rotation axis line 0 in the rotor core cross section. The recess front-side corner portion 1161b is, of the two corner portions 1161a to 1161b in the open end portion 1151a of the recess portion 815a, the corner portion on the front side in the rotation direction, in the rotor core cross section. The straight line 1175 is the straight line passing through the recess rear-side corner portion 1161a and the rotation axis line 0 in the rotor core cross section. In the following explanation, the angle θc is referred to as the recess opening angle θc as necessary.

[0096] Further, a maximum value Cd of a depth of the recess portion 815a is preferably set within a range of not less than 0.01 times nor more than 0.1 a diameter of the rotor core 811, and preferably set within a range of not less than 0.04 times nor more than 0.07 times the diameter of the rotor core 811. In the following explanation, the maximum value Cd of the depth of the recess portion 815a is referred to as the maximum recess-depth value Cd as necessary.

[0097] Further, a shape of the recess portion 815a is not limited. Fig. 11A exemplifies a case where a planar shape (a shape of the rotor core cross section) of the recess portion 815a is a quadrangle

having a relationship of a line symmetry with a straight line passing through a position at the center of gravity of the recess portion 815a, and the rotation axis line 0 of the rotor core 811 set as a symmetry axis. However, the planar shape of the recess portion 815a may be a shape having no symmetry. Further, the planar shape of the recess portion 815a may be a triangle or a polygon having sides equal to or more than sides of a pentagon. Further, the corner portion of the recess portion 815a may have curvature.

[0098] Next, the second end portions 1112a to 1112b will be explained. The second end portions 1112a to 1112b are end portions positioned on the inner peripheral side in the left-right direction Ds of the magnet holes 817a to 817b. The second end portions 1112a to 1112b coincide with end portions of the inter-magnet flux barriers 814a to 814b, and are closed. That is, the magnet holes 817a to 817b have such shapes as to form spaces serving as flux barriers extending along the rotation axis line 0 between the permanent magnet 812a and the second end portion 1112a and between the permanent magnet 812b and the second end portion 1112b with the permanent magnets 812a to 812b installed therethrough.

[0099] In the example illustrated in Fig. 11A, the second end portions 1112a to 1112b are regions along contours of the magnet holes 817a to 817b from one to the other of the two corner portions 1132a to 1132b

and from one to the other of the two corner portions 1132c to 1132d of the magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed in the rotor core cross section. The corner portions 1132a to 1132b and the corner portions 1132c to 1132d forming the second end portions 1112a to 1112b are defined by the designer of the IPMSM 800 in such a manner that the magnet holes 817a and 817b face each other with the inter-magnet bridge portion 821 interposed therebetween. In the example illustrated in Fig. 11A, the second end portions 1112a to 1112b include positions at both ends of a straight line connecting the respective second end portions 1112a to 1112b of the two magnet holes 817a to 817b facing each other with the inter-magnet bridge portion 821 interposed therebetween at the shortest distance in the rotor core cross section.

[0100] In the example illustrated in Fig. 11A, a region of the soft magnetic material on which stress is most concentrated while the rotor 810 (the rotor core 811) is rotating is included between the second end portions 1112a and 1112b. In the example illustrated in Fig. 11A, the previously-described straight line connecting the second end portions 1112a to 1112b at the shortest distance is a straight line 1141a connecting the corner portions 1132a, 1132c. In the example illustrated in Fig. 11A, the inter-magnet bridge portion 821a is defined as a region of the soft magnetic material surrounded by

the straight line 1141a connecting the two corner portions 1132a, 1132c and a straight line 1141b connecting the two corner portions 1132b, 1132d, for example.

[0101] Note that Fig. 11A exemplifies a case where the entire region between the two magnet holes 817a and 817b is the region of the soft magnetic material. Accordingly, the straight line 1141a connecting the respective second end portions 1112a to 1112b of the two magnet holes 817a to 817b at the shortest distance is the same as a straight line drawn to make a length of an overlap of the respective second end portions 1112a to 1112b with the region of the soft magnetic material shortest. On the other hand, a case where a flux barrier is formed in the region between the two magnet holes 817a and 817b is not necessarily as described above. This is because the straight line connecting the respective second end portions 1112a to 1112b of the two magnet holes 817a to 817b at the shortest distance sometimes overlaps with the flux barrier. As previously described, the region of the soft magnetic material on which stress is most concentrated while the rotor 810 (the rotor core 811) is rotating is included between the second end portions 1112a and 1112b. Further, the second end portions include positions at both ends of the straight line drawn to make the length of the overlap of the respective second end portions 1112a to 1112b with the region of the soft magnetic material

shortest. This manner allows, regardless of whether or not the flux barrier is present in the region between the respective second end portions 1112a and 1112b, the region of the soft magnetic material on which stress is most concentrated while the rotor 810 (the rotor core 811) is rotating to be included between the second end portions 1112a and 1112b.

[0102] Fig. 11B is a view illustrating a first modified example of the configuration of the rotor core 811 (rotor core cross section).

In the example illustrated in Fig. 11B, for example, a region of the soft magnetic material surrounded by a straight line 1141c connecting two corner portions 1132e, 1132h and a straight line 1141d connecting two corner portions 1132g, 1132j is defined as a region of an inter-magnet bridge portion 821i. In this case, second end portions 1112c, 1112d are the regions along contours of magnet holes 817c to 817d from one to the other of the two corner portions 1132e and 1132g and from one to the other of the two corner portions 1132h and 1132j of the magnet holes 817c, 817d through which the permanent magnets 812a, 812b are installed.

[0103] Further, in Fig. 11B, in a different manner from the above, for example, a region of the soft magnetic material surrounded by a straight line 1141c connecting the two corner portions 1132e, 1132h and a straight line 1141e connecting two corner portions 1132f, 1132i may be defined as a region serving as an

inter-magnet bridge portion. In this case, the second end portions 1112c, 1112d are the regions along contours of magnet holes 817 from one to the other of the two corner portions 1132e and 1132f and from one to the other of the two corner portions 1132h and 1132i of the magnet holes 817c, 817d through which the permanent magnets 812a to 812b are installed. Further, the second end portions 1112 may be regions along contours of the magnet holes 817c, 817d from one to the other of the two corner portions 1132f and 1132g and from one to the other of the two corner portions 1132i to 1132j of the magnet holes 817c, 817d through which the permanent magnets 812a, 812b are installed.

[0104] Note that in the example illustrated in Fig. 11B, positions at both ends of a straight line drawn so that a length of an overlap with the soft magnetic material composing the soft magnetic material portion 820 has the shortest distance are positions of the corner portions 1132f, 1132i. Accordingly, the second end portions 1112c to 1112d include the positions of the corner portions 1132f, 1132i.

[0105] The examples illustrated in Fig. 11A and Fig. 11B exemplify a case where the two corner portions 1132 defining the second end portions 1112 each have no curvature in the rotor core cross section. Fig. 11C is a view illustrating a second modified example of the configuration of the rotor core 811 (rotor core cross section). Fig. 11C exemplifies, with

respect to Fig. 11A, a case where the corner portions 1132a to 1132d of the second end portions 1112a to 1112b are changed to corner portions 1132k to 1132n each having curvature.

[0106] When the corner portions 1132k to 1132n each have curvature, positions of the corner portions 1132k to 1132n are each set as a position of a representative point in a region having the curvature. The representative point of the corner portion is selected so that the inter-magnet bridge portion has the largest size, for example. For this manner, in the example illustrated in Fig. 11c, positions of black circles (●) indicating the corner portions 1132k to 1132n are the positions of the representative points of the corner portions 1132k to 1132n. The positions of the representative points of the corner portions 1132k to 1132n defined in this manner are used as the positions of the corner portions 1132k to 1132n. Note that the representative point of the corner portion need not necessarily be selected so that the inter-magnet bridge portion has the largest size. For example, the center position of a region forming the corner portion may be selected as the representative point of the corner portion. In the example illustrated in Fig. 11C, the second end portions 1112e, 1112f are regions along contours of magnet holes 817e, 817f from one to the other of the two corner portions 1132k and 1132l and from one to the other of the two

corner portions 1132m to 1132n of the magnet holes 817e, 817f through which the permanent magnets 812a, 812b are installed. Alternatively, the representative point of the corner portion may be selected so that the inter-magnet bridge portion has the smallest size.

[0107] Note that in the example illustrated in Fig. 11C, positions at both ends of a straight line drawn so that a length of an overlap with the soft magnetic material composing the soft magnetic material portion 820 has the shortest distance are positions at both ends of a straight line 1141h. Accordingly, the second end portions 1112e to 1112f include the positions at both ends of the straight line 1141h.

[0108] Further, when the corner portion of the first end portion 1111 has curvature, a representative point of a region having the curvature only needs to be set as a position of the corner portion of the first end portion 1111. The representative point of the corner portion of the first end portion 1111 is set at a position on the outer peripheral surface 818 of the rotor core 811 so that the first end portion 1111 has the largest size, for example. However, this need not necessarily be adopted. For example, the center position of the region having the curvature may be set as the representative point of the corner portion of the first end portion 1111.

[0109] Back to the explanation of Fig. 11A, the third end portions 1113a to 1113b will be explained.

The third end portions 1113a to 1113b are end portions positioned on the outer peripheral side in the magnetization direction D_m of the permanent magnets 812a to 812b. The outer peripheral side in the magnetization direction D_m of the permanent magnets 812a to 812b is a side close to the outer peripheral surface 818 of the rotor core 811. In the example illustrated in Fig. 11A, the third end portions 1113a, 1113b are regions along contours of the magnet holes 817a, 817b from the corner portions 1131b, 1131c positioned on inner sides, of the two corner portions 1131a to 1131b and the two corner portions 1131c to 1131d defining the first end portions 1111a, 1111b, to the corner portions 1132a, 1132c positioned on the outer peripheral side in the magnetization direction D_m of the permanent magnets 812a, 812b, of the two corner portions 1132a to 1132b and the two corner portions 1132c to 1132d defining the second end portions 1112a, 1112b. The inner side is a side close to the central position in the circumferential direction of the region of one pole of the rotor. In the example illustrated in Fig. 11B, third end portions 1113c, 1113d are regions along contours of the magnet holes 817c, 817d from the corner portions 1131b, 1131c defining the first end portions 1111 to the corner portions 1132e, 1132h defining the second end portions 1112, for example. In the example illustrated in Fig. 11C, third end portions 1113e, 1113f are regions along contours of

the magnet holes 817e, 817f from the corner portions 1131b, 1131c defining the first end portions 1111 to the corner portions 1132k, 1132m defining the second end portions 1112.

[0110] Back to the explanation of Fig. 11A, the fourth end portions 1114a to 1114b will be explained. The fourth end portions 1114a to 1114b are end portions positioned on the inner peripheral side in the magnetization direction D_m of the permanent magnets 812a, 812b. In the example illustrated in Fig. 11A, the fourth end portions 1114a, 1114b are regions along contours of the magnet holes 817a, 817b from the corner portions 1131a, 1131d positioned on outer sides, of the two corner portions 1131a to 1131b and the two corner portions 1131c to 1131d defining the first end portions 1111a, 1111b, to the corner portions 1132b, 1132d positioned on the inner peripheral side in the magnetization direction D_m of the permanent magnets 812a, 812b, of the two corner portions 1132a to 1132b and the two corner portions 1132c to 1132d defining the second end portions 1112a, 1112b. The outer side is a side close to an end in the circumferential direction of the region of one pole of the rotor. In the example illustrated in Fig. 11B, fourth end portions 1114c, 1114d are regions along contours of the magnet holes 817c, 817d from the corner portions 1131a, 1131d defining the first end portions 1011 to the corner portions 1132g, 1132j defining the second end portions 1112c, 1112d,

for example. In the example illustrated in Fig. 11C, fourth end portions 1114e, 1114f are regions along contours of the magnet holes 817e, 817f from the corner portions 1131a, 1131d defining the first end portions 1111 to the corner portions 1132l, 1132n defining the second end portions 1112.

[0111] In Fig. 11A to Fig. 11c, each two of the magnet holes 817a to 817b, 817d to 817e, 817f to 817g through which the permanent magnets 812a to 812b are installed have spaces 1121a to 1121b in which the permanent magnets 812a to 812b are installed.

Further, the magnet holes 817a to 817b, 817d to 817e, 817f to 817g through each two of which the permanent magnets 812a to 812b are installed have spaces 1122a to 1122b, 1122c to 1122d, 1122e to 1122f serving as the inter-magnet flux barriers between the spaces 1121a and 1121b in which the permanent magnets 812a to 812b are installed, and each two of second end portions 1112a to 1112b, 1112c to 1112d, 1112e to 1112f. Further, each two of the magnet holes 817a to 817b, 817d to 817e, 817f to 817g through which the permanent magnets 812a to 812b are installed have spaces 1123a to 1123b, 1123c to 1123d, 1123e to 1123f, each serving as the outer-peripheral-side flux barriers 813a to 813b illustrated in Fig. 8 between the spaces 1121a and 1121b in which the permanent magnets are installed and the first end portions 1111a to 1111b.

