



to the magnetic resistance of the main magnetic flux path and the leakage magnetic flux path, the magnetomotive force of the magnets and the stator.

9 Claims, 4 Drawing Sheets

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 See application file for complete search history.

(56)

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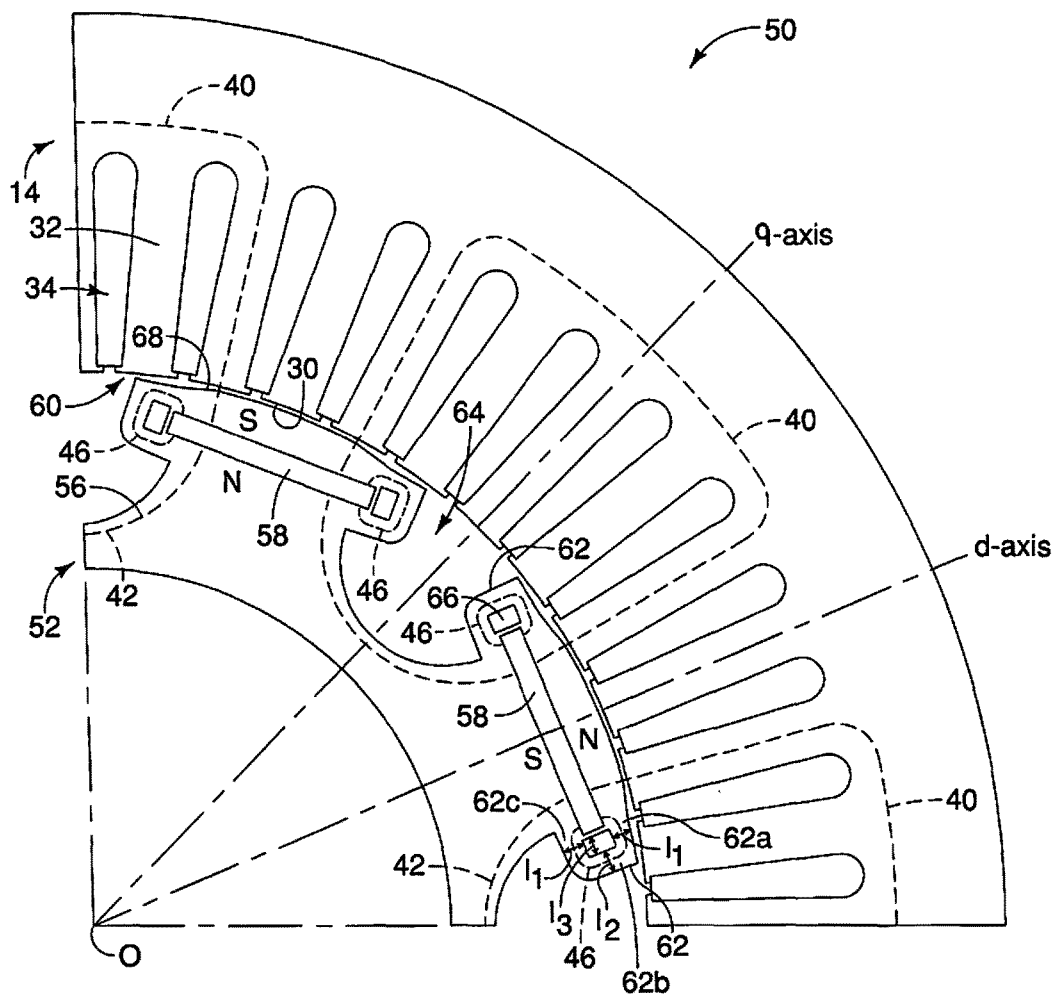