[0112] In the following explanation, the spaces

1121a to 1121b in which the permanent magnets 812a to 812b are installed, the spaces 1122a to 1122b, 1122c to 1122d, 1122e to 1122f serving as the inter-magnet flux barriers, and the spaces 1123a to 1123b, 1123c to 1123d, 1123e to 1123f serving as the outer-peripheral-side flux barriers are respectively referred to as the magnet installation spaces 1121a to 1122b, the inter-magnet flux barrier spaces 1122a to 1122b, 1122c to 1122d, 1122e to 1122f, and the outer-peripheral-side flux barrier spaces 1123a to 1123b, 1123c to 1123d, 1123e to 1123f as necessary. The magnet installation spaces 1121a to 1122b, the inter-magnet flux barrier spaces 1122a to 1122b, 1122c to 1122d, 1122e to 1122f, and the outer-peripheral-side flux barrier spaces 1123a to 1123b, 1123c to 1123d, 1123e to 1123f will be explained.

[0113] In the front-side magnet hole 817a, the outer-peripheral-side flux barrier space 1123a is one example of the space serving as a front-side flux barrier. In the rear-side magnet hole 817b, the outer-peripheral-side flux barrier space 1123b is one example of the space serving as a rear-side flux barrier. Further, in the front-side magnet hole 817a, the inter-magnet flux barrier space 1122a is one example of the space serving as a rear-side flux barrier. In the rear-side magnet hole 817b, the inter-magnet flux barrier space 1122b is one example of the space serving as a front-side flux barrier. That is, in the front-side magnet hole 817a and the

rear-side magnet hole 817b, the spaces serving as the front-side flux barriers (the outer-peripheral-side flux barrier space 1123a, the inter-magnet flux barrier space 1122b) are positioned on the front side in the rotation direction further than the spaces serving as the rear-side flux barriers (the inter-magnet flux barrier space 1122a, the outer-peripheral-side flux barrier space 1123b).

[0114] More specifically, the outer-peripheral-side flux barrier space 1123a included in the front-side magnet hole 817a is on the front side in the rotation direction further than the inter-magnet flux barrier space 1122a included in the front-side magnet hole 817a, and on the outer peripheral side of the rotor core 811 further than the inter-magnet flux barrier space 1122a included in the front-side magnet hole 817a. Further, the outer-peripheral-side flux barrier space 1123b included in the rear-side magnet hole 817b is on the rear side in the rotation direction further than the inter-magnet flux barrier space 1122b included in the rear-side magnet hole 817b, and on the outer peripheral side of the rotor core 811 further than the inter-magnet flux barrier space 1122b included in the rear-side magnet hole 817b. Further, the outer-peripheral-side flux barrier space 1123a included in the front-side magnet hole 817a and the outer-peripheral-side flux barrier space 1123b included in the rear-side magnet hole 817b have the first end portions 1111a to 1111b which

are the open end portions. Both of the outer-peripheral-side flux barrier spaces 1123a, 1123b preferably have the open end portions (the first end portions 1111a to 1111b) in this manner. However, only one of the outer-peripheral-side flux barrier spaces 1123a, 1123b may have the open end portion (the first end portion 1111).

[0115] In the rotor core cross sections illustrated in Fig. 11A to Fig. 11C, the length L2, in a width direction which is a direction along the magnetization direction D_m of the permanent magnets 812a to 812b, of the magnet installation spaces 1121a to 1121b, is equal to a length corresponding to a length in the magnetization direction D_m of the permanent magnets 812a to 812b and almost fixed. The length L2 in the width direction of the magnet installation spaces 1121a to 1121b may be the same as the length in the magnetization direction D_m of the permanent magnets 812a to 812b, or may be (slightly) longer than the length in the magnetization direction D_m of the permanent magnets 812a to 812b for easy installation of the permanent magnets 812a to 812b through the magnet holes 817a to 817b. Note that this embodiment exemplifies a case where the length in the magnetization direction D_m of the permanent magnets 812a to 812b is fixed. However, the length in the magnetization direction D_m of the permanent magnets 812a to 812b need not necessarily be fixed. When the length in the magnetization direction D_m of

the permanent magnets 812a to 812b is not fixed, the length in the width direction of the magnet installation spaces 1121a to 1121b may be equal to the length corresponding to the length in the magnetization direction D_m of the permanent magnets 812a to 812b. In this case, the length in the width direction of the magnet installation spaces 1121a to 1121b is not fixed.

[0116] When the permanent magnets 812a to 812b are installed, at least a part of the region of the magnet installation spaces 1121a to 1121b is occupied by the permanent magnets 812a to 812b, thereby serving as no space. The inter-magnet flux barrier spaces 1122a to 1122b correspond to the inter-magnet flux barriers 814a to 814b illustrated in Fig. 8, and remain spaces even though the permanent magnets 812a to 812b are installed. The outer-peripheral-side flux barrier spaces 1123a to 1123b correspond to the outer-peripheral-side flux barriers 813a to 813b illustrated in Fig. 9, and remain spaces even though the permanent magnets 812a to 812b are installed.

Note that when a nonmagnetic material is installed in the inter-magnet flux barrier spaces 1122a to 1122f and the outer-peripheral-side flux barrier spaces 1123a to 1123f, at least a part of a region of the inter-magnet flux barrier spaces 1122a to 1122f and the outer-peripheral-side flux barrier spaces 1123a to 1123f is occupied by the nonmagnetic material.

[0117] Next, one example of a configuration of the

soft magnetic material portion 820 will be explained while referring to Fig. 10 and Fig. 11A to Fig. 11C. Note that here, Fig. 11B exemplifies a case where the corner portions 1132e, 1132g are two corner portions of the second end portion 1112c, and the corner portions 1132h, 1132j are two corner portions of the second end portion 1112d.

[0118] In Fig. 10, the soft magnetic material portion 820 has the inter-magnet bridge portions 821a to 821h, the outer side portions 822a to 822h, and an inner side portion 823a.

[0119] The inter-magnet bridge portions 821a to 821h are each a region where the soft magnetic material is present in a bridge outer edge portion. In the example illustrated in Fig. 10 and Fig. 11A, the bridge outer edge portion is a region surrounded by the straight line connecting the corner portions 1132a, 1132c on the outer peripheral side of the second end portions 1112a to 1112b of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed in the same pole (refer to a two-dot chain line connecting the ends on the outer peripheral side of the second end portions 1112a to 1112b in Fig. 10), the straight line connecting the corner portions 1132b, 1132d on the inner peripheral side of the second end portions 1112a to 1112b of the two magnet holes 817a to 817b (refer to a two-dot chain line connecting the ends on the inner peripheral side of the second end portions

1112a to 1112b in Fig. 10), and the second end portions 1112a to 1112b of the two magnet holes 817a to 817b. In Fig. 10, this embodiment exemplifies a case where only the soft magnetic material is present in the bridge outer edge portion 831a. The presence of only the soft magnetic material means that a region except for the soft magnetic material, such as the flux barrier, is not included. Accordingly, in this embodiment, the inter-magnet bridge portion 821a coincides with the bridge outer edge portion 831a. Note that in Fig. 10 and Fig. 11A, the bridge outer edge portion 831a corresponds to the region between the second end portions 1112a and 1112b of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed in the same pole. Further, the region between the second end portions 1112a and 1112b of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed in the same pole may include the region except for the soft magnetic material, such as the flux barrier. In this case, the inter-magnet bridge portion 821a is a region eliminating the region except for the soft magnetic material from the bridge outer edge portion 831a. Further, the number of the inter-magnet bridge portions 821a to 821h is equal to the number of poles of the rotor 810 (eight in this embodiment).

[0120] Specifically in the example illustrated in Fig. 11A, the bridge outer edge portion 831a is a

region surrounded by the straight line 1141a connecting the corner portions 1132a, 1132c on the outer peripheral side of the second end portions 1112a to 1112b of the magnet holes 817a to 817b, the straight line 1141b connecting the corner portions 1132d, 1132d on the inner peripheral side of the second end portions 1112a to 1112b of the two magnet holes 817a to 817b, and the second end portions 1112a to 1112b of the two magnet holes 817a to 817b. The inter-magnet bridge portion 821a coincides with the bridge outer edge portion 831a. Fig. 10 and Fig. 11A illustrate the reference signs 821a and 831a side by side, which means this.

[0121] Further, in the examples illustrated in Fig. 11B and Fig. 11C, the bridge outer edge portions are defined as follows.

In the example illustrated in Fig. 11B, the bridge outer edge portion 831b is a region surrounded by the straight line 1141c connecting the corner portions 1132e, 1132h on the outer peripheral side of the second end portions 1112c to 1112d of the magnet holes 817a to 817b, the straight line 1141d connecting the corner portions 1132g, 1132j on the inner peripheral side of the second end portions 1112c to 1112d of the two magnet holes 817a to 817b, and the second end portions 1112c to 1112d of the two magnet holes 817a to 817b. The inter-magnet bridge portion 821i coincides with the bridge outer edge portion 831b. Fig. 11B illustrates the reference

signs 821i and 831b side by side, which means this.

[0122] In the example illustrated in Fig. 11C, the bridge outer edge portion 831c is a region surrounded by the straight line 1141f connecting the corner portions 1132k, 1132m on the outer peripheral side of the second end portions 1112e to 1112f of the magnet holes 817a to 817b, the straight line 1141g connecting the corner portions 1132l, 1132n on the inner peripheral side of the second end portions 1112e to 1112f of the two magnet holes 817a to 817b, and the second end portions 1112e to 1112f of the two magnet holes 817a to 817b. The inter-magnet bridge portion 821j coincides with the bridge outer edge portion 831c. Fig. 11C illustrates the reference signs 821j and 831c side by side, which means this.

[0123] The outer side portion 822a is a region where the soft magnetic material is present in an outer-side outer edge portion. The outer-side outer edge portion is a region coupled to the inter-magnet bridge portion 821 on the outer peripheral side of the inter-magnet bridge portion 821a. In the examples illustrated in Fig. 10 and Fig. 11A, the outer-side outer edge portion is a region surrounded by the third end portions 1113a to 1113b of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed and the outer peripheral surface 818 of the rotor core 811. In Fig. 9, this embodiment exemplifies a case where only the soft magnetic material is present in the outer-side

outer edge portion 832a (the region except for the soft magnetic material, such as the flux barrier, is not included). Accordingly, the outer side portion 822a coincides with the outer-side outer edge portion 832a. However, the outer-side outer edge portion 832a may include the region except for the soft magnetic material, such as the flux barrier. In this case, the outer side portion 822a is a region eliminating the region except for the soft magnetic material from the outer-side outer edge portion 832a. Further, the number of the outer side portions 822a to 822h is equal to the number of poles of the rotor 810 (eight in this embodiment).

[0124] Specifically in the example illustrated in Fig. 11A, the outer-side outer edge portion 832a is a region surrounded by the straight line 1141a connecting the corner portions 1132a, 1132c on the outer peripheral side of the second end portions 1112a to 1112b of the magnet holes 817a to 817b, the third end portions 1113a to 1113b of the two magnet holes 817a to 817b, and the outer peripheral surface 818 of the rotor core 811. The outer side portion 822a coincides with the outer-side outer edge portion 832a. Fig. 10 and Fig. 11A illustrate the reference signs 822a and 832a side by side, which means this.

[0125] Further, in the examples illustrated in Fig. 11B and Fig. 11C, the outer-side outer edge portions are defined as follows.

In the example illustrated in Fig. 11B, the

outer-side outer edge portion 832b is a region surrounded by the straight line 1141c connecting the corner portions 1132e, 1132h on the outer peripheral side of the second end portions 1112c to 1112d of the magnet holes 817a to 817b, the third end portions 1113c to 1113d of the two magnet holes 817c to 817d, and the outer peripheral surface 818 of the rotor core 811. The outer side portion 822i coincides with the outer-side outer edge portion 832b. Fig. 11B illustrates the reference signs 822i and 832b side by side, which means this.

[0126] In the example illustrated in Fig. 11C, the outer-side outer edge portion 832c is a region surrounded by the straight line 1141f connecting the corner portions 1132k, 1132m on the outer peripheral side of the second end portions 1112e to 1112f of the magnet holes 817a to 817b, the third end portions 1113e to 1113f of the two magnet holes 817e to 817f, and the outer peripheral surface 818 of the rotor core 811. The outer side portion 822j coincides with the outer-side outer edge portion 832c. Fig. 11C illustrates the reference signs 822j and 832c side by side, which means this.