FIG. 2

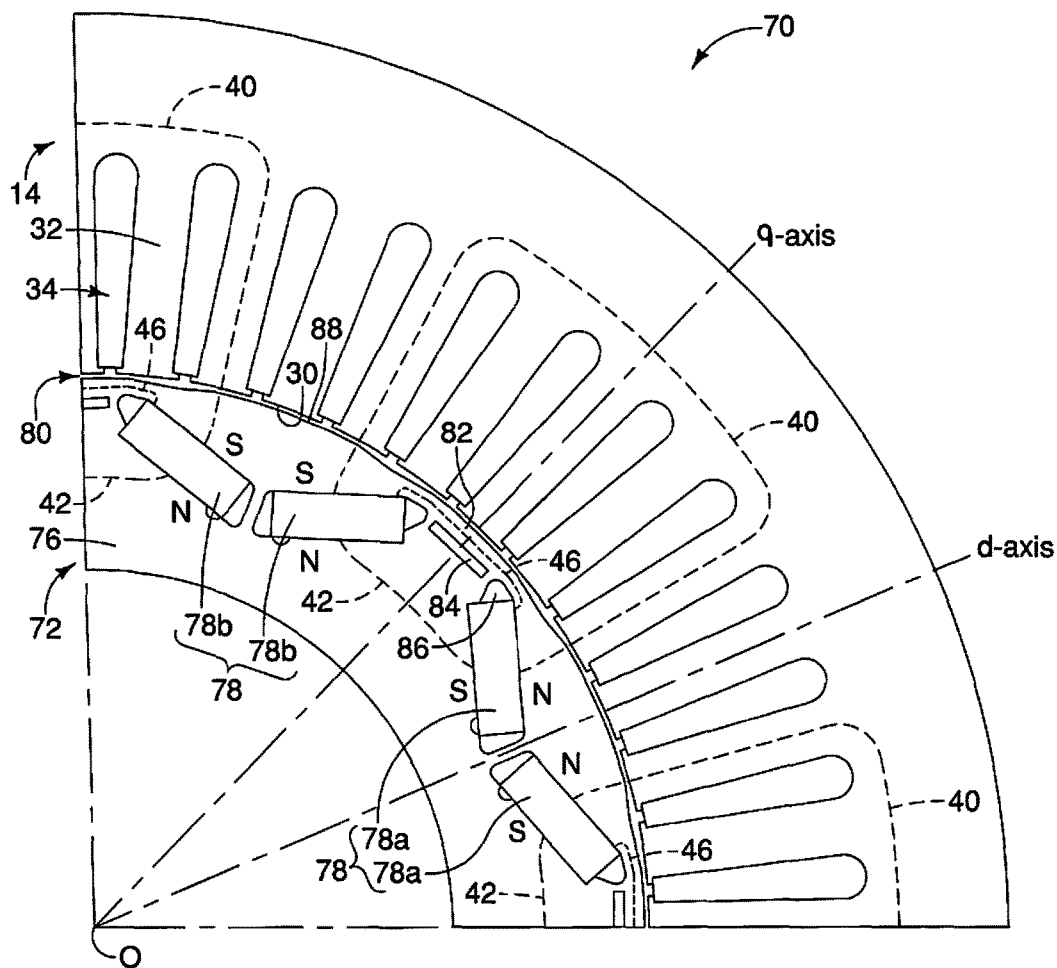


FIG. 3

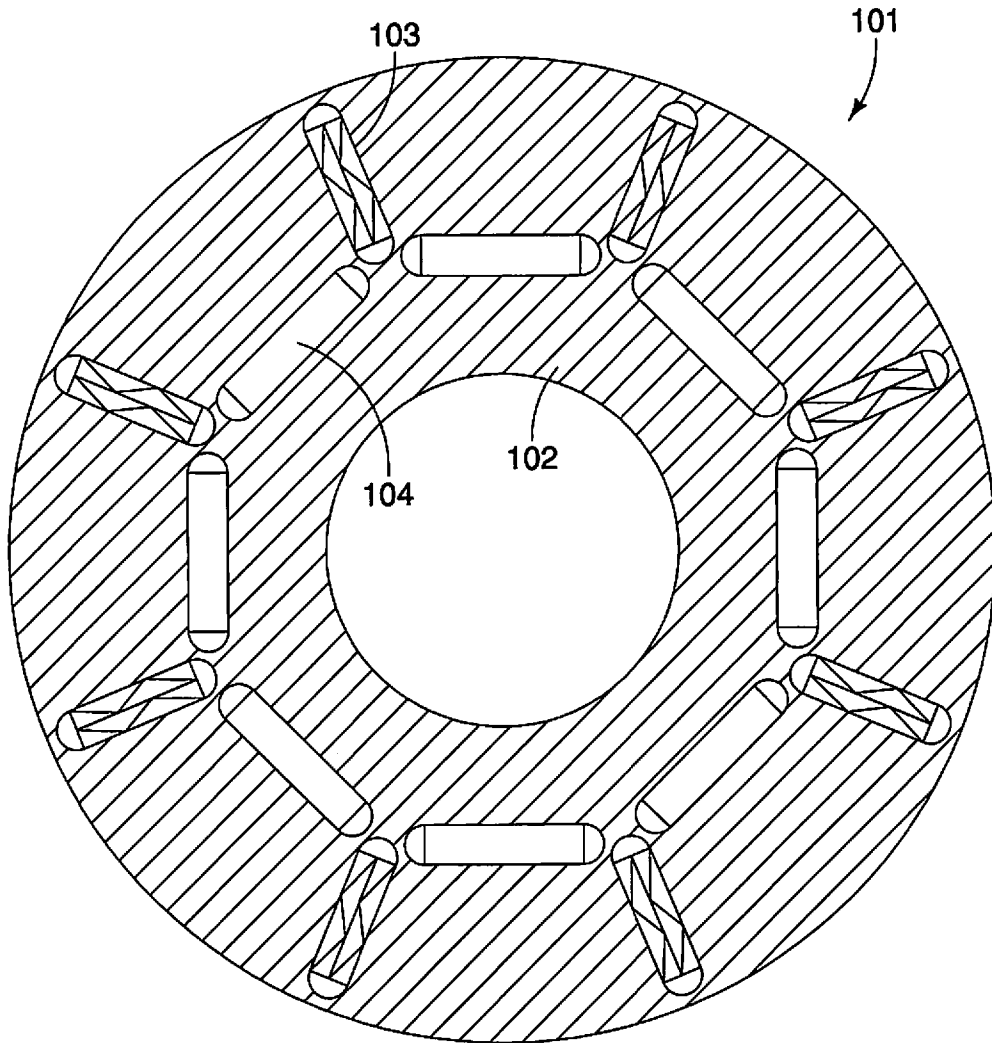


FIG. 4

**PERMANENT MAGNET SYNCHRONOUS MOTOR**

CROSS-REFERENCE TO RELATED APPLICATION

This application is a U.S. National stage of International Application No. PCT/JP2014/055049, filed Sep. 11, 2014, the entire contents of International Application No. PCT/JP2014/055049 are hereby incorporated herein by reference.

BACKGROUND

Field of the Invention

The present invention generally relates to a permanent magnet synchronous motor. More specifically, the present invention relates to a permanent magnet synchronous motor with a rotor having a permanent magnet.

Background Information

Electric vehicles and hybrid electric vehicles (HEV) include an electric motor that operates as a drive source for the vehicle. In a purely electric vehicle, the electric motor operates as the sole drive source. On the other hand, an HEV includes an electric motor and a conventional combustion engine that operate as the drive sources for the vehicle based on conditions as understood in the art.

An electric motor which includes a rotor with a low-coercive-force magnet to achieve variable magnetization characteristics (which is called variable magnetization motor hereinafter) is known (see Japanese Unexamined Patent Application Publication No. 2006-280195, for example). For example, as shown in FIG. 4, the variable magnetization motor has a rotor 101 having a rotor core 102, a plurality of low-coercive-force magnets 103, and a plurality of high-coercive-force magnets 104. With this configuration, the magnetization level of the low-coercive-force magnets 103 can be changed by a magnetic field generated by a current in a stator winding of a stator. Specifically, the magnetization level of the low-coercive-force magnets 103 can be changed by d-axis flux according to the operational state of the motor to improve the efficiency of the motor. In particular, the magnetization level can be increased to increase the torque generated by the motor.

SUMMARY

However, with the variable magnetization motor, in order to change the magnetization level of the motor, an instantaneous increase in load current applied to the stator winding is required, which increases the copper loss in the motor. Thus, although efficiency of variable magnetization motor is improved compared to conventional machines, the additional copper losses that occur during the change of magnetization state limits the amount of improvement.

Accordingly, it is desirable to provide an improved motor with an improved efficiency by reducing the copper loss accompanied by changing the magnetization level of the variable magnetization motor.

In view of the state of the known technology, one aspect of a permanent magnet synchronous motor includes a stator with a stator winding, a rotor with a rotor core rotatable relative to the stator, and a magnetic structure with at least one permanent magnet mounted to the rotor core. The rotor being radially inwardly or outwardly disposed relative to the

stator with an air gap therebetween. The magnetic structure produces a magnetic flux that flows between different magnetic poles of the magnetic structure through a main magnetic flux path that passes through the stator winding of the stator via the air gap and a leakage magnetic flux path that is located within the rotor core about an end portion of the permanent magnet near the air gap. The stator, the rotor and the magnetic structure being further configured to satisfy the following expressions:

$$V_s \geq \frac{R_g + R_s}{R_r} V_m$$

$$\eta = \frac{R_g + R_s}{R_b + R_g + R_s} \geq 0.2$$

where  $V_s$  represents magnetomotive force of the stator winding,  $V_m$  represents magnetomotive force of the magnetic structure,  $R_g$  represents magnetic resistance of the air gap,  $R_s$  represents magnetic resistance of the stator along the main magnetic flux path,  $R_r$  represents magnetic resistance of the rotor core along the main magnetic flux path,  $R_b$  represents magnetic resistance of the rotor core along the leakage magnetic flux path, and  $\eta$  represents a ratio of a leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path relative to a total magnetic flux of the magnetic flux that is produced by the magnetic structure.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the attached drawings which form a part of this original disclosure:

FIG. 1 is a partial cross-sectional schematic view of a permanent magnet synchronous motor in accordance with to a first embodiment;

FIG. 2 is a partial cross-sectional schematic view of a permanent magnet synchronous motor in accordance with a second embodiment;

FIG. 3 is a partial cross-sectional schematic view of a permanent magnet synchronous motor in accordance with a third embodiment; and

FIG. 4 is a cross-sectional schematic view of a variable magnetization motor.

DETAILED DESCRIPTION OF EMBODIMENTS

Selected embodiments will now be explained with reference to the drawings. It will be apparent to those skilled in the art from this disclosure that the following descriptions of the embodiments are provided for illustration only and not for the purpose of limiting the invention as defined by the appended claims and their equivalents.

First Embodiment

Referring to FIG. 1, a permanent magnet synchronous motor 10, which can also be referred to as an interior permanent magnet motor, is illustrated in accordance with to a first embodiment. As shown in FIG. 1, the motor 10 basically includes a rotor 12 and a stator 14. The motor 10 can be employed in any type of electric vehicle or HEV such as an automobile, truck, SUV and so on, and in any other type of apparatus as understood in the art. The rotor 12 and the stator 14 can be made of metal or any other suitable material as understood in the art.

In the illustrated embodiment, the rotor **12** has a rotor core **16**. The motor **10** also includes a plurality of magnets **18** that is fixedly mounted to the rotor core **16**. The rotor core **16** is rotatable relative to the stator **14** about a center rotational axis **O** of the motor **10**, and is radially inwardly disposed relative to the stator **14** with an air gap **20** therebetween. The rotor core **16** is configured to include a plurality pairs of leakage sections **22**, a plurality of flux barriers **24** and a plurality pairs of side openings **26**. The rotor core **16** is basically formed as a one-piece, unitary member. The configurations of the rotor core **16** will be further described in detail below. In the illustrated embodiment, the rotor core **16** is radially inwardly disposed relative to the stator **14** with the air gap **20** therebetween. However, the rotor core **16** can be radially outwardly disposed relative to the stator **14** with an air gap therebetween as understood in the art.

In the illustrated embodiment, the stator **14** is concentrically arranged relative to the rotor **12** with respect to the center rotational axis **O** of the motor **10**. As mentioned above, the stator **14** is radially outwardly disposed relative to the rotor **12** with the air gap **20** therebetween. In particular, as illustrated in FIG. **1**, the air gap **20** is present between an outer circumference **28** of the rotor **12** and an inner circumference **30** of the stator **14** to enable the rotor **12** to rotate unrestrictedly or substantially unrestrictedly about the center rotational axis **O**. The stator **14** basically includes a plurality of stator teeth **32**, a plurality of stator windings **34**, and other components which can be configured in any conventional manner. In the illustrated embodiment, the stator teeth **32** are configured as wide stator teeth as known in the art. However, the stator teeth **32** can have any suitable size, and the stator **14** can include any number of stator teeth **32** to achieve the operability of the embodiments discussed herein. In this example, the stator teeth **32** are open to the inner circumference **30** of the stator **14**, but can be closed if desired. The stator windings **34** are made of copper or aluminum wires wound about the stator teeth **32**. However, the stator windings **34** can be made of any suitable type of material as known in the art. In the illustrated embodiment, the stator **14** can be employ a conventional stator as known in the art. Thus, detailed descriptions will be omitted for the sake of brevity.