[0127] The inner side portion 823a is a region where the soft magnetic material is present in an inner-side outer edge portion. The inner-side outer edge portion is a region of the soft magnetic material coupled to the inter-magnet bridge portion 821a on the inner peripheral side of the inter-magnet bridge

portion 821a. In the examples illustrated in Fig. 10 and Fig. 11A, the inner-side outer edge portion is a region surrounded by the fourth end portions 1114a to 1114b of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed, the outer peripheral surface 818 of the rotor core 811, and the inner peripheral surface 819 of the rotor core 811. In Fig. 9, this embodiment exemplifies a case where only the soft magnetic material is present in the inner-side outer edge portion 833a. The presence of only the soft magnetic material means that the region except for the soft magnetic material, such as the flux barrier, is not included. Accordingly, the inner side portion 823a coincides with the inner-side outer edge portion 833a. However, the inner-side outer edge portion 833a may include the region except for the soft magnetic material, such as the flux barrier. In this case, the inner side portion 823a is a region eliminating the region except for the soft magnetic material from the inner-side outer edge portion 833a. Further, in the example illustrated in Fig. 9, the inner side portion 823a is one in number. Note that the inner side portion 823a need not necessarily be surrounded by the outer peripheral surface 818 of the rotor core 811. For example, when the rotor core 811 is formed in such a manner that the soft magnetic material is absent between the outer-peripheral-side flux barriers 813a (outer-peripheral-side flux barrier

spaces 1123a) of the poles adjacent to each other, the inner side portion 823a is not surrounded by the outer peripheral surface 818 of the rotor core 811.

[0128] Specifically in the example illustrated in Fig. 11A, the inner-side outer edge portion 833a is a region surrounded by the straight line 1141b connecting the corner portions 1132b, 1132d on the inner peripheral side of the second end portions 1112a to 1112b of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed, the fourth end portions 1114a to 1114b of the two magnet holes 817a to 817b, the outer peripheral surface 818 of the rotor core 811, and the inner peripheral surface 819 of the rotor core 811. The inner side portion 823a coincides with the inner-side outer edge portion 833a. Fig. 10 and 11A illustrate the reference signs 823a and 833a side by side, which means this.

[0129] Further, in the examples illustrated in Fig. 11B and Fig. 11C, the inner-side outer edge portions are defined as follows.

In the example illustrated in Fig. 11B, an inner-side outer edge portion 833b is a region surrounded by the straight line 1141c connecting the corner portions 1132e, 1132h on the inner peripheral side of the second end portions 1112c to 1112d of the two magnet holes 817c to 817d through which the permanent magnets 812a to 812b are installed, the fourth end portions 1114c to 1114d of the two magnet holes 817c

to 817d, the outer peripheral surface 818 of the rotor core 811, and the inner peripheral surface 819 of the rotor core 811. An inner side portion 823b coincides with the inner-side outer edge portion 833b. Fig. 11B illustrates the reference signs 823b and 833b side by side, which means this.

[0130] In the example illustrated in Fig. 11C, an inner-side outer edge portion 833c is a region surrounded by the straight line 1141g connecting the corner portions 1132l, 1132n on the inner peripheral side of the second end portions 1112e to 1112f of the two magnet holes 817e to 817f through which the permanent magnets 812a to 812b are installed, the fourth end portions 1114e to 1114f of the two magnet holes 817e to 817f, the outer peripheral surface 818 of the rotor core 811, and the inner peripheral surface 819 of the rotor core 811. An inner side portion 823c coincides with the inner-side outer edge portion 833c. Fig. 11C illustrates the reference signs 823c and 833c side by side, which means this.

[0131] Next, widths w of the inter-magnet bridge portions 821a will be explained. The widths w of the inter-magnet bridge portions 821a are indicated by lengths, of portions overlapping with the soft magnetic material, of bridge-width specified lines 1142a to 1142c in the rotor core cross section. As illustrated in Fig. 11A to Fig. 11C, the bridge-width specified lines 1142a to 1142c are each a straight line connecting each two of the second end portions

1112a to 1112b, 1112c to 1112d, 1112e to 1112f of the magnet holes 817a to 817b, 817c to 817d, 817e to 817f, through each two of which the permanent magnets 812a to 812b are installed, in such a manner as to make the length of the overlap with the soft magnetic material shortest.

[0132] Specifically in the example illustrated in Fig. 11A, the straight line connecting the second end portions 1112a to 1112b of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed in such a manner as to make the length of the overlap with the soft magnetic material shortest is the straight line 1142a, and coincides with the previously-described straight line 1141a. Fig. 11A illustrates the reference signs 1141a and 1142a side by side, which means this. In this case, the width w of the inter-magnet bridge portion 821a is the length, of the portion overlapping with the soft magnetic material, of the bridge-width specified line 1142a, in the rotor core cross section. In the example illustrated in Fig. 11A, the entire bridge-width specified line 1142a overlaps with the soft magnetic substance material. Accordingly, the width w of the inter-magnet bridge portion 821a is equal to the length of the bridge-width specified line 1142a. A hole is formed through the inter-magnet bridge portion, and thus when a part of the bridge-width specified line overlaps with the soft magnetic material, the width w of the inter-magnet bridge

portion is a length, of the portion overlapping with the soft magnetic material, of the bridge-width specified line. Note that the length, of the portion overlapping with the soft magnetic material, of the bridge-width specified line is a length obtained by subtracting a length, of the portion not overlapping with the soft magnetic material, of the bridge-width specified line from the length of the bridge-width specified line.

[0133] In the example illustrated in Fig. 11B, the straight line connecting the second end portions 1112c to 1112d of the two magnet holes 817c to 817d through which the permanent magnets 812a to 812b are installed in such a manner as to make the length of the overlap with the soft magnetic material shortest is the straight line 1142b, and coincides with the previously-described straight line 1141e. Fig. 11B illustrates the reference signs 1141e and 1142b side by side, which means this. Accordingly, the bridge-width specified line is the straight line 1142b. In this case, the width w of the inter-magnet bridge portion 821i is the length, of the portion overlapping with the soft magnetic material, of the bridge-width specified line 1142b in the rotor core cross section. Also in the example illustrated in Fig. 11B, the entire bridge-width specified line 1142b overlaps with the soft magnetic substance material. Accordingly, the width w of the inter-magnet bridge portion 821i is equal to the length of

the bridge-width specified line 1142b.

[0134] In the example illustrated in Fig. 11C, the straight line connecting the second end portions 1112e to 1112f of the two magnet holes 817e to 817f through which the permanent magnets 812a to 812b are installed in such a manner as to make the length of the overlap with the soft magnetic material shortest is the straight line 1142c, and coincides with the previously-described straight line 1141f. Fig. 11C illustrates the reference signs 1141f and 1142c side by side, which means this. Accordingly, the bridge-width specified line is the straight line 1142c. In this case, the width w of the inter-magnet bridge portion 821j is the length, of the portion overlapping with the soft magnetic material, of the bridge-width specified line 1142c, in the rotor core cross section. Also in the example illustrated in Fig. 11C, the entire bridge-width specified line 1142c overlaps with the soft magnetic substance material. Accordingly, the width w of the inter-magnet bridge portion 821j is equal to the length of the bridge-width specified line 1142c.

[0135] The widths w of the inter-magnet bridge portions 821 defined in such a manner as described above are each preferably 0.02 times or less the diameter of the rotor core 811. When the widths w of the inter-magnet bridge portions 821 each exceed 0.02 times the diameter of the rotor core 811, an increase in a magnetic flux passing through the inter-magnet

bridge portions 821 increases a reflux magnetic flux included in the magnetic flux passing through the inter-magnet bridge portions 821. Consequently, the effect of the increase in torque of the rotor 810 caused by the magnetic fluxes becoming no reflux magnetic flux (refer to the magnetic fluxes ϕ_{13} , ϕ_{14} illustrated in Fig. 5B) decreases.

[0136] Further, the widths w of the inter-magnet bridge portions 821 each preferably exceed a length $w_{\min}$ defined by the following formula (1).

$$w_{\min} = \rho \times S \times r_g \times \omega \div Y_s \dots (1)$$

Here, ρ is a density (kg/m^3) of the soft magnetic material composing the soft magnetic material portion 820. ρ is defined in advance by specifications of the IPMSM 800, for example. Y_s is a yield stress (Pa) at room temperature of the soft magnetic material composing the soft magnetic material portion 820.

[0137] The yield stress (Y_s) is defined in advance by specifications of the soft magnetic material, for example. The yield stress (Y_s) may be a measured value. When the measured value is used as the yield stress (Y_s), the value may be measured as follows, for example. First, a JIS No.5 test piece is picked as a tensile test piece from a central portion in a sheet thickness direction of the soft magnetic material. Then, the yield stress (Y_s) is measured by performing a tensile test on the tensile test piece based on the description of JIS·Z·2241: 2011. At

this time, a rolling direction of the tensile test piece is set as a tensile direction. In detail, when an upper yield point and a lower yield point described in JIS·Z·2241: 2011 are measured by the tensile test, the yield stress (Y_s) may be set as the upper yield point. On the other hand, in a case of a material in which a yield phenomenon does not clearly occur by the tensile test, the yield stress (Y_s) may be set as the 0.2% proof stress measured by the offset method described in JIS·Z·2241: 2011.

[0138] S is an area (m^2) in the rotor core cross section of each of external force influence portions 824 to be described later (refer to 824a to 824c illustrated in Fig. 11A to Fig. 11C). r_g is a distance (m) in the radial direction from the center of rotation (the rotation axis line 0) of the rotor 810 (the rotor core 811) to a position of a center of gravity G in the rotor core cross section of each of the external force influence portions 824 (refer to a straight line 1178 connecting the center of gravity G in the rotor core cross section of each of the external force influence portions 824 and the rotation axis line 0 in Fig. 11A to Fig. 11C). The position of the center of gravity G is defined based on a definition of the center of gravity as a point at which a resultant force of gravity acting on portions of the external force influence portion 824 is exerted. Incidentally, for the convenience of explanation and notation, Fig. 11A to Fig. 11C

illustrate the general positions of the center of gravity G of the external force influence portions 824a to 824c. ω is an angular speed (rad/sec) of the rotor 810 at the time of rotation at a maximum rotation speed. The maximum rotation speed of the rotor 810 is an upper limit value of a rotation speed of the rotor 810 allowable in the IPMSM 800, and is defined in advance by the specifications of the IPMSM 800.

When the widths w of the inter-magnet bridge portions 821 are too large, the torque decreases, and thus the widths w are each preferably set to 3.0 times or less the length $w_{\min}$ defined by the formula (1).

[0139] Here, the external force influence portion 824 is a region of the soft magnetic material surrounded by the third end portions 1113 of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed in the same pole, the outer peripheral surface 818 of the rotor core 811 (the soft magnetic material portion 820), and the bridge-width specified line 1142.

In the example illustrated in Fig. 11A, the external force influence portion 824a is the region of the soft magnetic material surrounded by the third end portions 1113a to 1113b of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed, the outer peripheral surface 818 of the rotor core 811, and the bridge-width

specified line 1142a.

[0140] In the example illustrated in Fig. 11B, the external force influence portion 824b is a region of the soft magnetic material surrounded by the third end portions 1113c to 1113d of the two magnet holes 817c to 817d through which the permanent magnets 812a to 812b are installed, the outer peripheral surface 818 of the rotor core 811, and the bridge-width specified line 1142b.

[0141] In the example illustrated in Fig. 11C, the external force influence portion 824c is a region of the soft magnetic material surrounded by the third end portions 1113e to 1113f of the two magnet holes 817e to 817f through which the permanent magnets 812a to 812b are installed, the outer peripheral surface 818 of the rotor core 811, and the bridge-width specified line 1142c.

Note that the number of the external force influence portions 824 included in the one rotor 810 is equal to the number of poles of the rotor 810 (eight in this embodiment). S in the formula (1) is not the total value of the areas in the rotor core cross section of the eight external force influence portions 824, but the area in the rotor core cross section of the one external force influence portion 824.

[0142] In the rotor core 811, the regions each of on which stress is most concentrated while the rotor 810 (the rotor core 811) is rotating are regions of the

soft magnetic material in the positions overlapping with the bridge-width specified lines 1142a to 1142c. In the following explanation, the regions are each referred to as a stress concentration region as necessary. When the widths w of the inter-magnet bridge portions 821 are each equal to $w_{\min}$ in the formula (1), the stress produced in the stress concentration regions while the rotor 810 (the rotor core 811) is rotating at the maximum rotation speed are each (theoretically) equal to the yield stress of the soft magnetic material. Consequently, to suppress a fracture of the stress concentration regions while the rotor 810 (the rotor core 811) is rotating at the maximum rotation speed, the widths w of the inter-magnet bridge portions 821 each preferably exceed $w_{\min}$ in the formula (1).

[0143] (Calculation example)

Next, a calculation example will be explained. In this calculation example, a calculation was made by performing the electromagnetic field analysis based on a finite element method on a magnetic flux density vector, an eddy current vector, and torque in a minute region (mesh) of each of rotor cores when the IPMSM in which the two permanent magnets were disposed in a V-shape per one pole as illustrated in Fig. 8 was operated (rotated) in accordance with electromagnetic field analysis conditions including excitation conditions. Note that the torque was set to be Maxwell stress. Further, a stress vector in

the minute region (mesh) of each of the rotor cores when the IPMSM was operated (rotated) in accordance with stress analysis conditions including physical property values of a Young's modulus, a Poisson's ratio, and the like was calculated by performing stress analysis based on the finite element method. The methods of the electromagnetic field analysis and the stress analysis based on the finite element method are general methods, and thus the detailed explanation thereof is omitted here. Note that in each calculation example, conditions except for the flux barrier and the recess portion of the rotor core are the same conditions including the electromagnetic field analysis conditions. In this calculation example, as the electromagnetic field analysis conditions, a residual magnetic flux density of the permanent magnet was set to 0.4 T. Further, an exciting current flowing through the stator coil was set as a three-phase alternating current whose peak value is 20 A and frequency is 50 Hz. Further, a lead angle was set to 30°. In addition, any of diameters of the rotor cores is 27 mm. Further, the number of slots of the stator core are 24.