In the illustrated embodiment, the magnets **18** are spaced between adjacent pairs of the flux barriers **24** about the circumference of the rotor **12**. As shown in FIG. **1**, each of the magnets **18** has a pair of permanent magnet pieces **18a** or **18b** (e.g., at least one permanent magnet) to define each of the motor poles of the motor **10** with alternate polarities. In the illustrated embodiment, four pairs of the magnet pieces **18a** and four pairs of the magnet pieces **18b** are alternately arranged in the circumferential direction about the center rotational axis **O** to define eight motor poles of the motor **10**. Specifically, in the illustrated embodiment, the north poles of the magnet pieces **18a** are radially outwardly arranged relative to the south poles of the magnet pieces **18a**, while the south poles of the magnet pieces **18b** are radially outwardly arranged relative to the north poles of the magnet pieces **18b**, for example. Thus, in the illustrated embodiment, the rotor **12** includes eight pairs of the magnet pieces **18a** and **18b** which are positioned between eight flux barriers **24** and spaced at 45 degree intervals in the circumferential direction about the center rotational axis **O**. However, the number of the magnet pieces **18a** and **18b** or the number of the magnets **18** can change with respect to a change in the number of flux barriers **24**. Furthermore, each magnet **18** can be configured as a single magnet piece or more than two magnet pieces. As shown in FIG. **1**, a d-axis

passes through a center of each magnet **18**. In other words, the d-axis passes through between the pair of magnet pieces **18a** or **18b**. On the other hand, a q-axis passes through each flux barriers **24**. In other words, the q-axis passes between adjacent pair of magnets **18**, or adjacent pair of the magnet pieces **18a** and **18b**. However, the magnets **18** or the flux barriers **24** can be positioned at any suitable location with respect to the d-axis and the q-axis to achieve the operability of the embodiments discussed herein. In the illustrated embodiment, the pair of the magnet pieces **18a** extends radially and inwardly as circumferentially moving towards each other. Similarly, the pair of the magnet pieces **18b** extends radially and inwardly as circumferentially moving towards each other. However, the magnet pieces **18a** and **18b** can be arranged in a different manner as needed and/or desired.

In the illustrated embodiment, the magnets **18** form a magnetic structure that produces magnetic flux that flows between different magnetic poles of the magnets **18** through a plurality of first main magnetic flux paths **40**, a plurality of second main magnetic flux paths **42**, and a plurality of leakage magnetic flux paths **46**. In the illustrated embodiment, as shown in FIG. **1**, each of the first main magnetic flux paths **40** extends from one magnetic pole of one of the magnets **18** (e.g., the north pole of the magnet piece **18a**) to the other magnetic pole of adjacent one of the magnets **18** (e.g., the south pole of the magnet piece **18b**), and passes through the stator winding **34** of the stator **14** via the air gap **20**, while each of the second main magnetic flux paths **42** extends from the one magnetic pole of the adjacent one of the magnets **18** (e.g., the north pole of the magnet piece **18b**) to the other magnetic pole of the one of the magnets **18** (e.g., the south pole of the magnet piece **18a**), and passes through the rotor core **16**. In the illustrated embodiment, a pair of the first and second main magnetic flux paths **40** and **42** forms a main magnetic flux path that passes through the stator winding **34** of the stator **14** via the air gap **20**. On the other hand, each of the leakage magnetic flux paths **46** is located within the rotor core **16** about an end portion of respective one of the magnet pieces **18a** and **18b** near the air gap **20**. In the illustrated embodiment, each of the leakage magnetic flux paths **46** extends between different magnetic poles of respective one of the magnet pieces **18a** and **18b** (e.g., between north pole and south pole of the magnet piece **18a** or **18b**) through respective one of the leakage sections **22** of the rotor core **16**.

As mentioned above, the rotor core **16** has the leakage sections **22**, the flux barriers **24** and the side openings **26**. Although only two pairs of the leakage sections **22** and only two pairs of the side openings **26** for two magnets **18** or two motor poles of the motor **10** are shown in FIG. **1**, the rotor core **16** has eight pairs of the leakage sections **22** and eight pairs of the side openings **26** corresponding to eight magnets **18** or eight motor poles of the motor **10** in total. Similarly, Although only one full and two partial flux barriers **24** for two magnets **18** or two motor poles of the motor **10** are shown in FIG. **1**, the rotor core **16** has eight flux barriers **24** between adjacent pairs of eight magnets **18** or eight motor poles of the motor **10** in total. However, the rotor core **16** can include as many numbers of the leakage sections **22**, the flux barriers **24** and the side openings **26** as deemed appropriate for the environment in which the motor **10** is employed. In the illustrated embodiment, the rotor core **16** is configured in a mirror symmetric manner with respect to the d-axis and the q-axis.

As shown in FIG. **1**, the leakage sections **22** basically include a U-shaped part that extends between different



magnetic poles of the magnets 18 to define the leakage magnetic flux paths 46 therewithin, respectively. In other words, in the illustrated embodiment, the leakage magnetic flux paths 46 extend through the leakage sections 22, respectively. As shown in FIG. 1, the leakage sections 22 for adjacent pairs of the magnets 18 circumferentially face with each other via the flux barriers 24, respectively. In other words, the flux barriers 24 are disposed between adjacent pairs of the leakage sections 22. Specifically, the flux barriers 24 are disposed between the adjacent pairs of the magnets 18 or the adjacent pairs of the motor poles of the motor 10 (e.g., between the magnet piece 18a and the magnet piece 18b that is adjacent to the magnet piece 18a). In the illustrated embodiment, the flux barriers 24 are configured as air gaps between the adjacent pairs of the leakage sections 22. Thus, the magnetic resistance calculated based on a magnetic path width and a magnetic path length of the leakage magnetic flux path 46 on the leakage section 22 is smaller than the magnetic resistance of a magnetic path extending between different magnetic poles of the adjacent pair of the magnets 18 (e.g., between the north pole of the magnet piece 18a and the south pole of the magnet piece 18b that is adjacent to the magnet piece 18a) through the flux barriers 24. In the illustrated embodiment, the flux barriers 24 are radially outwardly open to face with the inner circumference 30 of the stator 14, and radially extend from the outer circumference 28 of the rotor 12 to a position radially inward relative to a radially inward boundary of the side openings 26. In the illustrated embodiment, the flux barriers 24 are configured as air gaps. However, the flux barriers 24 can also include any suitable type of insulating material as is conventional in the art. The side openings 26 are circumferentially adjacent to the end portions of the magnet pieces 18a and 18b such that the leakage sections 22 are disposed between the flux barriers 24 and the side openings 26, respectively. Thus, the leakage magnetic flux paths 46 that extend through the leakage sections 22 extend on the rotor core 16 between the flux barriers 24 and the side openings 26, respectively.

In the illustrated embodiment, the rotor 12, the stator 14, and the magnets 18 (e.g., the magnetic structure) are further configured to satisfy the following expressions (1) and (2) for one motor pole of the motor 10.

$$V_s \geq \frac{R_g + R_s}{R_r} V_m \quad (1)$$

$$\eta = \frac{R_g + R_s}{R_b + R_g + R_s} \geq 0.2 \quad (2)$$

Here,  $V_s$  represents the magnetomotive force of the stator windings 34 for one motor pole of the motor 10, and  $V_m$  represents the magnetomotive force of the magnet 18 for one motor pole of the motor 10.  $R_g$  represents the magnetic resistance of the air gap 20 for one motor pole of the motor 10,  $R_s$  represents the magnetic resistance of the stator 14 along the first main magnetic flux path 40 for one motor pole of the motor 10,  $R_r$  represents the magnetic resistance of the rotor core 16 along the second main magnetic flux path 42 for one motor pole of the motor 10,  $R_b$  represents the magnetic resistance of the rotor core 16 along the leakage magnetic flux path 46, and  $\eta$  represents a ratio of a leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path 46 relative to a total magnetic flux of the magnetic flux that is produced by the magnet 18 for one motor pole of the motor 10. In particular,  $\eta$  repre-

sents a ratio of the leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path 46 relative to the total magnetic flux of the magnetic flux that is produced by the magnet 18 while the stator 14 is unloaded (i.e., while the magnetomotive force of the stator windings 34 is zero).

In the illustrated embodiment, the expression (1) represents the relationship between the magnetic resistance of the first and second main magnetic flux paths 40 and 42 and the leakage magnetic flux path 46, the magnetomotive force of the magnets 18, and the magnetomotive force of the stator 14 under the loaded condition of the stator 14 in which load current is applied to the stator 14. On the other hand, the expression (2) represents the relationship under the no-load condition in which load current is not applied to the stator 14.