[0144] First, as explained in the section of ((First finding)) in the section of (Circumstances), Table 1 presents the result of examining the effect of setting positions of the open-end front-side corner portions 1131a, 1131c on the rear side in the rotation direction of the rotor core 111 further than

the reference positions 831a, 831b in the rotor core cross section.

[0145] [Table 1]

[TABLE 1]

NUMBER	θ_f	θ_b	RECESS PORTION	INCREASE AND DECREASE IN TORQUE	REMARKS
1	REFERENCE POSITION	REFERENCE POSITION	ABSENCE	$\pm 0\%$	—
2	0.625°	REFERENCE POSITION	ABSENCE	$+3.6\%$	INVENTION EXAMPLE
3	1.25°	REFERENCE POSITION	ABSENCE	$+5.6\%$	INVENTION EXAMPLE
4	1.875°	REFERENCE POSITION	ABSENCE	$+8.3\%$	INVENTION EXAMPLE
5	2.5°	REFERENCE POSITION	ABSENCE	$+9.4\%$	INVENTION EXAMPLE
6	3.125°	REFERENCE POSITION	ABSENCE	$+10.4\%$	INVENTION EXAMPLE
7	3.75°	REFERENCE POSITION	ABSENCE	$+12.7\%$	INVENTION EXAMPLE
8	4.325°	REFERENCE POSITION	ABSENCE	$+13.6\%$	INVENTION EXAMPLE
9	5.0°	REFERENCE POSITION	ABSENCE	$+13.7\%$	INVENTION EXAMPLE
10	5.625°	REFERENCE POSITION	ABSENCE	$+13.2\%$	INVENTION EXAMPLE
11	6.25°	REFERENCE POSITION	ABSENCE	$+12.8\%$	INVENTION EXAMPLE
12	6.875°	REFERENCE POSITION	ABSENCE	$+11.4\%$	INVENTION EXAMPLE
13	7.5°	REFERENCE POSITION	ABSENCE	$+9.8\%$	INVENTION EXAMPLE
14	8.125°	REFERENCE POSITION	ABSENCE	$+8.3\%$	INVENTION EXAMPLE
15	8.75°	REFERENCE POSITION	ABSENCE	$+6.2\%$	INVENTION EXAMPLE
16	9.375°	REFERENCE POSITION	ABSENCE	$+2.0\%$	INVENTION EXAMPLE
17	10°	REFERENCE POSITION	ABSENCE	-3.4%	COMPARATIVE EXAMPLE
18	REFERENCE POSITION	0.625°	ABSENCE	$+1.3\%$	INVENTION EXAMPLE
19	REFERENCE POSITION	1.25°	ABSENCE	$+5.6\%$	INVENTION EXAMPLE
20	REFERENCE POSITION	1.875°	ABSENCE	$+1.5\%$	INVENTION EXAMPLE
21	REFERENCE POSITION	2.5°	ABSENCE	$+0.3\%$	COMPARATIVE EXAMPLE
22	REFERENCE POSITION	3.125°	ABSENCE	-0.6%	COMPARATIVE EXAMPLE
23	5.0°	1.25°	ABSENCE	$+15.4\%$	INVENTION EXAMPLE
24	5.0°	1.25°	PRESENCE	$+16.5\%$	INVENTION EXAMPLE

[0146] Table 1 presents, in a section of θ_f , the movement angle θ_f ($^\circ$) of the outer-peripheral-side

flux barrier on the front side illustrated in Fig. 11A. Further, Table 1 presents, in a section of θ_b , the movement angle θ_b ($^\circ$) of the outer-peripheral-side flux barrier on the rear side illustrated in Fig. 11A. Further, in Table 1, the reference position indicates that the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side are each 0° . Further, Table 1 presents the presence/absence of the recess portion in a section of the recess portion.

[0147] As defined in this embodiment, the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side are each an angle formed by the two straight lines (for example, the straight lines 1171, 1172), and thus take on values of 0 or more. Note that for example, the polar coordinate system is defined in such a manner that the positive direction of the argument θ is the same direction as the rotation direction of the rotor, and the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side are indicated in the polar coordinate system. In this case, the movement angles θ_f , θ_b are each a negative value, which indicates positioning on the negative direction side relative to the reference position

(the rear side in the rotation direction). A case of the recess opening angle θ_c is also the same as the above.

[0148] A section of increase and decrease in torque presents values each expressing, as a percentage, an increase and an decrease relative to the torque of the rotor when the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side are each 0° . Accordingly, a larger value in the section of the increase and decrease in torque indicates a larger torque of the rotor than the torque of the rotor when the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side are each 0° .

[0149] Fig. 12A, Fig. 12B are views illustrating configurations of rotors (rotor cross sections) targeted for being analyzed in the numbers 9, 19 in Table 1, respectively. Fig. 12C, Fig. 12D are views illustrating configurations of rotors (rotor cross sections) targeted for being analyzed in the numbers 23, 24 in Table 1, respectively. Fig. 12A to Fig. 12D also each illustrate one region of four regions obtained by dividing the cross section cut perpendicularly to the rotation axis line 0 of the IPMSM into quarters (a region forming two poles of the rotor in the region of the IPMSM) similarly to

Fig. 1. Note that the electromagnetic field analysis of only this one region results in the electromagnetic field analysis of the entire rotor cross section by using the rotational symmetry of the IPMSM. Further, as previously described, also in Fig. 12A to Fig. 12D, similarly to Fig. 1 or the like, reference signs are given to only a section forming one pole of the rotor, and reference signs in a section forming the other poles of the rotor are omitted.

[0150] In Fig. 12A to Fig. 12D, as explained in this embodiment, the outer-peripheral-side flux barriers 1201a to 1201e reach the outer peripheral surfaces 1211a to 1211d of the rotor cores to be open in the rotor core cross sections. Further, inter-magnet flux barriers 1202a to 1202b are not coupled, and the soft magnetic material (inter-magnet bridge portion) is present between the inter-magnet flux barriers 1202a and 1202b.

[0151] In this calculation example as previously described, the number of slots N_{s10t} in the stator core is 24. Accordingly, the reference-position movement angle θ_a is $\pi/12$ rad = 15° (θ_a (rad) = $2\pi/N_{s10t}$). As explained in this embodiment, the movement angle θ_f of the outer-peripheral-side flux barrier on the front side is preferably set to not less than $\theta_a/24$ nor more than $15\theta_a/24$, and more preferably set within the range of $\theta_a/3 \pm \theta_a/24$. In this calculation example, the movement angle θ_f of the outer-

peripheral-side flux barrier on the front side is preferably set to not less than 0.625° nor more than 9.375° , and more preferably set within a range of $5 \pm 0.625^\circ$.

[0152] In Table 1, the numbers 2 to 16 in each of which the movement angle θ_f of the outer-peripheral-side flux barrier on the front side is not less than 0.625° nor more than 9.375° demonstrate that indicating positive values as the increase and decrease in torque allows the improvement in the torque of the rotors. Further, the numbers 8 to 10 in each of which the movement angle θ_f of the outer-peripheral-side flux barrier on the front side is within the range of $5 \pm 0.625^\circ$ demonstrate that the torque of the rotors can be further improved. In particular, the number 9 in which the movement angle θ_f of the outer-peripheral-side flux barrier on the front side is 5° of the center value within the range of $5 \pm 0.625^\circ$ indicates the maximum value as the value of the increase and decrease in torque. On the other hand, the number 17 in which the movement angle θ_f of the outer-peripheral-side flux barrier on the front side exceeds 9.375° demonstrates that indicating a negative value as the increase and decrease in torque fails to improve the torque of the rotor.

[0153] Further, the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side is preferably set to not less than $\theta_a/24$ nor more than

$\theta_a/8$, and preferably set within the range of $\theta_a/12 \pm \theta_a/24$. In this calculation example, the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side is preferably set to not less than 0.625° nor more than 1.875° , and preferably set within a range of $1.25 \pm 0.625^\circ$.

[0154] In Table 1, the numbers 18 to 21 in each of which the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side is not less than 0.625° nor more than 1.875° demonstrate that indicating positive values as the increase and decrease in torque allows the improvement in the torque of the rotors. Further, the numbers 18 to 20 in each of which the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side is within the range of $1.25 \pm 0.625^\circ$ demonstrate that the torque of the rotors can be further improved. In particular, the number 19 in which the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side is 1.25° of the center value within the range of $1.25 \pm 0.625^\circ$ indicates the maximum value as the value of the increase and decrease in torque. On the other hand, the numbers 21, 22 in each of which the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side exceeds 1.875° demonstrate that indicating approximately 0 or a negative value as the increase and decrease in torque fails to improve the torque of the rotors.

[0155] The above results of the numbers 2 to 22 in

Table 1 reveal that even though only one or the other of the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the flux barrier on the rear side is in the ranges explained in this embodiment, the torque of the rotors can be improved.

[0156] However, in Table 1, the number 23 in which both the movement angle θ_f of the outer-peripheral-side flux barrier on the front side defined as indicated in the number 9 and the movement angle θ_b of the flux barrier on the rear side as indicated in the number 19 are set within the ranges defined in this embodiment demonstrates that a value of the increase and decrease in torque is larger than those in the numbers 2 to 16, 18 to 20, which allows further improvement in the torque of the rotor.

[0157] Further, as explained in this embodiment, the recess opening angle θ_c is preferably set to not less than $\theta_a/8$ nor more than $25\theta_a/24\theta_a$, and more preferably set within the range of $3\theta_a/4 \pm \theta_a/12$. In this calculation example, the reference-position movement angle θ_a is $2\pi/24$ (rad) = $15(^{\circ})$.

Accordingly, the recess opening angle θ_c is preferably set to not less than 1.975° nor more than 15.625° , and preferably set within a range of $11.25^{\circ} \pm 1.25^{\circ}$. Further, the maximum recess-depth value C_d is preferably set within the range of not less than 0.01 times nor more than 0.1 the diameter of the rotor core. In this calculation example as

previously described, any of the diameters of the rotor cores is 27 mm. The number 24 presented in Table 1 is the same as the number 27 in Table 2 to be described later. The recess opening angle θ_c of a recess portion 1242a illustrated in Fig. 12D is 3.125° . Further, the maximum recess-depth value C_d of the recess portion 1242a illustrated in Fig. 12D is 0.05 times the diameter of the rotor core.

[0158] In Table 1, the number 24 indicates the result under the same conditions as those in the number 23 except to provide the above recess portion 1242a. A comparison between the numbers 23 and 24 demonstrates that providing the recess portion 1242a having the recess opening angle θ_c and the maximum recess-depth value C_d in the ranges explained in this embodiment allows further improvement in the torque of the rotor.

[0159] Next, as explained in the section of ((Second finding)) in the section of (Circumstances), Table 2 presents the result of examining the effect of providing the recess portion 815a in the position facing the teeth 123a, 123b with a higher magnetic flux density than the lowest magnetic flux density in the region of the outer peripheral surface 818 of the rotor core 811.

[0160] [Table 2]

[TABLE 2]

NUMBER	θf	θb	θc	Cd [mm]	INCREASE AND DECREASE IN TORQUE	REMARKS
23	5.0°	1.25°	0	0	+15.4%	INVENTION EXAMPLE
25	5.0°	1.25°	1.25°	ROTOR DIAMETER*0.05	+15.4%	INVENTION EXAMPLE
26	5.0°	1.25°	1.875°	ROTOR DIAMETER*0.05	+15.8%	INVENTION EXAMPLE
27(=24)	5.0°	1.25°	3.125°	ROTOR DIAMETER*0.05	+16.5%	INVENTION EXAMPLE
28	5.0°	1.25°	5.0°	ROTOR DIAMETER*0.05	+17.8%	INVENTION EXAMPLE
29	5.0°	1.25°	10.0°	ROTOR DIAMETER*0.05	+22.4%	INVENTION EXAMPLE
30	5.0°	1.25°	11.25	ROTOR DIAMETER*0.05	+22.7%	INVENTION EXAMPLE
31	5.0°	1.25°	15.0	ROTOR DIAMETER*0.05	+18.0%	INVENTION EXAMPLE
32	5.0°	1.25°	15.625	ROTOR DIAMETER*0.05	+16.6%	INVENTION EXAMPLE
33	5.0°	1.25°	16.25	ROTOR DIAMETER*0.05	+15.0%	INVENTION EXAMPLE
34	5.0°	1.25°	11.25	ROTOR DIAMETER*0.01	+18.6%	INVENTION EXAMPLE
35	5.0°	1.25°	11.25	ROTOR DIAMETER*0.04	+22.0%	INVENTION EXAMPLE
36	5.0°	1.25°	11.25	ROTOR DIAMETER*0.06	+22.9%	INVENTION EXAMPLE
37	5.0°	1.25°	11.25	ROTOR DIAMETER*0.07	+22.7%	INVENTION EXAMPLE
38	5.0°	1.25°	11.25	ROTOR DIAMETER*0.1	+17.6%	INVENTION EXAMPLE
39	5.0°	1.25°	11.25	ROTOR DIAMETER*0.11	+15.4%	INVENTION EXAMPLE

[0161] Table 2 presents the recess opening angle θc and the maximum recess-depth value Cd illustrated in Fig. 11A in a section of θc and a section of Cd, respectively. In Table 2, a rotor diameter*numerical value is a value obtained by multiplying this numerical value by the diameter of the rotor core. The notation other than those in Table 2 is the same as that in Table 1. Incidentally, Table 2 presents the number 23 presented in Table 1 again.