With the motor 10 configured as above, the motor 10 has the flux barrier 24 serving as a magnetic barrier on the magnetic flux path of the magnetic flux induced by the stator 14 between adjacent pair of the magnets 18 such that the magnetic resistance of the leakage magnetic flux path 46 connecting between the different magnetic poles of the same magnet 18 is smaller than the magnetic resistance of the magnetic flux path connecting between different magnetic poles of the adjacent pair of the magnets 18. The motor 10 also has the side opening 26 about the end portion of the magnet 18. With this configuration, the motor 10 can achieve a motor property in which the flux linkage is maximized at the same level as that of the conventional motors under maximum loaded condition while keeping the flux linkage lower than that of conventional motors under low-loaded condition or no-load condition by configuring the motor 10 to satisfy the conditions expressed by the expressions (1) and (2).

In particular, in the illustrated embodiment, with the motor 10, more than 20% of the total magnetic flux of the magnetic flux that is produced by the magnets 18 leaks via the leakage magnetic flux paths 46 on the leakage sections 22 under the no-load condition. Furthermore, due to the flux barrier 24 and the side opening 26, the magnetic flux induced by the stator 14 mainly flows through the leakage magnetic flux paths 46, thereby canceling the leakage magnetic flux on the leakage magnetic flux paths 46 under the loaded condition. In particular, the leakage magnetic flux paths 46 are located near the flux barriers 24 to cross-couple with the q-axis, which cancels the leakage magnetic flux on the leakage magnetic flux paths 46 under the loaded condition. As a result, with the motor 10, high variable flux property in the amount of the flux linkage can be expected. For example, loss reduction by more than 20% can be expected at a high speed and low torque operation without eliminating torque capability. Also, maximum flux linkage can be obtained under the maximum loaded condition.

Also, the leakage sections 22 can serve as a reinforcement member that receives the centrifugal force exerted on the magnets 18 during rotation of the rotor 12. In the illustrated embodiment, the width of the leakage sections 22 naturally becomes larger. As a result, the motor 10 can be driven in a higher speed than the conventional motor, or the motor 10 can have a larger diameter than the conventional motor without deteriorating the motor output property.

Accordingly, with this configuration, the motor 10 can have a magnetic flux property that interlinks with the stator 14 such that the magnetic flux property changes according to the magnetic flux induced by the stator 14 without changing the magnetization level of the permanent magnet as in the conventional motor. Also, with the motor 10, the increase of

the copper loss can be suppressed and thus the motor efficiency in high speed and low torque operation can be improved. Also, since the same maximum magnetic flux linkage can be obtained at full load, the maximum motor output torque property can be maintained without any increase in the size of the motor.

In the illustrated embodiment, with the motor 10 in accordance with one aspect, the rotor 12, the stator 14, and the magnets 18 are configured to satisfy the expressions (1) and (2).

With this configuration, the flux linkage in the stator 14 due to the magnets 18 increases as the magnetic flux induced by the stator 14 increases. Thus, the flux linkage in the stator 14 is maximized at the maximum loaded condition. Furthermore, with this configuration, the rigidity of the rotor 12 is increased relative to a conventional rotor. Thus, the motor 10 can be provided with a rotor with a larger diameter, or can bear a higher speed operation. Accordingly, with this configuration, the increase of the copper loss can be suppressed and the iron loss in a high speed and low torque operation can be decreased while maintaining a maximum output, which improves the motor efficiency. Also, high variable flux property can be obtained by leaking the magnetic flux via the leakage magnetic flux path 46 that is highly cross-coupled with the q-axis.

In the illustrated embodiment, with the motor 10 in accordance with one aspect, the leakage magnetic flux path 46 extends between different magnetic poles of the same magnet piece 18a or 18b. In particular, the motor 10 has the leakage magnetic flux path 46 between opposite sides of the same magnet piece 18a or 18b.

With this configuration, the flux linkage can be changed according to the change in the magnetic flux induced by the stator 14 by merely providing a small leakage section 22 about the end portion of the magnet piece 18a or 18b. Thus, with this configuration, the motor efficiency can be improved while suppressing the increase in the size of the motor 10. Also, higher variable flux property can be obtained by highly cross-coupling the leakage magnetic flux path 46 with the q-axis.

In the illustrated embodiment, with the motor 10 in accordance with one aspect, the magnetic resistance calculated based on the magnetic path width and the magnetic path length of the leakage section 22 along the leakage magnetic flux path 46 is smaller than the magnetic resistance of the magnetic path extending between different magnetic poles of the adjacent pair of the magnets 18 (e.g., the magnet piece 18a and the adjacent magnet piece 18b that is adjacent to the magnet piece 18a).

With this configuration, the magnetic flux induced by the stator 14 and the leakage magnetic flux can be cross-coupled, and the change amount in the flux linkage due to increase of the load current in the stator 14 can be made larger. Thus, the iron loss in a high speed and low torque operation can be decreased, which improves the motor efficiency.

In the illustrated embodiment, with the motor 10 in accordance with one aspect, the rotor core 16 has the flux barrier 24 (e.g., the magnetic barrier) disposed between the adjacent pair of the magnets 18 (e.g., the magnet piece 18a and the adjacent magnet piece 18b that is adjacent to the magnet piece 18a), and the side opening 26 circumferentially adjacent to the end portion of the magnet piece 18a or 18b. The leakage magnetic flux path 46 extends on the rotor core 16 between the flux barrier 24 and the side opening 26.

With this configuration, the magnetic flux induced by the stator 14 and the leakage magnetic flux can be well cross-

coupled, and the change amount in the flux linkage due to increase of the load current in the stator 14 can be made larger. Thus, the iron loss in a high speed and low torque operation can be decreased, which improves the motor efficiency.

### Second Embodiment

Referring now to FIG. 2, a permanent magnet synchronous motor 50, which can also be referred to as an interior permanent magnet motor, is illustrated in accordance with a second embodiment will now be explained. In view of the similarity between the first and second embodiments, the parts of the second embodiment that are identical to or substantially identical to the parts of the first embodiment will be given the same reference numerals as the parts of the first embodiment. Moreover, the descriptions of the parts of the second embodiment that are identical to the parts of the first embodiment may be omitted for the sake of brevity. Specifically, the motor 50 can be identical to or substantially identical to the motor 10 in accordance with the first embodiment, except for the configuration of a rotor 52. Thus, detail description of the stator 14 will be omitted for the sake of brevity.

As shown in FIG. 2, the rotor 52 has a rotor core 56. The motor 50 also includes a plurality of magnets 58 that is fixedly mounted to the rotor core 56. The rotor core 56 is rotatable relative to the stator 14 about a center rotational axis O of the motor 50, and is radially inwardly disposed relative to the stator 14 with an air gap 60 therebetween. The rotor core 56 is configured to include a plurality pairs of leakage sections 62, a plurality of flux barriers 64 and a plurality pairs of side openings 66. The rotor core 56 is basically formed as a one-piece, unitary member. The configurations of the rotor core 56 will be further described in detail below.

In the illustrated embodiment, the stator 14 is concentrically arranged relative to the rotor 52 with respect to the center rotational axis O of the motor 50. As mentioned above, the stator 14 is radially outwardly disposed relative to the rotor 52 with the air gap 60 therebetween. In particular, as illustrated in FIG. 2, the air gap 60 is present between an outer circumference 68 of the rotor 52 and an inner circumference 30 of the stator 14 to enable the rotor 52 to rotate unrestrictedly or substantially unrestrictedly about the center rotational axis O.

In the illustrated embodiment, the magnets 58 are spaced between adjacent pairs of the flux barriers 64 about the circumference of the rotor 52. As shown in FIG. 2, each of the magnets 58 is formed as a one-piece, unitary member to define each of the motor poles of the motor 50 with alternate polarities. In the illustrated embodiment, eight magnets 58 are alternately arranged in the circumferential direction about the center rotational axis O to define eight motor poles of the motor 50. Specifically, in the illustrated embodiment, the magnets 58 longitudinally extend in a direction perpendicular or substantially perpendicular to a radial direction such that one magnetic pole of the magnets 58 is radially outwardly arranged relative to the other magnetic pole of the magnets 58, for example. Thus, in the illustrated embodiment, the rotor 52 includes eight magnets 58 which are positioned between eight flux barriers 64 and spaced at 45 degree intervals in the circumferential direction about the center rotational axis O. However, the number of the magnets 58 can change with respect to a change in the number of flux barriers 64. Furthermore, each magnet 58 can be configured as a plurality of magnet pieces. As shown in FIG.

2, a d-axis passes through a center of each magnet **58**. On the other hand, a q-axis passes through each flux barrier **64**. In other words, the q-axis passes between adjacent pair of magnets **58**. However, the magnets **58** or the flux barriers **64** can be positioned at any suitable location with respect to the d-axis and the q-axis to achieve the operability of the embodiments discussed herein. Also, the magnets **58** can be arranged in a different manner as needed and/or desired.

In the illustrated embodiment, the magnets **58** form a magnetic structure that produces magnetic fluxes that flow between different magnetic poles of the magnets **58** through a plurality of first main magnetic flux paths **40**, a plurality of second main magnetic flux paths **42**, and a plurality of leakage magnetic flux paths **46**. In the illustrated embodiment, as shown in FIG. 2, each of the first main magnetic flux paths **40** extends from one magnetic pole of one of the magnets **58** to the other magnetic pole of adjacent one of the magnets **58**, and passes through the stator winding **34** of the stator **14** via the air gap **60**, while each of the second main magnetic flux paths **42** extends from the one magnetic pole of the adjacent one of the magnets **58** to the other magnetic pole of the one of the magnets **58**, and passes through the rotor core **56**. In the illustrated embodiment, a pair of the first and second main magnetic flux paths **40** and **42** forms a main magnetic flux path that passes through the stator winding **34** of the stator **14** via the air gap **60**. On the other hand, the leakage magnetic flux path **46** is located within the rotor core **56** about an end portion of respective one of the magnets **58** near the air gap **60**. In the illustrated embodiment, each of the leakage magnetic flux paths **46** extends between different magnetic poles of respective one of the magnets **58** through respective one of the leakage sections **62** of the rotor core **56**, respectively.

As mentioned above, the rotor core **56** has the leakage sections **62**, the flux barriers **64** and the side openings **66**. Although only two pairs of the leakage sections **62** and only two pairs of side openings **66** for two magnets **58** or two motor poles of the motor **50** are shown in FIG. 2, the rotor core **56** has eight pairs of the leakage sections **62** and eight pairs of the side openings **66** corresponding to eight magnets **58** or eight motor poles of the motor **50** in total. Similarly, although only one full and two partial flux barriers **64** for two magnets **58** or two motor poles of the motor **50** are shown in FIG. 2, the rotor core **56** has eight flux barriers **64** between adjacent pairs of eight magnets **58** or eight motor poles of the motor **50** in total. However, the rotor core **56** can include as many numbers of the leakage sections **62**, the flux barriers **64** and the side openings **66** as deemed appropriate for the environment in which the motor **50** is employed. In the illustrated embodiment, the rotor core **56** is configured in a mirror symmetric manner with respect to the d-axis and the q-axis.

As shown in FIG. 2, the leakage sections **62** basically include a squared U-shaped part that extends between different magnetic poles of the magnets **58** to define the leakage magnetic flux paths **46** therewithin, respectively. In other words, in the illustrated embodiment, the leakage magnetic flux paths **46** extend through the leakage sections **62**, respectively. More specifically, as shown in FIG. 2, each of the leakage sections **62** mainly includes an outside circumferential portion **62a** (e.g., a circumferential portion), a radial portion **62b**, and an inside circumferential portion **62c** (e.g., a circumferential portion). The outside circumferential portion **62a** circumferentially extends away from respective one of the magnets **58**. The radial portion **62b** radially inwardly extends from the outside circumferential portion **62a**. In the illustrated embodiment, the radial portion **62b** extends per-

pendicular to or substantially perpendicular to the outside circumferential portion **62a**. The inside circumferential portion **62c** is disposed radially inwardly relative to the outside circumferential portion **62a**, and circumferentially extends towards the respective one of the magnets **58** from the radial portion **62b**. In the illustrated embodiment, the inside circumferential portion **62c** extends perpendicular to or substantially perpendicular to the radial portion **62b**. With this configuration, the leakage sections **62** define rectangular side openings **66** therewithin, respectively.

In the illustrated embodiment, as shown in FIG. 2, the leakage magnetic flux path **46** extends along the outside circumferential portion **62a**, the radial portion **62b**, and the inside circumferential portion **62c**. Specifically, as shown in FIG. 2, the outside and inside circumferential portions **62a** and **62c** have a magnetic path width **11** relative to the leakage magnetic flux path **46**, while the radial portion **62b** has a magnetic path width **12** relative to the leakage magnetic flux path **46** that is smaller than the magnetic path width **11** ( $11 > 12$ ). Also, as shown in FIG. 2, the outside and inside circumferential portions **62a** and **62c** have a magnetic path length **13** along the leakage magnetic flux path **46**, which also defines the dimension of one side of the rectangle side opening **66**. In the illustrated embodiment, the leakage sections **62** are configured such that the magnetic resistance of the circumferential portion calculated based on the magnetic path width (**11**) and the magnetic path length (**13**) of the leakage magnetic flux path **46** along the outside and inside circumferential portions **62a** and **62c** is smaller than the magnetic resistance of the radial portion **62b** calculated based on the magnetic path width (**12**) and a magnetic path length (between the outside and inside circumferential portions **62a** and **62c**) of the leakage magnetic flux path **46** along the radial portion **62b**. In particular, in the illustrated embodiment, the leakage sections **62** are configured such that the magnetic resistance of the outside and inside circumferential portions **62a** and **62c** calculated with the ratio of the magnetic path length (**13**) and magnetic path width (**11**) is smaller than the magnetic resistance of the radial portion **62b** calculated with the ratio of the magnetic path length (between the outside and inside circumferential portions **62a** and **62c**) and the magnetic path width (**12**). In particular, in the illustrated embodiment, the leakage sections **62** are configured such that the total magnetic resistance of the outside and inside circumferential portions **62a** and **62c** is smaller than the magnetic resistance of the radial portion **62b**. However, the leakage sections **62** can also be configured such that at least one of the magnetic resistance of the outside circumferential portion **62a** and the magnetic resistance of the inside circumferential portion **62c** is smaller than the magnetic resistance of the radial portion **62b**.

As shown in FIG. 2, the leakage sections **62** for adjacent pairs of the magnets **58** circumferentially face with each other via the flux barriers **64**, respectively. In other words, the flux barriers **64** are disposed between adjacent pairs of the leakage sections **62**. Specifically, the flux barriers **64** are disposed between the adjacent pairs of the magnets **58** or the adjacent pairs of the motor poles of the motor **50**. In the illustrated embodiment, the flux barriers **64** are configured as air gaps between the adjacent pairs of the leakage sections **62**. Thus, the magnetic resistance calculated based on a magnetic path width and a magnetic path length of the leakage magnetic flux path **46** on the leakage section **62** is smaller than the magnetic resistance of a magnetic path extending between different magnetic poles of the adjacent pair of the magnets **58** through the flux barriers **64**. In the

illustrated embodiment, the flux barriers **64** are radially outwardly open to face with the inner circumference **30** of the stator **14**, and radially extend from the outer circumference **68** of the rotor **52** to a position radially inward relative to a radially inward boundary of the magnets **58** or the leakage sections **62**. In the illustrated embodiment, the flux barriers **64** are configured as air gaps. However, the flux barriers **64** can also include any suitable type of insulating material as is conventional in the art. The side openings **66** are circumferentially adjacent to the end portions of the magnets **58** such that the leakage sections **62** are disposed between the flux barriers **64** and the side openings **66**, respectively. Thus, the leakage magnetic flux paths **46** that extend through the leakage sections **62** extend on the rotor core **56** between the flux barriers **64** and the side openings **66**, respectively.

In the illustrated embodiment, the rotor **52**, the stator **14**, and the magnets **58** (e.g., the magnetic structure) are further configured to satisfy the following expressions (1) and (2) for one motor pole of the motor **50**.

$$V_s \geq \frac{R_g + R_s}{R_r} V_m \quad (1)$$

$$\eta = \frac{R_g + R_s}{R_b + R_g + R_s} \geq 0.2 \quad (2)$$

Here,  $V_s$  represents the magnetomotive force of the stator windings **34** for one motor pole of the motor **50**, and  $V_m$  represents the magnetomotive force of the magnet **58** for one motor pole of the motor **50**.  $R_g$  represents the magnetic resistance of the air gap **60** for one motor pole of the motor **50**,  $R_s$  represents the magnetic resistance of the stator **14** along the first main magnetic flux path **40** for one motor pole of the motor **50**,  $R_r$  represents the magnetic resistance of the rotor core **56** along the second main magnetic flux path **42** for one motor pole of the motor **50**,  $R_b$  represents the magnetic resistance of the rotor core **56** along the leakage magnetic flux path **46**, and  $\eta$  represents a ratio of a leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path **46** relative to a total magnetic flux of the magnetic flux that is produced by the magnet **58** for one motor pole of the motor **50**. In particular,  $\eta$  represents a ratio of the leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path **46** relative to the total magnetic flux of the magnetic flux that is produced by the magnet **58** while the stator **14** is unloaded (i.e., while the magnetomotive force of the stator windings **34** is zero).

In the illustrated embodiment, the expression (1) represents the relationship between the magnetic resistance of the first and second main magnetic flux paths **40** and **42** and the leakage magnetic flux path **46**, the magnetomotive force of the magnets **58**, and the magnetomotive force of the stator **14** under the loaded condition of the stator **14** in which load current is applied to the stator **14**. On the other hand, the expression (2) represents the relationship under the no-load condition in which load current is not applied to the stator **14**.