[0162] Fig. 12E is a view illustrating a configuration of a rotor (rotor cross section)

targeted for being analyzed in the number 36 in Table 2. Further, Fig. 12D is the view illustrating the configuration of the rotor (rotor cross section) targeted for being analyzed in the number 27 in Table 2 (the number 24 in Table 1) as previously described. The number 36 in Table 2 is different in the recess opening angle θ_c between the recess portions 1242a and 1242b from the number 27 in Table 2 (the number 24 in Table 1).

[0163] In this calculation example as previously described, the recess opening angle θ_c is preferably set to not less than 1.975° nor more than 15.625° , and more preferably set within the range of $11.25^\circ \pm 1.25^\circ$. Further, the maximum recess-depth value C_d is preferably set within the range of not less than 0.01 times nor more than 0.1 the diameter of the rotor core.

[0164] In Table 2, a comparison between the number 23 and the number 25 reveals that the recess opening angle θ_c of less than 1.975° as in the number 25 fails to contribute to the improvement in the torque of the rotor even though the recess portion is provided. Similarly, a comparison between the number 23 and the number 33 reveals that the recess opening angle θ_c of more than 15.625° as in the number 33 fails to contribute to the improvement in the torque of the rotor even though the recess portion is provided. Further, a comparison between the number 23 and the number 39 reveals that the maximum recess-

depth value C_d of more than 0.1 times the diameter of the rotor core as in the number 39 fails to contribute to the improvement in the torque of the rotor even though the recess portion is provided.

[0165] On the other hand, in the numbers 26 to 32, 34 to 38 in each of which the recess opening angle θ_c is not less than 1.975° nor more than 15.625° and the maximum recess-depth value C_d is not less than 0.01 times nor more than 0.1 the diameter of the rotor core, values of the increase and decrease in torque become larger than that in the number 23.

Accordingly, the numbers 26 to 32, 34 to 38 demonstrate that the torque of the rotors can be further improved as compared with the number 23.

[0166] Further, the numbers 29 to 30 in each of which the recess opening angle θ_c is within the range of $11.25^\circ \pm 1.25^\circ$ demonstrate that the torque of the rotors can be further improved. In particular, the number 30 in which the recess opening angle θ_c is 11.25° of the center value within the range of $11.25^\circ \pm 1.25^\circ$ indicates the maximum value as the value of the increase and decrease in torque. Further, the numbers 35 to 37 in each of which the maximum recess-depth value C_d is within the range of not less than 0.04 times nor more than 0.07 times the diameter of the rotor core demonstrate that the torque of the rotors can be further improved. In particular, the number 36 in which the maximum recess-depth value C_d indicates a value near the center within the range of

not less than 0.04 times nor more than 0.07 times the diameter of the rotor core indicates the maximum value as the value of the increase and decrease in torque.

[0167] Further, in Table 2, for example, a comparison between the number 23 and the number 36 reveals that even though the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the flux barrier on the rear side are not set in the ranges explained in this embodiment, setting the recess opening angle θ_c and the maximum recess-depth value C_d in the ranges explained in this embodiment allows the improvement in the torque of the rotor.

[0168] The above reveals that as long as any of the movement angle θ_f of the outer-peripheral-side flux barrier on the front side, the movement angle θ_b of the flux barrier on the rear side, and, the recess opening angle θ_c and the maximum recess-depth value C_d is/are set in the ranges explained in this embodiment, the others need not be in the ranges explained in this embodiment.

[0169] Next, as explained in the section of ((third finding)) in the section of (Circumstances), Table 3 presents the result of examining the effect of actively providing the inter-magnet bridge portion 821 and extending the outer-peripheral-side flux barriers 813 to the outer peripheral surface 818 of the rotor core 811 to be opened.

[0170] [Table 3]

[TABLE 3]

NUMBER	TORQUE [Nm]	
40	0.62	FIG. 12F
41	0.37	FIG. 12G
42	0.55	FIG. 12H
43	0.48	FIG. 12I

[0171] Fig. 12F to Fig. 12I are views illustrating configurations of rotors (rotor cross sections) targeted for being analyzed in the numbers 40 to 43 in Table 3. Note that here, to examine only the effect in the section of ((Third finding)), the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the flux barrier on the rear side are not in the ranges explained in this embodiment.

[0172] In Fig. 12F, outer-peripheral-side flux barriers 1201f to 1201g reach an outer peripheral surface 1211f of the rotor core to be open in the rotor core cross section. Further, the inter-magnet flux barriers 1202a to 1202b are not coupled, and the soft magnetic material (an inter-magnet bridge portion 1232a) is present between the inter-magnet flux barriers 1202a and 1202b. In the example illustrated in Fig. 12F, a width w of the inter-magnet bridge portion is 0.3 mm. Further, in the

example illustrated in Fig. 12F, $w_{\min}$ in the formula (1) is 0.075 mm.

[0173] A shape and a size of each of the inter-magnet flux barriers 1202a to 1202b illustrated in Fig. 12G are the same as a shape and a size of each of the inter-magnet flux barriers 1202a to 1202b of the rotor illustrated in Fig. 12F. Accordingly, a shape and a size of the inter-magnet bridge portion 1232a of the rotor illustrated in Fig. 12G are the same as a shape and a size of the inter-magnet bridge portion 1232a of the rotor illustrated in Fig. 12F. Further, a shape and a size of each of outer-peripheral-side flux barriers 1201h to 1201i are the same as the shape and the size of each of the inter-magnet flux barriers 1202a to 1202b, illustrated in Fig. 12G. In Fig. 12G, the outer-peripheral-side flux barriers 1201h to 1201i and the inter-magnet flux barriers 1202a to 1202b are disposed in such a manner that a width of the outer-peripheral-side bridge portion and a width of the inter-magnet bridge portion are roughly equal. Further, the outer-peripheral-side flux barriers 1201h to 1201i illustrated in Fig. 12G do not reach the outer peripheral surface 1211g of the rotor core, and are not open in the rotor core cross section.

[0174] In this calculation example, the width of the outer-peripheral-side bridge portion is indicated by a length in a direction perpendicular to a direction in which a magnetic flux passing through this inter-

magnet bridge portion flows in the rotor core cross section. The width of the inter-magnet bridge portion is the shortest length in this length in this inter-magnet bridge portion (the length in the direction perpendicular to the direction in which the magnetic flux flows).

[0175] In Fig. 12H, the soft magnetic material (an inter-magnet bridge portion 1232b) is present between permanent magnets 1221a and 1221b (inter-magnet flux barriers 1202d and 1202e). A shape and a size of each of outer-peripheral-side flux barriers 1202d to 1202e are the same as a shape and a size of the inter-magnet flux barrier 1232b, illustrated in Fig. 12H. Further, in Fig. 12H, the outer-peripheral-side flux barriers 1201j to 1201k and the inter-magnet flux barriers 1202d to 1202e are disposed in such a manner that a width of each of outer-peripheral-side bridge portions 1231c to 1231d and a width of the inter-magnet bridge portion 1232b are roughly equal. Further, the width of each of the outer-peripheral-side bridge portions 1231c to 1231d and the width of the inter-magnet bridge portion 1232b, illustrated in Fig. 12H, are shorter than the width of each of the outer-peripheral-side bridge portions 1231a to 1231b and the width of the inter-magnet bridge portion 1132a, illustrated in Fig. 12G, respectively.

[0176] As previously described while referring to Fig. 11A to Fig. 11C, the width of the inter-magnet bridge portion is indicated by the length, of the

portion overlapping with the soft magnetic material, of the bridge-width specified line in the rotor core cross section. The bridge-width specified line is the straight line connecting the second end portions of the two magnet holes through which the permanent magnets are installed in such a manner as to make the length of the overlap with the soft magnetic material shortest. As previously described while referring to Fig. 11B and Fig. 11C, the second end portions include the positions at both ends of the straight line drawn so that the length of the overlap with the soft magnetic material composing the soft magnetic material portion has the shortest distance.

Accordingly, in the example illustrated in Fig. 12H, a length of a straight line connecting a region between the inter-magnet flux barriers 1202d and 1202e at the shortest distance is the width of the inter-magnetic pole bridge portion.

[0177] Further, the outer-peripheral-side flux barriers 1201j to 1201k illustrated in Fig. 12H do not reach an outer peripheral surface 1211h of the rotor core, and are not open in the rotor core cross section. Further, the inter-magnet flux barriers 1202d to 1202e illustrated in Fig. 12H are not coupled. Accordingly, the soft magnetic material (inter-magnet bridge portion) is present between the inter-magnet flux barriers 1202 (1202d to 1202e)).

[0178] The shape and the size of each of the outer-peripheral-side flux barriers 1201h to 1201i

illustrated in Fig. 12I are the same as the shape and the size of each of the outer-peripheral-side flux barriers 1201h to 1201i of the rotor illustrated in Fig. 12G. Accordingly, the shape and the size of each of the outer-peripheral-side bridge portions 1231a to 1231b illustrated in Fig. 12I are the same as the shape and the size of each of the outer-peripheral-side bridge portions 1231a to 1231b of the rotor illustrated in Fig. 12G. Further, in Fig. 12I, a flux barrier on the inner peripheral side in the left-right direction Ds further than the permanent magnets 1221a to 1221b (an inter-magnet flux barrier 1202f) is one in number.

[0179] Table 3 reveals that setting the width of each of the outer-peripheral-side bridge portions 1131a to 1131b and the width of the inter-magnet bridge portion 1132a to be the same as the width of the inter-magnetic pole bridge portion 1132a illustrated in Fig. 12F and to be larger than the inter-magnetic pole bridge portion 1232b illustrated in Fig. 12H, as illustrated in Fig. 12G, further decreases the torque of the rotor than the case of setting the width of each of the outer-peripheral-side bridge portions 1231c to 1231d and the width of the inter-magnet bridge portion 1232b to be smaller as illustrated in Fig. 12H. Further, providing the outer-peripheral-side bridge portions 1231a to 1231b and eliminating the inter-magnet bridge portion as illustrated in Fig. 12I causes the torque of the

rotor to increase more than the case of providing the outer-peripheral-side bridge portions 1231a to 1231b and the inter-magnet bridge portion 1232a as illustrated in Fig. 12G and setting the width of the inter-magnet bridge portion 1232a to be the same as the width of the inter-magnetic pole bridge portion 1232a illustrated in Fig. 12F and to be larger than the inter-magnetic pole bridge portion 1232b illustrated in Fig. 12H. However, eliminating the inter-magnet bridge portion as illustrated in Fig. 12I demonstrates that the torque of the rotor further decreases than the case of providing the outer-peripheral-side bridge portions 1231c to 1231d and the inter-magnet bridge portion 1232b as illustrated in Fig. 12H and setting the width of each of the outer-peripheral-side bridge portions 1231c to 1231d and the width of the inter-magnet bridge portion 1232b to be smaller than the width of each of the outer-peripheral-side bridge portions 1231a to 1231b and the width of the inter-magnet bridge portion 1232a, illustrated in Fig. 12G. Further, providing the inter-magnet bridge portion 1232a without providing the outer-peripheral-side bridge portion as illustrated in Fig. 12F demonstrates that the torque of the rotor increases more than the case of providing the outer-peripheral-side bridge portions 1231a to 1231b and the inter-magnet bridge portion 1232a as illustrated in Fig. 12G and a case of setting the width of each of the outer-peripheral-

side bridge portions 1231c to 1231d and the inter-magnet bridge portion 1232b to be smaller than the width of each of the outer-peripheral-side bridge portions 1231a to 1231b and the width of the inter-magnet bridge portion 1232a illustrated in Fig. 12G, as illustrated in Fig. 12H. That is, as illustrated in Fig. 12F, the case of providing the inter-magnet bridge portion 1232a and extending the outer-peripheral-side flux barriers 1201f to 1201g to the outer peripheral surface of the rotor core to be opened demonstrates the highest torque of the rotor.

[0180] Table 4 presents calculation results of stresses of the rotor illustrated in Fig. 12F and the rotor illustrated in Fig. 12H. Values presented in Table 4 are values calculated as follows. First, the maximum stress value of calculated values of stresses applied to the rotor core during rotation at rotation speeds indicated in a section of a rotation speed is set as the maximum value of the stresses applied to the rotor core during the rotation at the rotation speeds. Further, the maximum value of the stresses applied to the rotor core during the rotation at the rotation speeds is normalized (made non-dimensional) by setting the maximum value of stresses applied to the rotor core of this rotor while the rotor illustrated in Fig. 12H is rotating at 20000 rpm as 100. Table 4 presents the values normalized in this manner in sections thereof.

[0181] [Table 4]

[TABLE 4]

ROTATION SPEED [rpm]	FIG. 12F	FIG. 12H
1000	0.17	0.25
3000	1.55	2.25
5000	4.32	6.25
10000	17.2	25.0
15000	38.8	56.3
20000	69.0	100

[0182] As presented in Table 3, a torque of the rotor illustrated in Fig. 12G and a torque of the rotor illustrated in Fig. 12I are smaller than torques of the rotors illustrated in Fig. 12F and Fig. 12H. Accordingly, the rotors illustrated in Fig. 12F and Fig. 12H also have an electromagnetic advantage over the rotor illustrated in Fig. 12I. Thus, from the mechanical viewpoint, the rotor illustrated in Fig. 12F and the rotor illustrated in Fig. 12H are compared using Table 4. The width of the inter-magnet bridge portion 1231a illustrated in Fig. 12F and the sum of the widths of the outer-peripheral-side bridge portions 1231c to 1231d and the inter-magnet bridge portion 1232b illustrated in Fig. 12H are roughly the same. However, as presented in Table 4, the rotor illustrated in Fig. 12F is lower in the maximum value of the stress applied to the rotor core than the rotor illustrated in Fig. 12H. Accordingly,

the rotor illustrated in Fig. 12F demonstrates that a proof stress against centrifugal force can be further improved than that of the rotor illustrated in Fig. 12H.

As described above, the rotor (rotor core) illustrated in Fig. 12F is said to have a shape with mechanical and electromagnetic advantages as compared with the rotors (rotor cores) illustrated in Fig. 12G to Fig. 12I.

[0183] (Summary)

In this embodiment as described above, in the rotor core cross section, the positions of the open-end front-side corner portions 1131a, 1131c are on the rear side in the rotation direction of the rotor core 811 further than the reference positions 831a to 831b. Here, the open-end front-side corner portions 1131a, 1131c are the corner portions on the front side in the rotation direction of the rotor core 811, of the two corner portions 1131a to 1131b and the two corner portions 1131c to 1131d in the circumferential direction of the rotor core 811, of at least one of the open end portions 1111a to 1111b which are provided in the same pole, in the rotor core cross section. Further, the reference positions 831a, 831b are the reference positions relative to the magnet holes 817a, 817b having the open end portions 1111a, 1111b, respectively. Accordingly, the torque of the rotor 810 can be increased.

[0184] Further, in this embodiment, the position of

the front-side open-end front-side corner portion 1131a of the front-side open end portion 1111a is on the rear side in the rotation direction of the rotor core 811 further than the reference position 831a relative to the magnet hole 817a having the front-side open end portion 1111a. Further, the position of the rear-side open-end front-side corner portion 1131b of the rear-side open end portion 1111b is on the rear side in the rotation direction of the rotor core 811 further than the reference position 831b relative to the magnet hole 817b having the rear-side open end portion 1111b. Accordingly, the torque of the rotor 810 in which the permanent magnets 812a to 812b are disposed in a so-called V-shape can be increased.

[0185] Further, in this embodiment, the movement angle θ_f of the outer-peripheral-side flux barrier on the front side is set to not less than $\theta_a/24$ nor more than $15\theta_a/24$ (θ_a is the reference-position movement angle). Accordingly, the torque of the rotor 810 can be surely increased.

[0186] Further, in this embodiment, the movement angle θ_b of the outer-peripheral-side flux barrier on the rear side is set to not less than $\theta_a/24$ nor more than $\theta_a/8$. Accordingly, the torque of the rotor 810 can be surely increased.

[0187] Further, in this embodiment, the length L_1 , in the circumferential direction of the rotor core 811, of the open end portions 1111a to 1111b, is set

to not less than 0.1 times nor more than 1.0 times the length L_2 in the magnetization direction D_m of the permanent magnets 812a to 812b. Accordingly, the reflux magnetic flux can be surely suppressed.

[0188] Further, in this embodiment, the recess portion 815a is provided in the position opposite apart from the teeth 123a, 123b of the stator core 121 installed in the position opposite apart from the outer peripheral surface 818 of the rotor core 811. The teeth 123a, 123b are the teeth different from the teeth 123b, 123d having the lowest magnetic flux density of the teeth 123a to 123d. Accordingly, the torque of the rotor 810 can be further increased.

[0189] Further, in this embodiment, in the rotor core cross section, the recess opening angle θ_c is set to not less than $\theta_a/8$ nor more than $25\theta_a/24\theta_a$ (θ_a is the reference-position movement angle).

Accordingly, the torque of the rotor 810 can be surely increased.

[0190] Further, in this embodiment, the maximum recess-depth value C_d is set within the range of not less than 0.01 times nor more than 0.1 the diameter of the rotor core 811. Accordingly, the torque of the rotor 810 can be surely increased.

[0191] Further, in this embodiment, the rotor core 811 has a plurality of magnetic pole holes per one pole. Further, the plurality of magnet holes include the two permanent magnets 817a to 817b respectively having the first end portions 1111a to 1111b

positioned on the outer peripheral side in the left-right direction D_s and the second end portions 1112a to 1112b positioned on the inner peripheral side further than the first end portions 1111a to 1111b in the left-right direction D_s per the one pole. The soft magnetic material portion 820 has the inter-magnet bridge portion 821a between the respective second end portions 1112a and 1112b of the two magnet holes 817a to 817b. The second end portions 1112a to 1112b of the two magnet holes 817a to 817b coincide with the end portions of the inter-magnet flux barrier spaces 1122a to 1122b, and are closed. On the other hand, the first end portions 1111a to 1111b of the two magnet holes 817a to 817b are opened. Accordingly, the torque of the IPMSM 800 can be more increased.

[0192] Further, in this embodiment, the width w of the inter-magnet bridge portion 821a is set to 0.02 times or less the diameter of the rotor core 811. Accordingly, the width w of the inter-magnet bridge portion 821a can be further reduced. Thus, the reflux magnetic flux included in the magnetic flux passing through the inter-magnet bridge portion 821a can be further reduced. This allows an increase in the magnetic flux contributing to the torque of the rotor 810 (the magnetic flux becoming no reflux magnetic flux).

[0193] Further, in this embodiment, the width w of the inter-magnet bridge portion 821a exceeds $w_{\min}$ in

the formula (1). Accordingly, the occurrence of the fracture with the inter-magnet bridge portion 821a as a starting point due to the stress produced by the rotation of the rotor 810 (the rotor core 811) can be suppressed.

[0194] Further, in this embodiment, setting the region between the second end portions 1112a and 1112b of the two magnet holes 817a to 817b through which the permanent magnets 812a to 812b are installed in the same pole as the region of the soft magnetic material prevents the presence of the space serving as the flux barrier. Accordingly, as long as the region between the second end portions 1112a and 1112b has the same size, the bridge portion included in the region between the second end portions 1112a and 1112b (the inter-magnet bridge portion 821a) can be increased more than the case of the presence of the region serving as the flux barrier in the region between the second end portions 1112a and 1112b.

Thus, the size of the region between the second end portions 1112a and 1112b can be set to be a required minimum size. This allows a reduction in the size of the region per one pole of the rotor 810 (the rotor core 811, for example).

[0195] Further, in this embodiment, the residual magnetic flux density at room temperature of the permanent magnets 812a to 812b is set to 0.8 T or less. Accordingly, the reflux magnetic flux included in the magnetic flux passing through the inter-magnet

bridge portion 821a can be further reduced. Thus, the magnetic flux contributing to the torque of the rotor 810 (the magnetic flux becoming no reflux magnetic flux) can be increased. Further, setting the residual magnetic flux density at room temperature of the permanent magnets 812a to 812b to 0.4 T or less allows a further reduction in the reflux magnetic flux included in the magnetic flux passing through the inter-magnet bridge portion 821a. Thus, the magnetic flux contributing to the torque of the rotor 810 (the magnetic flux becoming no reflux magnetic flux) can be more increased.

[0196] Further, in this embodiment, the permanent magnet containing no rare earth as the permanent magnets 812a to 812b is used. Accordingly, without using limitedly available materials, the torque of the rotor 810 can be increased.

[0197] (Modified example)

This embodiment exemplified a case of providing the two permanent magnets 812a to 812b per one pole. However, the number of permanent magnets per one pole may be one or may be three or more.

[0198] However, when the number of permanent magnets is three or more, the following manner is preferable. That is, in the region between the end portions on the outer peripheral surface side of the rotor core (the third end portions 1113 in the example illustrated in Fig. 11A), of end portions in the magnetization direction D_m of the permanent magnets

installed through the magnet holes having the outer-peripheral-side flux barriers required to define the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the flux barrier on the rear side, and the outer peripheral surface of the rotor core, no permanent magnet is preferably installed. This is because this manner allows the torque of the rotor to be surely improved with the movement angle θ_f of the outer-peripheral-side flux barrier on the front side and the movement angle θ_b of the flux barrier on the rear side set in the ranges explained in this embodiment.

[0199] Further, when the one permanent magnet is installed per one pole, in the magnet hole through which this permanent magnet is installed, the spaces serving as the flux barriers on both sides in the left-right direction D_s of this permanent magnet serve as the front-side flux barrier and the rear-side flux barrier. In this case, both or one of the front-side flux barrier and the rear-side flux barrier have/has the open end portions or the open end portion.

[0200] Further, this embodiment exemplified the IPMSM as a permanent magnet-embedded rotary electric machine. However, the permanent magnet-embedded rotary electric machine is not limited to the IPMSM. For example, the permanent magnet-embedded rotary electric machine may be an IPMSG (Interior Permanent Magnet Synchronous Generator).

[0201] It should be noted that the above explained embodiments of the present invention merely illustrate concrete examples of implementing the present invention, and the technical scope of the present invention is not to be construed in a restrictive manner by these embodiments. That is, the present invention may be implemented in various forms without departing from the technical spirit or main features thereof.

[0202] Note that the disclosures of the above embodiment are as follows, for example.

[Disclosure 1]

A rotor core includes a soft magnetic material portion formed using a soft magnetic material, and having at least one magnet hole per one pole, wherein:

the magnet hole has, relative to a permanent magnet installed through the magnet hole, a space serving as a front-side flux barrier and a space serving as a rear-side flux barrier on both sides in a left-right direction perpendicular to a magnetization direction of the permanent magnet and a direction parallel to a rotation axis line serving as the center of rotation;

the space serving as at least one flux barrier, of the space serving as the front-side flux barrier and the space serving as the rear-side flux barrier, has an open end portion opened in an outer peripheral surface of the rotor core;

in a cross section perpendicular to the rotation axis line, a position of an open-end front-side corner portion of at least one of the open end portions provided in the same pole of a rotor is on a rear side in a rotation direction of the rotor core further than a reference position relative to the magnet hole having the open end portion;

in the cross section, the open-end front-side corner portion is a corner portion on a front side in the rotation direction of the rotor core, of two corner portions in a circumferential direction of the rotor core, of at least one of the open end portions provided in the same pole of the rotor;

in the cross section, the reference position relative to the magnet hole having the open end portion is a position at an intersection point of a straight line passing through a permanent-magnet reference end portion which is one of end portions of the permanent magnet at a position closest to the open end portion, in the permanent magnet installed through the magnet hole, and the rotation axis line, and, the outer peripheral surface of the rotor core; and

in the cross section, the permanent-magnet reference end portion of the permanent magnet at the position closest to the open end portion is, of end portions of the permanent magnet, an end portion at a position at the farthest distance in the circumferential direction from a straight line

passing through a central position in the circumferential direction of a region of one pole including the permanent magnet, and the rotation axis line, and the distance in the circumferential direction from a straight line passing through the central position in the circumferential direction of the region of one pole including the permanent magnet, at the position closest to the open end portion, and the rotation axis line is a distance defined on a side, of the front side and the rear side in the rotation direction of the rotor core, in which the open end portion is present.

[Disclosure 2]

The rotor core according to disclosure 1, wherein in the cross section, positions of the open-end front-side corner portions of all the open end portions provided in the same pole of the rotor are each on the rear side in the rotation direction of the rotor core further than the reference position relative to the magnet hole having the open end portion.