With the motor **50** configured as above, the motor **50** basically has the same advantages as the motor **10** in accordance with the first embodiment. Furthermore, in the illustrated embodiment, each of the leakage sections **62** has the outside and inside circumferential portions **62a** and **62c** and the radial portion **62b**, and the leakage magnetic flux path **46** extends along the outside circumferential portion

**62a**, the radial portion **62b**, and the inside circumferential portion **62c**. Also, the magnetic resistance of the outside and inside circumferential portions **62a** and **62c** along the leakage magnetic flux path **46** is smaller than the magnetic resistance of the radial portion **62b** along the leakage magnetic flux path **46**. Thus, the motor **50** can achieve a motor property in which the flux linkage is maximized at the same level as that of the conventional motors under maximum load condition while keeping the flux linkage lower than that of conventional motors under low-loaded condition or no-load condition. Furthermore, the instantaneous change in the saliency ratio accompanied by the increase in the magnetic flux induced by the stator **14** can be suppressed. The saliency ratio is defined by the ratio of the inductance in the d-axis direction and the inductance in the q-axis. Generally, with the saliency-based rotor position sensing method, the variation of the saliency largely affects the detection accuracy. However, with the motor **50**, the detection accuracy can be largely improved. As a result, with this configuration, the manufacturing cost can be lowered by eliminating the rotor position sensor while improving the motor efficiency.

In the illustrated embodiment, with the motor **50** in accordance with one aspect, the rotor core **56** has the outside and inside circumferential portions **62a** and **62c** circumferentially extending and the radial portion **62b** radially extending between the outside and inside circumferential portions **62a** and **62c**. The leakage magnetic flux path **46** extends along the outside circumferential portion **62a**, the radial portion **62b**, and the inside circumferential portion **62c** of the rotor core **56**. The magnetic resistance of the outside and inside circumferential portions **62a** and **62c** calculated based on the magnetic path width **11** and the magnetic path length **13** of the leakage magnetic flux path **46** along the outside and inside circumferential portions **62a** and **62c** is smaller than the magnetic resistance of the radial portion **62b** calculated based on the magnetic path width **12** and the magnetic path length of the leakage magnetic flux path **46** along the radial portion **62b**.

With this configuration, the deterioration of the rotor position sensing property due to increase of the magnetic flux induced by the stator **14** can be suppressed. Thus, the manufacturing cost can be lowered by eliminating the rotor position sensor while improving the motor efficiency.

Also, with the motor **50**, the leakage magnet flux path **46** has a rectangular shape about the end portion of the magnet **58** along the leakage section **62**, which balances variable flux linkage and the self-sensing property. Furthermore, with the motor **50**, the magnetic path width **11** of the outside and inside circumferential portions **62a** and **62c** is larger than the magnetic path width **12** of the radial portion **62b**, which also improves the self-sensing property.

### Third Embodiment

Referring now to FIG. 3, a permanent magnet synchronous motor **70**, which can also be referred to as an interior permanent magnet motor, is illustrated in accordance with a second embodiment will now be explained. In view of the similarity between the first to third embodiments, the parts of the third embodiment that are identical to or substantially identical to the parts of the first and second embodiments will be given the same reference numerals as the parts of the first and second embodiment. Moreover, the descriptions of the parts of the third embodiment that are identical to the parts of the first and second embodiments may be omitted for the sake of brevity. Specifically, the motor **70** can be identical to or substantially identical to the motor **10** in

accordance with the first embodiment, except for the configuration of a rotor 72. Thus, detail description of the stator 14 will be omitted for the sake of brevity.

In the illustrated embodiment, the rotor 72 has a rotor core 76. The motor 70 also includes a plurality of magnets 78 that is fixedly mounted to the rotor core 76. The rotor core 76 is rotatable relative to the stator 14 about a center rotational axis O of the motor 70, and is radially inwardly disposed relative to the stator 14 with an air gap 80 therebetween. The rotor core 76 is configured to include a plurality of leakage sections 82, a plurality of flux barriers 84 and a plurality pairs of side openings 86. The rotor core 76 is basically formed as a one-piece, unitary member. The configurations of the rotor core 76 will be further described in detail below.

In the illustrated embodiment, the stator 14 is concentrically arranged relative to the rotor 72 with respect to the center rotational axis O of the motor 70. As mentioned above, the stator 14 is radially outwardly disposed relative to the rotor 72 with the air gap 80 therebetween. In particular, as illustrated in FIG. 3, the air gap 80 is present between an outer circumference 88 of the rotor 72 and an inner circumference 30 of the stator 14 to enable the rotor 72 to rotate unrestrictedly or substantially unrestrictedly about the center rotational axis O.

In the illustrated embodiment, the magnets 78 are spaced between adjacent pairs of the flux barriers 84 about the circumference of the rotor 72. As shown in FIG. 3, each of the magnets 78 has a pair of permanent magnet pieces 78a or 78b (e.g., at least one permanent magnet) to define each of the motor poles of the motor 70 with alternate polarities. In the illustrated embodiment, four pairs of the magnet pieces 78a and four pairs of the magnet pieces 78b are alternately arranged in the circumferential direction about the center rotational axis O to define eight motor poles of the motor 70. Specifically, in the illustrated embodiment, the north poles of the magnet pieces 78a are radially outwardly arranged relative to the south poles of the magnet pieces 78a, while the south poles of the magnet pieces 78b are radially outwardly arranged relative to the north poles of the magnet pieces 78b, for example. Thus, in the illustrated embodiment, the rotor 72 includes eight pairs of the magnet pieces 78a and 78b which are positioned between eight flux barriers 84 and spaced at 45 degree intervals in the circumferential direction about the center rotational axis O. However, the number of the magnet pieces 78a and 78b or the number of the magnets 78 can change with respect to a change in the number of flux barriers 84. Furthermore, each magnet 78 can be configured as a single magnet piece or more than two magnet pieces. As shown in FIG. 3, a d-axis passes through a center of each magnet 78. In other words, the d-axis passes through between the pair of magnet pieces 78a or 78b. On the other hand, a q-axis passes through each flux barriers 84. In other words, the q-axis passes between adjacent pair of magnets 78, or adjacent pair of the magnet pieces 78a and 78b. However, the magnets 78 or the flux barriers 84 can be positioned at any suitable location with respect to the d-axis and the q-axis to achieve the operability of the embodiments discussed herein. In the illustrated embodiment, the pair of the magnet pieces 78a extends radially and inwardly as circumferentially moving towards each other. Similarly, the pair of the magnet pieces 78b extends radially and inwardly as circumferentially moving towards each other. However, the magnet pieces 78a and 78b can be arranged in a different manner as needed and/or desired.

In the illustrated embodiment, the magnets 78 form a magnetic structure that produces magnetic flux that flows

between different magnetic poles of the magnets 78 through a plurality of first main magnetic flux paths 40, a plurality of second main magnetic flux paths 42, and a plurality of leakage magnetic flux paths 46. In the illustrated embodiment, as shown in FIG. 3, each of the first main magnetic flux paths 40 extends from one magnetic pole of one of the magnets 78 (e.g., the north pole of the magnet piece 78a) to the other magnetic pole of adjacent one of the magnets 78 (e.g., the south pole of the magnet piece 78b), and passes through the stator winding 34 of the stator 14 via the air gap 80, while each of the second main magnetic flux paths 42 extends from the one magnetic pole of the adjacent one of the magnets 78 (e.g., the north pole of the magnet piece 78b) to the other magnetic pole of the one of the magnets 78 (e.g., the south pole of the magnet piece 78a), and passes through the rotor core 76. In the illustrated embodiment, a pair of the first and second main magnetic flux paths 40 and 42 forms a main magnetic flux path that passes through the stator winding 34 of the stator 14 via the air gap 80. On the other hand, each of the leakage magnetic flux paths 46 is located within the rotor core 76 about an end portion of respective one of the magnet pieces 78a and 78b near the air gap 80. In the illustrated embodiment, each of the leakage magnetic flux paths 46 extends between different magnetic poles of an adjacent pair of the magnets 78 (e.g., between the north pole of the magnet piece 78a and the south pole of the magnet piece 78b) through respective one of the leakage sections 82 of the rotor core 76.