[Disclosure 3]

The rotor core according to disclosure 1 or 2, wherein:

the rotor core has a plurality of magnetic pole holes per one pole;

the plurality of magnet holes have a front-side magnet hole positioned on the front side in the rotation direction, and a rear-side magnet hole

positioned on the rear side in the rotation direction;

the space serving as the front-side flux barrier included in the front-side magnet hole is an outer-peripheral-side flux barrier on the front side in the rotation direction and on an outer peripheral side of the rotor core further than the space serving as the rear-side flux barrier included in the front-side magnet hole;

the space serving as the rear-side flux barrier included in the rear-side magnet hole is an outer-peripheral-side flux barrier on the rear side in the rotation direction and on the outer peripheral side of the rotor core further than the space serving as the front-side flux barrier included in the rear-side magnet hole;

the space serving as at least one flux barrier, of the space serving as the front-side flux barrier included in the front-side magnet hole and the space serving as the rear-side flux barrier included in the rear-side magnet hole, has the open end portion;

in the cross section, the open-end front-side corner portion has at least one of a front-side open-end front-side corner portion and a rear-side open-end front-side corner portion;

in the cross section, the front-side open-end front-side corner portion is, of two corner portions in the circumferential direction of the rotor core of a front-side open end portion, a corner portion on

the front side in the rotation direction;

in the cross section, the front-side open end portion is the open end portion of the space serving as the front-side flux barrier included in the front-side magnet hole;

in the cross section, the rear-side open end portion is, of two corner portions in the circumferential direction of the rotor core of a rear-side open end portion, a corner portion on the front side in the rotation direction;

in the cross section, the rear-side open-end front-side corner portion is the open end portion of the space serving as the rear-side flux barrier included in the rear-side magnet hole;

in the cross section, the permanent-magnet reference end portion has at least one of a front-side permanent magnet end portion and a rear-side permanent magnet end portion;

in the cross section, the front-side permanent magnet end portion is, of the end portions of the permanent magnet installed through the front-side magnet hole, the end portion at a position on the foremost side in the rotation direction;

in the cross section, the rear-side permanent magnet end portion is, of the end portions of the permanent magnet installed through the rear-side magnet hole, the end portion at a position on the rearmost side in the rotation direction;

in the cross section, the reference position has

at least one of a front-side reference position and a rear-side reference position;

in the cross section, the front-side reference position is the position at an intersection point of a straight line passing through the front-side permanent magnet end portion and the rotation axis line, and the outer peripheral surface of the rotor core; and

in the core cross section, the rear-side reference position is the position at an intersection point of a straight line passing through the rear-side permanent magnet end portion and the rotation axis line, and the outer peripheral surface of the rotor core.

[Disclosure 4]

The rotor core according to disclosure 3, wherein:

the open-end front-side corner portion has the front-side open-end front-side corner portion and the rear-side open-end front-side corner portion;

the permanent-magnet reference end portion has the front-side permanent magnet end portion and the rear-side permanent magnet end portion;

the reference position has the front-side reference position and the rear-side reference position; and

the space serving as the front-side flux barrier included in the front-side magnet hole and the space serving as the rear-side flux barrier included in the

rear-side magnet hole each have the open end portion.

[Disclosure 5]

The rotor core according to any one of disclosures 1 to 4, wherein:

in the cross section, an angle formed by a straight line passing through the open-end front-side corner portion positioned on the front side in the rotation direction further than the center in the circumferential direction in the same pole, of the open-end front-side corner portions, and the rotation axis line, and, a straight line passing through the reference position relative to the magnet hole having the open end portion with the open-end front-side corner portion set as one of corner portions, and the rotation axis line is not less than $\theta_a/24$ nor more than $15\theta_a/24$;

θ_a is a movement angle (rad) which is an angle around the rotation axis line from the reference position;

θ_a is calculated by $2\pi/N_{slot}$; and

N_{slot} is the number (piece) of slots in a stator core installed in a position opposite apart from the outer peripheral surface of the rotor core.

[Disclosure 6]

The rotor core according to any one of disclosures 1 to 5, wherein:

in the cross section, an angle formed by a straight line passing through the open-end front-side corner portion positioned on the rear side in the

rotation direction further than the center in the circumferential direction in the same pole, of the open-end front-side corner portions, and the rotation axis line, and, a straight line passing through the reference position relative to the magnet hole having the open end portion with the open-end front-side corner portion set as one of corner portions, and the rotation axis line is not less than $\theta_a/24$ nor more than $\theta_a/8$;

θ_a is a movement angle (rad) which is the angle around the rotation axis line from the reference position;

θ_a is calculated by $2\pi/N_{slot}$; and

N_{slot} is the number (piece) of slots in the stator core installed in the position opposite apart the outer peripheral surface of the rotor core.

[Disclosure 7]

The rotor core according to any one of disclosures 1 to 6, wherein a length in the circumferential direction of the open end portion is not less than 0.1 times nor more than 1.0 times a length in the magnetization direction of the permanent magnet installed through the magnet hole having the open end portion.

[Disclosure 8]

The rotor core according to any one of disclosures 1 to 7, wherein:

the soft magnetic material portion further has a recess portion having an open end portion opened in

the outer peripheral surface of the rotor core as a recess portion different from the space serving as the flux barrier; and

the recess portion is in a position opposite apart from teeth different from teeth having the lowest magnetic flux density of teeth of the stator core installed in the position opposite apart from the outer peripheral surface of the rotor core.

[Disclosure 9]

The rotor core according to disclosure 8, wherein:

in the cross section, an angle formed by a straight line passing through a recess rear-side corner portion which is, of two corner portions in the open end portion of the recess portion, a corner portion on the rear side in the rotation direction, and the rotation axis line, and, a straight line passing through the open-end front-side corner portion positioned on the rear side in the rotation direction further than the recess portion in the same pole as a pole in which the recess portion is provided, and the rotation axis line is θa ;

an angle formed by a straight line passing through a recess front-side corner portion which is, of the two corner portions in the open end portion of the recess portion, the corner portion on the front side in the rotation direction, and the rotation axis line, and, a straight line passing through the recess rear-side corner portion and the rotation axis line

is not less than $\theta a/8$ nor more than $25\theta a/24\theta a$;

θa is the movement angle (rad) which is the angle around the rotation axis line from a rear-side reference position which is the position at an intersection point of a straight line passing through a rear-side permanent magnet end portion and the rotation axis line, and the outer peripheral surface of the rotor core, in the cross section;

the rear-side permanent magnet end portion is, of the end portions of the permanent magnet installed in the same pole, the end portion positioned on the rearmost side in the circumferential direction;

θa is calculated by $2\pi/N_{s1ot}$; and

N_{s1ot} is the number (piece) of slots in the stator core installed in the position opposite apart from the outer peripheral surface of the rotor core.

[Disclosure 10]

The rotor core according to disclosure 8 or 9, wherein a maximum value of a depth of the recess portion is within a range of not less than 0.01 times nor more than 0.1 times a diameter of the rotor core.

[Disclosure 11]

The rotor core according to any one of disclosures 1 to 10, wherein:

the rotor core has a plurality of magnetic pole holes per one pole;

the plurality of magnet holes have a front-side magnet hole positioned on the front side in the rotation direction, and a rear-side magnet hole

positioned on the rear side in the rotation direction;

the space serving as the front-side flux barrier included in the front-side magnet hole is on the front side in the rotation direction further than the space serving as the rear-side flux barrier included in the front-side magnet hole;

the space serving as the front-side flux barrier included in the rear-side magnet hole is on the rear side in the rotation direction further than the space serving as the rear-side flux barrier included in the rear-side magnet hole;

the soft magnetic material portion has an inter-magnet bridge portion disposed in a region between the space serving as the rear-side flux barrier included in the front-side magnet hole and the space serving as the rear-side flux barrier included in the rear-side magnet hole;

the front-side magnet hole has a first end portion serving as the open end portion on the front side in the rotation direction relative to the permanent magnet installed through the front-side magnet hole;

the front-side magnet hole has a second end portion on the rear side in the rotation direction relative to the permanent magnet installed through the front-side magnet hole;

the rear-side magnet hole has a first end portion serving as the open end portion on the rear side in

the rotation direction relative to the permanent magnet installed through the rear-side magnet hole;

the rear-side magnet hole has a second end portion on the front side in the rotation direction relative to the permanent magnet installed through the rear-side magnet hole; and

the second end portion of each of the front-side magnet hole and the rear-side magnet hole coincides with an end portion of the space serving as the flux barrier, and is closed.

[Disclosure 12]

The rotor core according to disclosure 11, wherein:

in the cross section, a length, of a portion overlapping with the soft magnetic material, of a bridge-width specified line is 0.02 times or less the diameter of the rotor core; and

the bridge-width specified line is a straight line connecting the second end portions of the front-side magnet hole and the rear-side magnet hole to make a length of the overlap with the soft magnetic material shortest.

[Disclosure 13]

The rotor core according to disclosure 11 or 12, wherein:

in the cross section, each of a front-side magnet hole and the rear-side magnet hole further has a third end portion positioned on the outer peripheral side in the magnetization direction of the permanent

magnet installed through each of the front-side magnet hole and the rear-side magnet hole, and a fourth end portion positioned on an inner peripheral side in the magnetization direction of the permanent magnet further than the third end portion;

in the cross section, a length, of a portion overlapping with the soft magnetic material, of a bridge-width specified line exceeds $w_{\min}$;

the bridge-width specified line is a straight line connecting the second end portions of the front-side magnet hole and the rear-side magnet hole to make a length of the overlap with the soft magnetic material shortest;

$w_{\min}$ is calculated by $\rho \times S \times r_g \times \omega \div Y_s$;

ρ is a density (kg/m^3) of the soft magnetic material;

Y_s is a yield stress (Pa) at room temperature of the soft magnetic material;

S is an area (m^2) of an external force influence portion;

the external force influence portion is a region of the soft magnetic material surrounded by the third end portion of the front-side magnet hole positioned at one end of the bridge-width specified line, the third end portion of the rear-side magnet hole positioned at the other end of the bridge-width specified line, an outer peripheral surface of the soft magnetic material portion, and the bridge-width specified line, in the cross section;

r_g is a distance (m) in a radial direction between a position of the center of gravity of the external force influence portion and the center of the rotation in the cross section; and

ω is an angular speed (rad/sec) of the rotor at the time of rotation at a maximum rotation speed.

[Disclosure 14]

A rotor core including a soft magnetic material portion formed using a soft magnetic material, and having at least one magnet hole per one pole, wherein:

the soft magnetic material portion has a recess portion in an outer peripheral surface;

the magnet hole has a first end portion and a second end portion in a left-right direction perpendicular to a magnetization direction of a permanent magnet installed through the magnet hole and a direction parallel to a rotation axis line serving as a center of rotation;

at least one end portion, of the first end portion and the second end portion, is an opened open end portion;

the recess portion is in a position different from the open end portion; and

the recess portion is in a position opposite apart from teeth different from teeth having the lowest magnetic flux density of teeth of a stator core installed in a position opposite apart from the outer peripheral surface of the rotor core.

[Disclosure 15]

The rotor core according to disclosure 14,
wherein:

in the cross section, an angle formed by a straight line passing through a recess rear-side corner portion which is, of two corner portions in an open end portion of the recess portion, a corner portion on a rear side in a rotation direction of the rotor core, and the rotation axis line, and, a straight line passing through an open-end front-side corner portion positioned on the rear side in the rotation direction further than the recess portion in the same pole as a pole in which the recess portion is provided, and the rotation axis line is θ_a ;

in the cross section, the open-end front-side corner portion is a corner portion on a front side in the rotation direction of the rotor core, of two corner portions in a circumferential direction of the rotor core, of at least one of the open end portions installed in the same pole of a rotor;

an angle formed by a straight line passing through a recess front-side-corner portion which is, of the two corner portions in the open end portion of the recess portion, a corner portion on the front side in the rotation direction, and the rotation axis line, and, a straight line passing through the recess rear-side corner portion and the rotation axis line is not less than $\theta_a/8$ nor more than $25\theta_a/24\theta_a$;

θ_a is a movement angle (rad) which is an angle

around the rotation axis line from a rear-side reference position which is a position at an intersection point of a straight line passing through a rear-side permanent magnet end portion and the rotation axis line, and the outer peripheral surface of the rotor core, in the cross section;

the rear-side permanent magnet end portion is, of end portions of the permanent magnet installed in the same pole, an end portion positioned on the rearmost side in the circumferential direction;

θ_a is calculated by $2\pi/N_{slot}$; and

N_{slot} is the number (piece) of slots in the stator core installed in a position opposite apart from the outer peripheral surface of the rotor core.

[Disclosure 16]

The rotor core according to disclosure 14 or 15, wherein a maximum value of a depth of the recess portion is within a range of not less than 0.01 times nor more than 0.1 times a diameter of the rotor core.

[Disclosure 17]

A rotor includes:

the rotor core according to any one of disclosures 1 to 16; and

a plurality of permanent magnets installed in the rotor core.

[Disclosure 18]

The rotor according to disclosure 17, wherein a residual magnetic flux density at room temperature of the permanent magnet is 0.8 T or less.

[Disclosure 19]

The rotor according to disclosure 17 or 18,
wherein the permanent magnet contains no rare earth.

[Disclosure 20]

A rotary electric machine includes:

the rotor according to any one of disclosures 17
to 19; and

a stator.

INDUSTRIAL APPLICABILITY

[0203] The present invention can be used for a
rotary electric machine, for example.

CLAIMS

[Claim 1] A rotor core comprising a soft magnetic material portion formed using a soft magnetic material, and having at least one magnet hole per one pole, wherein:

the magnet hole has, relative to a permanent magnet installed through the magnet hole, a space serving as a front-side flux barrier and a space serving as a rear-side flux barrier on both sides in a left-right direction perpendicular to a magnetization direction of the permanent magnet and a direction parallel to a rotation axis line serving as a center of rotation;

the space serving as at least one flux barrier, of the space serving as the front-side flux barrier and the space serving as the rear-side flux barrier, has an open end portion opened in an outer peripheral surface of the rotor core;

in a cross section perpendicular to the rotation axis line, a position of an open-end front-side corner portion of at least one of the open end portions provided in a same pole of a rotor is on a rear side in a rotation direction of the rotor core further than a reference position relative to the magnet hole having the open end portion;

in the cross section, the open-end front-side corner portion is a corner portion on a front side in the rotation direction of the rotor core, of two corner portions in a circumferential direction of the

rotor core, of at least one of the open end portions provided in the same pole of the rotor;

in the cross section, the reference position relative to the magnet hole having the open end portion is a position at an intersection point of a straight line passing through a permanent-magnet reference end portion which is one of end portions of the permanent magnet at a position closest to the open end portion in the permanent magnet installed through the magnet hole, and the rotation axis line, and, the outer peripheral surface of the rotor core;

in the cross section, the permanent-magnet reference end portion of the permanent magnet at the position closest to the open end portion is, of end portions of the permanent magnet, an end at a position at a farthest distance in the circumferential direction from a straight line passing through a central position in the circumferential direction of a region of one pole including the permanent magnet, and the rotation axis line; and

the distance in the circumferential direction from a straight line passing through the central position in the circumferential direction of the region in one pole including the permanent magnet at the position closest to the open end portion, and the rotation axis line is a distance defined on a side, of the front side and the rear side in the rotation direction of the rotor core, in which the open end

portion is present.

[Claim 2] The rotor core according to claim 1, wherein in the cross section, positions of the open-end front-side corner portions of all the open end portions provided in the same pole of the rotor are each on the rear side in the rotation direction of the rotor core further than the reference position relative to the magnet hole having the open end portion.

[Claim 3] The rotor core according to claim 1 or 2, wherein:

the rotor core has a plurality of magnetic pole holes per one pole;

the plurality of magnet holes have a front-side magnet hole positioned on the front side in the rotation direction, and a rear-side magnet hole positioned on the rear side in the rotation direction;

the space serving as the front-side flux barrier included in the front-side magnet hole is an outer-peripheral-side flux barrier on the front side in the rotation direction and on an outer peripheral side of the rotor core further than the space serving as the rear-side flux barrier included in the front-side magnet hole;

the space serving as the rear-side flux barrier included in the rear-side magnet hole is an outer-peripheral-side flux barrier on the rear side in the rotation direction and on the outer peripheral side

of the rotor core further than the space serving as the front-side flux barrier included in the rear-side magnet hole;

the space serving as at least one flux barrier, of the space serving as the front-side flux barrier included in the front-side magnet hole and the space serving as the rear-side flux barrier included in the rear-side magnet hole, has the open end portion;

in the cross section, the open-end front-side corner portion has at least one of a front-side open-end front-side corner portion and a rear-side open-end front-side corner portion;

in the cross section, the front-side open-end front-side corner portion is, of two corner portions in the circumferential direction of the rotor core of a front-side open end portion, a corner portion on the front side in the rotation direction;

in the cross section, the front-side open end portion is the open end portion of the space serving as the front-side flux barrier included in the front-side magnet hole;

in the cross section, the rear-side open end portion is, of two corner portions in the circumferential direction of the rotor core of a rear-side open end portion, a corner portion on the front side in the rotation direction;

in the cross section, the rear-side open-end front-side corner portion is the open end portion of the space serving as the rear-side flux barrier

included in the rear-side magnet hole;

in the cross section, the permanent-magnet reference end portion has at least one of a front-side permanent magnet end portion and a rear-side permanent magnet end portion;

in the cross section, the front-side permanent magnet end portion is, of the end portions of the permanent magnet installed through the front-side magnet hole, the end portion at a position on a foremost side in the rotation direction;

in the cross section, the rear-side permanent magnet end portion is, of the end portions of the permanent magnet installed through the rear-side magnet hole, the end portion at a position on a rearmost side in the rotation direction;

in the cross section, the reference position has at least one of a front-side reference position and a rear-side reference position;

in the cross section, the front-side reference position is the position at an intersection point of a straight line passing through the front-side permanent magnet end portion and the rotation axis line, and the outer peripheral surface of the rotor core; and

in the core cross section, the rear-side reference position is the position at an intersection point of a straight line passing through the rear-side permanent magnet end portion and the rotation axis line, and the outer peripheral surface of the

rotor core.

[Claim 4] The rotor core according to claim 3, wherein:

the open-end front-side corner portion has the front-side open-end front-side corner portion and the rear-side open-end front-side corner portion;

the permanent-magnet reference end portion has the front-side permanent magnet end portion and the rear-side permanent magnet end portion;

the reference position has the front-side reference position and the rear-side reference position; and

the space serving as the front-side flux barrier included in the front-side magnet hole and the space serving as the rear-side flux barrier included in the rear-side magnet hole each have the open end portion.

[Claim 5] The rotor core according to any one of claims 1 to 4, wherein:

in the cross section, an angle formed by a straight line passing through the open-end front-side corner portion positioned on the front side in the rotation direction further than a center in the circumferential direction in the same pole, of the open-end front-side corner portions, and the rotation axis line, and, a straight line passing through the reference position relative to the magnet hole having the open end portion with the open-end front-side corner portion set as one of corner portions, and the rotation axis line is not less than $\theta a/24$ nor more

than $15\theta_a/24$;

θ_a is a movement angle (rad) which is an angle around the rotation axis line from the reference position;

θ_a is calculated by $2\pi/N_{s1ot}$; and

N_{s1ot} is the number (piece) of slots in a stator core installed in a position opposite apart from the outer peripheral surface of the rotor core.

[Claim 6] The rotor core according to any one of claims 1 to 5, wherein:

in the cross section, an angle formed by a straight line passing through the open-end front-side corner portion positioned on the rear side in the rotation direction further than the center in the circumferential direction in the same pole, of the open-end front-side corner portions, and the rotation axis line, and, a straight line passing through the reference position relative to the magnet hole having the open end portion with the open-end front-side corner portion set as one of corner portions, and the rotation axis line is not less than $\theta_a/24$ nor more than $\theta_a/8$;

θ_a is a movement angle (rad) which is the angle around the rotation axis line from the reference position;

θ_a is calculated by $2\pi/N_{s1ot}$; and

N_{s1ot} is the number (piece) of slots in the stator core installed in the position opposite apart from the outer peripheral surface of the rotor core.

[Claim 7] The rotor core according to any one of claims 1 to 6, wherein a length in the circumferential direction of the open end portion is not less than 0.1 times nor more than 1.0 times a length in the magnetization direction of the permanent magnet installed through the magnet hole having the open end portion.

[Claim 8] The rotor core according to any one of claims 1 to 7, wherein:

the soft magnetic material portion further has a recess portion having an open end portion opened in the outer peripheral surface of the rotor core as a recess portion different from the space serving as the flux barrier; and

the recess portion is in a position opposite apart from teeth different from teeth having a lowest magnetic flux density of teeth of the stator core installed in the position opposite apart from the outer peripheral surface of the rotor core.

[Claim 9] The rotor core according to claim 8, wherein:

in the cross section, an angle formed by a straight line passing through a recess rear-side corner portion which is, of two corner portions in the open end portion of the recess portion, a corner portion on the rear side in the rotation direction, and the rotation axis line, and, a straight line passing through the open-end front-side corner portion positioned on the rear side in the rotation

direction further than the recess portion in the same pole as a pole in which the recess portion is installed, and the rotation axis is θa ;

an angle formed by a straight line passing through a recess front-side corner portion which is, of the two corner portions in the open end portion of the recess portion, the corner portion on the front side in the rotation direction, and the rotation axis line, and, a straight line passing through the recess rear-side corner portion and the rotation axis line is not less than $\theta a/8$ nor more than $25\theta a/24\theta a$;

θa is the movement angle (rad) which is the angle around the rotation axis line from a rear-side reference position which is the position at an intersection point of a straight line passing through a rear-side permanent magnet end portion and the rotation axis line, and the outer peripheral surface of the rotor core, in the cross section;

the rear-side permanent magnet end portion is, of the end portions of the permanent magnet installed in the same pole, the end portion positioned on a rearmost side in the circumferential direction;

θa is calculated by $2\pi/N_{s1ot}$; and

N_{s1ot} is the number (piece) of slots in the stator core installed in the position opposite apart from the outer peripheral surface of the rotor core.

[Claim 10] The rotor core according to claim 8 or 9, wherein a maximum value of a depth of the recess portion is within a range of not less than 0.01 times

nor more than 0.1 times a diameter of the rotor core.

[Claim 11] The rotor core according to any one of claims 1 to 10, wherein

the rotor core has a plurality of magnetic pole holes per one pole;

the plurality of magnet holes have a front-side magnet hole positioned on the front side in the rotation direction, and a rear-side magnet hole positioned on the rear side in the rotation direction;

the space serving as the front-side flux barrier included in the front-side magnet hole is on the front side in the rotation direction further than the space serving as the rear-side flux barrier included in the front-side magnet hole;

the space serving as the front-side flux barrier included in the rear-side magnet hole is on the rear side in the rotation direction further than the space serving as the rear-side flux barrier included in the rear-side magnet hole;

the soft magnetic material portion has an inter-magnet bridge portion disposed in a region between the space serving as the rear-side flux barrier included in the front-side magnet hole and the space serving as the rear-side flux barrier included in the rear-side magnet hole;

the front-side magnet hole has a first end portion serving as the open end portion on the front side in the rotation direction relative to the

permanent magnet installed through the front-side magnet hole;

the front-side magnet hole has a second end portion on the rear side in the rotation direction relative to the permanent magnet installed through the front-side magnet hole;

the rear-side magnet hole has a first end portion serving as the open end portion on the rear side in the rotation direction relative to the permanent magnet installed through the rear-side magnet hole;

the rear-side magnet hole has a second end portion on the front side in the rotation direction relative to the permanent magnet installed through the rear-side magnet hole; and

the second end portion of each of the front-side magnet hole and the rear-side magnet hole coincides with an end portion of the space serving as the flux barrier, and is closed.

[Claim 12] The rotor core according to claim 11, wherein:

in the cross section, a length, of a portion overlapping with the soft magnetic material, of a bridge-width specified line is 0.02 times or less the diameter of the rotor core; and

the bridge-width specified line is a straight line connecting the second end portions of the front-side magnet hole and the rear-side magnet hole to make a length of the overlap with the soft magnetic material shortest.

[Claim 13]

The rotor core according to claim 11 or 12,
wherein:

in the cross section, each of the front-side magnet hole and the rear-side magnet hole further has a third end portion positioned on the outer peripheral side in the magnetization direction of the permanent magnet installed through each of the front-side magnet hole and the rear-side magnet hole, and a fourth end portion positioned on an inner peripheral side in the magnetization direction of the permanent magnet further than the third end portion;

in the cross section, a length, of a portion overlapping with the soft magnetic material, of a bridge-width specified line exceeds w_{min} ;

the bridge-width specified line is a straight line connecting the second end portions of the front-side magnet hole and the rear-side magnet hole to make a length of the overlap with the soft magnetic material shortest;

w_{min} is calculated by $\rho \times S \times r_g \times \omega \div Y_s$;

ρ is a density (kg/m^3) of the soft magnetic material;

Y_s is a yield stress (Pa) at room temperature of the soft magnetic material;

S is an area (m^2) of an external force influence portion;

the external force influence portion is a region of the soft magnetic material surrounded by the third

end portion of the front-side magnet hole positioned at one end of the bridge-width specified line, the third end portion of the rear-side magnet hole positioned at the other end of the bridge-width specified line, an outer peripheral surface of the soft magnetic material portion, and the bridge-width specified line, in the cross section;

r_g is a distance (m) in a radial direction between a position of a center of gravity of the external force influence portion and the center of the rotation in the cross section; and

ω is an angular speed (rad/sec) of the rotor at a time of rotation at a maximum rotation speed.

[Claim 14] A rotor core comprising a soft magnetic material portion formed using a soft magnetic material, and having at least one magnet hole per one pole, wherein:

the soft magnetic material portion has a recess portion in an outer peripheral surface;

the magnet hole has a first end portion and a second end portion in a left-right direction perpendicular to a magnetization direction of a permanent magnet installed through the magnet hole and a direction parallel to a rotation axis line serving as a center of rotation;

at least one end portion of the first end portion and the second recess portion is an opened open end portion;

the recess portion is in a position different

from the open end portion; and

the recess portion is in a position opposite apart from teeth different from teeth having a lowest magnetic flux density of teeth of the stator core installed in a position opposite apart from the outer peripheral surface of the rotor core.

[Claim 15] A rotor comprising:

the rotor core according to any one of claims 1 to 14; and

a plurality of permanent magnets installed in the rotor core.

[Claim 16] The rotor according to claim 15, wherein a residual magnetic flux density at room temperature of the permanent magnet is 0.8 T or less.

[Claim 17] The rotor according to claim 15 or 16, wherein the permanent magnet contains no rare earth.

[Claim 18]

A rotary electric machine comprising:

the rotor according to any one of claims 15 to 17; and

a stator.