As mentioned above, the rotor core 76 has the leakage sections 82, the flux barriers 84 and the side openings 86. Although only one full and two partial leakage sections 82 and only one full and two partial flux barriers 84 for two magnets 78 or two motor poles of the motor 70 are shown in FIG. 3, the rotor core 76 has eight leakage sections 82 and eight flux barriers 84 corresponding to eight magnets 78 in total. Similarly, only two pairs the side openings 86 for two magnets 78 or two motor poles of the motor 70 are shown in FIG. 3, the rotor core 76 has eight pairs of the side openings 86 corresponding to eight magnets 78 or eight motor poles of the motor 70 in total. However, the rotor core 76 can include as many numbers of the leakage sections 82, the flux barriers 84 and the side openings 86 as deemed appropriate for the environment in which the motor 70 is employed. In the illustrated embodiment, the rotor core 76 is configured in a mirror symmetric manner with respect to the d-axis and the q-axis.

As shown in FIG. 3, the leakage sections 82 basically extend between different magnetic poles of adjacent pairs of the magnets 78, respectively, to define the leakage magnetic flux paths 46 therewithin, respectively. In other words, in the illustrated embodiment, the leakage magnetic flux paths 46 extend through the leakage sections 82, respectively. As shown in FIG. 3, the leakage sections 82 radially face with the inner circumference 30 of the stator 14 via the air gap 80. Specifically, each of the leakage sections 82 is present between the radially outward boundary of respective one of the flux barriers 84 and the outer circumference 88 of the rotor 72. Also, the leakage sections 82 circumferentially extend between adjacent pairs of the magnets 78. Thus, in the illustrated embodiment, the leakage magnetic flux paths 46 extend between different magnetic poles of the adjacent pairs of the magnets 78 (e.g., between the magnet piece 78a and the magnet piece 78b that is adjacent to the magnet piece 78a), respectively. As shown in FIG. 3, the flux barriers 84 are also circumferentially disposed between adjacent pairs of the magnets 78 or between adjacent pairs of the side openings 86. Specifically, the flux barriers 84 are disposed

between the adjacent pairs of the magnets **78** or the adjacent pairs of the motor poles of the motor **70** (e.g., between the magnet piece **78a** and the magnet piece **78b** that is adjacent to the magnet piece **78a**). In the illustrated embodiment, the flux barriers **84** are configured as air gaps between the adjacent pairs of the magnets **78** (e.g., between the magnet piece **78a** and the magnet piece **78b** that is adjacent to the magnet piece **78a**) such that the magnetic resistance calculated based on a magnetic path width and a magnetic path length of the leakage magnetic flux path **46** is smaller than the magnetic resistance of a magnetic path extending between different magnetic poles of the same magnets **78** (e.g., between the north pole of the magnet piece **78a** and the south pole of the same magnet piece **78a**) through the flux barriers **84**. In the illustrated embodiment, the flux barriers **84** are configured as air gaps. However, the flux barriers **84** can also include any suitable type of insulating material as is conventional in the art. The side openings **86** are circumferentially adjacent to the end portions of the magnet pieces **78a** and **78b**.

In the illustrated embodiment, the rotor **72**, the stator **14**, and the magnets **78** (e.g., the magnetic structure) are further configured to satisfy the following expressions (1) and (2) for one motor pole of the motor **70**.

$$V_s \geq \frac{R_g + R_s}{R_r} V_m \quad (1)$$

$$\eta = \frac{R_g + R_s}{R_b + R_g + R_s} \geq 0.2 \quad (2)$$

Here,  $V_s$  represents the magnetomotive force of the stator windings **34** for one motor pole of the motor **70**, and  $V_m$  represents the magnetomotive force of the magnet **78** for one motor pole of the motor **70**.  $R_g$  represents the magnetic resistance of the air gap **80** for one motor pole of the motor **70**,  $R_s$  represents the magnetic resistance of the stator **14** along the first main magnetic flux path **40** for one motor pole of the motor **70**,  $R_r$  represents the magnetic resistance of the rotor core **76** along the second main magnetic flux path **42** for one motor pole of the motor **70**,  $R_b$  represents the magnetic resistance of the rotor core **76** along the leakage magnetic flux path **46**, and  $\eta$  represents a ratio of a leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path **46** relative to a total magnetic flux of the magnetic flux that is produced by the magnet **78** for one motor pole of the motor **70**. In particular,  $\eta$  represents a ratio of the leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path **46** relative to the total magnetic flux of the magnetic flux that is produced by the magnet **78** while the stator **14** is unloaded (i.e., while the magnetomotive force of the stator windings **34** is zero).

In the illustrated embodiment, the expression (1) represents the relationship between the magnetic resistance of the first and second main magnetic flux paths **40** and **42** and the leakage magnetic flux path **46**, the magnetomotive force of the magnets **78**, and the magnetomotive force of the stator **14** under the loaded condition of the stator **14** in which load current is applied to the stator **14**. On the other hand, the expression (2) represents the relationship under the no-load condition in which load current is not applied to the stator **14**.

With the motor **70** configured as above, the motor **70** basically has the same advantages as the motor **10** in accordance with the first embodiment. Furthermore, in the

illustrated embodiment, as shown in FIG. 3, the motor **70** has the leakage magnetic flux paths **46** extending between different magnetic poles of the adjacent pairs of the magnets **78** (e.g., between the north pole of the magnet piece **78a** and the south pole of the magnet piece **78b** that is adjacent to the magnet piece **78a**), and the motor **70** is configured to satisfy the conditions expressed by the expressions (1) and (2).

As shown in FIG. 3, the motor **70** has the flux barriers **84** as a magnetic barrier between different magnetic poles of the same magnets **78** (e.g., the magnet piece **78a** or **78b**) such that the magnetic resistance of the leakage magnetic flux path **46** extending between different magnetic poles of the adjacent pair of the magnets **78** (e.g., between different magnetic poles of the magnet piece **78a** and the magnet piece **78b**) is smaller than the magnetic resistance of the magnetic flux path extending between different magnetic poles of the same magnet **78**. With this configuration, a large magnetic barrier does not need to be provided on the magnetic flux path of the magnetic flux induced by the stator **14**. Thus, the saliency ratio can be made larger, which can increase the reluctance torque and maintain high power factor of the motor under the load condition. Thus, with this configuration, the increase of the copper loss can be suppressed and thus the motor efficiency in the high speed and low torque operation can be improved. Also, since the same maximum magnetic flux linkage can be obtained at full load, the maximum motor output torque property can be maintained without any increase in the size of the motor.

In the illustrated embodiment, with the motor **70** in accordance with one aspect, the leakage magnetic flux path **46** extends between different magnetic poles of the adjacent pair of the magnets **78**.

With this configuration, the flux linkage can be changed according to the change in the magnetic flux induced by the stator **14** by merely providing a small leakage section **82** near the air gap **80**. Thus, with this configuration, the motor efficiency can be improved while suppressing the increase in the size of the motor. Also, with this configuration, high q-axis inductance can be maintained to obtain high power factor operation.

In the illustrated embodiment, with the motor **70** in accordance with one aspect, the rotor core **76** has the magnetic barrier **84** that extends between the adjacent pair of the magnets **78** such that the magnetic resistance calculated based on a magnetic path width and a magnetic path length of the leakage magnetic flux path **46** is smaller than the magnetic resistance of a magnetic path extending between different magnetic poles of the same magnet **78**.

With this configuration, a large magnetic barrier does not need to be provided on the magnetic flux path of the magnetic flux induced by the stator **14**, and the reluctance torque can be increased. Thus, the power factor of the motor under the load condition, and the motor efficiency can be improved while suppressing the drop of the motor output.

Also, with the motor **70**, the due to higher inductance in the q-axis direction, higher power factor can be obtained while keeping the same torque compared to a self-leakage type structure.

#### General Interpretation of Terms

In understanding the scope of the present invention, the term "comprising" and its derivatives, as used herein, are intended to be open ended terms that specify the presence of the stated features, elements, components, groups, integers, and/or steps, but do not exclude the presence of other unstated features, elements, components, groups, integers

and/or steps. The foregoing also applies to words having similar meanings such as the terms, “including”, “having” and their derivatives. Also, the terms “part,” “section,” “portion,” “member” or “element” when used in the singular can have the dual meaning of a single part or a plurality of parts. The terms of degree such as “substantially”, “about” and “approximately” as used herein mean a reasonable amount of deviation of the modified term such that the end result is not significantly changed.

While only selected embodiments have been chosen to illustrate the present invention, it will be apparent to those skilled in the art from this disclosure that various changes and modifications can be made herein without departing from the scope of the invention as defined in the appended claims. For example, the size, shape, location or orientation of the various components can be changed as needed and/or desired. Components that are shown directly connected or contacting each other can have intermediate structures disposed between them. The functions of one element can be performed by two, and vice versa. The structures and functions of one embodiment can be adopted in another embodiment. It is not necessary for all advantages to be present in a particular embodiment at the same time. Every feature which is unique from the prior art, alone or in combination with other features, also should be considered a separate description of further inventions by the applicant, including the structural and/or functional concepts embodied by such features. Thus, the foregoing descriptions of the embodiments according to the present invention are provided for illustration only, and not for the purpose of limiting the invention as defined by the appended claims and their equivalents.

What is claimed is:

1. A permanent magnet synchronous motor comprising: a stator with a stator winding;

a rotor with a rotor core rotatable relative to the stator, the rotor being radially inwardly or outwardly disposed relative to the stator with an air gap therebetween; and a magnetic structure with at least one permanent magnet mounted to the rotor core, the magnetic structure producing a magnetic flux that flows between different magnetic poles of the magnetic structure through a main magnetic flux path that passes through the stator winding of the stator via the air gap and a leakage magnetic flux path that is located within the rotor core about an end portion of the permanent magnet near the air gap,

the stator, the rotor and the magnetic structure being further configured to satisfy the following expressions while changing a magnetization state of the permanent magnet of the permanent magnet synchronous motor:

$$V_s \geq \frac{R_g + R_s}{R_r} V_m$$

$$\eta = \frac{R_g + R_s}{R_b + R_g + R_s} \geq 0.2$$

where  $V_s$  represents magnetomotive force of the stator winding,  $V_m$  represents magnetomotive force of the magnetic structure,  $R_g$  represents magnetic resistance of the air gap,  $R_s$  represents magnetic resistance of the stator along the main magnetic flux path,  $R_r$  represents magnetic resistance of the rotor core along the main magnetic flux path,  $R_b$  represents magnetic resistance of the rotor core along the leakage magnetic flux path, and  $\eta$  represents a ratio of a

leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path relative to a total magnetic flux of the magnetic flux that is produced by the magnetic structure.

2. The permanent magnet synchronous motor according to claim 1, wherein

the leakage magnetic flux path extends between different magnetic poles of the permanent magnet.

3. The permanent magnet synchronous motor according to claim 2, wherein

the rotor core has a magnetic barrier disposed between the permanent magnet and an adjacent permanent magnet that is adjacent to the permanent magnet, and a side opening circumferentially adjacent to the end portion of the permanent magnet, and

the leakage magnetic flux path extends on the rotor core between the magnetic barrier and the side opening.

4. A permanent magnet synchronous motor comprising:

a stator with a stator winding;

a rotor with a rotor core rotatable relative to the stator, the rotor being radially inwardly or outwardly disposed relative to the stator with an air gap therebetween; and a magnetic structure with at least one permanent magnet mounted to the rotor core, the magnetic structure producing a magnetic flux that flows between different magnetic poles of the magnetic structure through a main magnetic flux path that passes through the stator winding of the stator via the air gap and a leakage magnetic flux path that is located within the rotor core about an end portion of the permanent magnet near the air gap,

the stator, the rotor and the magnetic structure being further configured to satisfy the following expressions:

$$V_s \geq \frac{R_g + R_s}{R_r} V_m$$

$$\eta = \frac{R_g + R_s}{R_b + R_g + R_s} \geq 0.2$$

where  $V_s$  represents magnetomotive force of the stator winding,  $V_m$  represents magnetomotive force of the magnetic structure,  $R_g$  represents magnetic resistance of the air gap,  $R_s$  represents magnetic resistance of the stator along the main magnetic flux path,  $R_r$  represents magnetic resistance of the rotor core along the main magnetic flux path,  $R_b$  represents magnetic resistance of the rotor core along the leakage magnetic flux path, and  $\eta$  represents a ratio of a leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path relative to a total magnetic flux of the magnetic flux that is produced by the magnetic structure,

the leakage magnetic flux path extending between different magnetic poles of the permanent magnet,

the rotor core having a circumferential portion circumferentially extending and a radial portion radially extending from the circumferential portion,

the leakage magnetic flux path extending along the circumferential portion and the radial portion of the rotor core, and

the magnetic resistance of the circumferential portion calculated based on a magnetic path width and a magnetic path length of the leakage magnetic flux path along the circumferential portion being smaller than the magnetic resistance of the radial portion calculated

19

based on a magnetic path width and a magnetic path length of the leakage magnetic flux path along the radial portion.

5. The permanent magnet synchronous motor according to claim 1, wherein

the leakage magnetic flux path extends between different magnetic poles of the permanent magnet and an adjacent permanent magnet that is adjacent to the permanent magnet.

6. A permanent magnet synchronous motor comprising: a stator with a stator winding;

a rotor with a rotor core rotatable relative to the stator, the rotor being radially inwardly or outwardly disposed relative to the stator with an air gap therebetween; and a magnetic structure with at least one permanent magnet mounted to the rotor core, the magnetic structure producing a magnetic flux that flows between different magnetic poles of the magnetic structure through a main magnetic flux path that passes through the stator winding of the stator via the air gap and a leakage magnetic flux path that is located within the rotor core about an end portion of the permanent magnet near the air gap,

the stator, the rotor and the magnetic structure being further configured to satisfy the following expressions:

$$V_s \geq \frac{R_g + R_s}{R_r} V_m$$

$$\eta = \frac{R_g + R_s}{R_b + R_g + R_s} \geq 0.2$$

where  $V_s$  represents magnetomotive force of the stator winding,  $V_m$  represents magnetomotive force of the magnetic structure,  $R_g$  represents magnetic resistance of the air gap,  $R_s$  represents magnetic resistance of the stator along the main magnetic flux path,  $R_r$  represents magnetic resistance of the rotor core along the main magnetic flux path,  $R_b$  represents magnetic resistance of the rotor core along the leakage magnetic flux path, and  $\eta$  represents a ratio of a leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path relative to a total magnetic flux of the magnetic flux that is produced by the magnetic structure,

the leakage magnetic flux path extending between different magnetic poles of the permanent magnet and an adjacent permanent magnet that is adjacent to the permanent magnet, and

the rotor core having a magnetic barrier that extends between the permanent magnet and the adjacent permanent magnet such that the magnetic resistance calculated based on a magnetic path width and a magnetic path length of the leakage magnetic flux path is smaller than the magnetic resistance of a magnetic path extending between different magnetic poles of the permanent magnet.

7. A permanent magnet synchronous motor comprising: a stator with a stator winding;

a rotor with a rotor core rotatable relative to the stator, the rotor being radially inwardly or outwardly disposed relative to the stator with an air gap therebetween; and a magnetic structure with at least one permanent magnet mounted to the rotor core, the magnetic structure pro-

20

ducing a magnetic flux that flows between different magnetic poles of the magnetic structure through a main magnetic flux path that passes through the stator winding of the stator via the air gap and a leakage magnetic flux path that is located within the rotor core about an end portion of the permanent magnet near the air gap,

the stator, the rotor and the magnetic structure being further configured to satisfy the following expressions:

$$V_s \geq \frac{R_g + R_s}{R_r} V_m$$

$$\eta = \frac{R_g + R_s}{R_b + R_g + R_s} \geq 0.2$$

where  $V_s$  represents magnetomotive force of the stator winding,  $V_m$  represents magnetomotive force of the magnetic structure,  $R_g$  represents magnetic resistance of the air gap,  $R_s$  represents magnetic resistance of the stator along the main magnetic flux path,  $R_r$  represents magnetic resistance of the rotor core along the main magnetic flux path,  $R_b$  represents magnetic resistance of the rotor core along the leakage magnetic flux path, and  $\eta$  represents a ratio of a leakage magnetic flux of the magnetic flux that flows through the leakage magnetic flux path relative to a total magnetic flux of the magnetic flux that is produced by the magnetic structure,

the leakage magnetic flux path extending between different magnetic poles of the permanent magnet, and the magnetic resistance calculated based on a magnetic path width and a magnetic path length of the leakage magnetic flux path being smaller than the magnetic resistance of a magnetic path extending between different magnetic poles of the permanent magnet and an adjacent permanent magnet that is adjacent to the permanent magnet.

8. The permanent magnet synchronous motor according to claim 7, wherein

the rotor core has a magnetic barrier disposed between the permanent magnet and an adjacent permanent magnet that is adjacent to the permanent magnet, and a side opening circumferentially adjacent to the end portion of the permanent magnet, and

the leakage magnetic flux path extends on the rotor core between the magnetic barrier and the side opening.

9. The permanent magnet synchronous motor according to claim 7, wherein

the rotor core has a circumferential portion circumferentially extending and a radial portion radially extending from the circumferential portion,

the leakage magnetic flux path extends along the circumferential portion and the radial portion of the rotor core, and

the magnetic resistance of the circumferential portion calculated based on a magnetic path width and a magnetic path length of the leakage magnetic flux path along the circumferential portion is smaller than the magnetic resistance of the radial portion calculated based on a magnetic path width and a magnetic path length of the leakage magnetic flux path along the radial portion.

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