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Brushless Synchronous Motor With Low Cogging Torque

Abstract

A brushless synchronous motor includes a stator disposed about a rotational axis and defining radially inwardly extending teeth about which conductors are wound in a distributed winding layout to define multiple motor phases. Each tooth defines a shoe at a radially inner end spaced from a circumferentially adjacent shoe by a stator shoe gap. A rotor within the stator rotates relative to the stator about the rotational axis and includes a shaft and magnet tiles supported on the shaft and covered with a magnet tile retention sleeve. Each magnet tile is spaced from a circumferentially adjacent magnet tile by a magnet tile gap. The magnet tile gap tapers moving from a radially outer end to a radially inner end of the gap and a width of the gap at the radially outer end of the gap is less than or equal to a width of the stator shoe gap.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application claims priority to U.S. Provisional Patent Application No. 63/555,425 filed on Feb. 20, 2024, the entire disclosure of which is incorporated herein by reference herein.

BACKGROUND OF THE INVENTION
a. Field of the Invention
[0002] This disclosure relates to brushless synchronous motors. In particular, the disclosure relates to a brushless permanent magnet synchronous motor in which magnet tiles in the motor are profiled to minimize cogging torque in the motor.
b. Background Art
[0003] A conventional brushless synchronous motor includes a stator and a rotor. The stator includes a plurality of radially inwardly extending teeth defining slots between the teeth in which conductors are wound. The rotor includes a substantially square shaft supporting a plurality of magnet tiles. Conventional brushless synchronous motors produce an undesirable cogging torque resulting from the interaction of the magnet tiles and the ferromagnetic teeth of the stator. This cogging torque creates a non-uniform torque output, or torque ripple, for the motor that is particularly noticeable in low-speed operations and must be minimized in certain applications such as medical shavers. To reduce cogging torque, the magnet tiles of the motor may have a profile with a non-uniform thickness that is greatest at a circumferential center of the magnet tile (such that the magnet tile is sometimes referred to as a “bread-loaf” magnet tile). This magnet tile profile facilitates a reduction in cogging torque as well as generation of a sinusoidal back electromotive force (back-emf) constant (Ke) waveform. Nevertheless, this profile does not eliminate cogging torque and the existence of cogging torque remains a significant issue in certain motors including, for example, motors in which the ratio of an active length of the motor to an outer diameter of the motor is relatively large and motors having relatively small outer diameters (e.g., less than 12 mm).
[0004] One conventional method for further reducing cogging torque involves skewing the stator or rotor by rotationally shifting each lamination of the stator or rotor. Skewing increases the complexity and time required for assembly of the motor. The effectiveness of skewing is also limited in certain motors. In particular, in motors having a relatively long active length, skewing the stator results in slot configurations that create significant difficulties for inserting windings into the slots. In motors having bread-loaf shaped magnet tiles, skewing the rotor must be done in a step-wise fashion rather than continuously limiting the ability to further reduce cogging torque.
[0005] Another conventional method for reducing cogging torque is to optimize the ratio of the pole arc angle for a bread-loaf magnet tile (i.e., the angle centered on the rotational axis of the rotor and spanning from one circumferential end of the magnet tile to the opposite circumferential end of the magnet tile) to the pole pitch angle (i.e., the angle centered on the rotational axis of the rotor and spanning from a point on one magnet tile to a corresponding point on a circumferentially adjacent magnet tile). The effectiveness of this approach is again limited in certain motors. In particular, in motors having relatively small diameters, the ability to vary the ratio of the pole arc angle to the pole pitch angle is limited.
[0006] The inventor herein has recognized a need for a brushless synchronous motor that will minimize and/or eliminate one or more of the above-identified deficiencies.
BRIEF SUMMARY OF THE INVENTION
[0007] This disclosure relates to brushless synchronous motors. In particular, the disclosure relates

to a brushless permanent magnet synchronous motor profiled to minimize cogging torque in the motor.

[0008] A brushless synchronous motor in accordance with one embodiment includes a stator disposed about a rotational axis. The stator defines a plurality of radially inwardly extending teeth about which conductors are wound in a distributed winding layout to define multiple motor phases. Each tooth of the plurality of teeth defines a shoe at a radially inner end of the tooth and spaced from a circumferentially adjacent shoe of a circumferentially adjacent tooth by a stator shoe gap. The motor further includes a rotor disposed within the stator and configured for rotation relative to the stator about the rotational axis. The rotor includes a shaft and a plurality of magnet tiles supported on the shaft and covered with a magnet tile retention sleeve. Each magnet tile of the plurality of magnet tiles is spaced from a circumferentially adjacent magnet tile by a magnet tile gap. The magnet tile gap tapers moving from a radially outer end of the magnet tile gap to a radially inner end of the magnet tile gap and a width of the magnet tile gap at the radially outer end of the magnet tile gap is less than or equal to a width of the stator shoe gap.

[0009] A brushless synchronous motor in accordance with the teachings herein is advantageous relative to conventional brushless synchronous motors. In particular, the motor produces less cogging torque than conventional motors and is particularly useful for motors having a relatively large ratio of the active length of the motor to the outer diameter of the motor in which conventional methods for reducing cogging torque are impractical. Further, the motor enables a reduction in cogging torque without negatively impacting other performance factors associated with the motor such as back-emf constant, torque to weight ratio and thermal performance.

[0010] The foregoing and other aspects, features, details, utilities, and advantages of the present teachings will be apparent from reading the following description and claims, and from reviewing the accompanying drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIGS. **1-2** are cross-sectional views of prior art brushless synchronous motors.

[0012] FIG. **3** is a cross-sectional view of one embodiment of a brushless synchronous motor in accordance with teachings herein.

[0013] FIG. **4** is a cross-sectional view of one embodiment of a brushless synchronous motor in accordance with teachings herein.

[0014] FIG. **5** is an enlarged cross-sectional view of a portion of the motor of FIGS. **3-4** illustrating various dimensions associated with the motor.

[0015] FIG. **6** is a graph illustrating cogging torque at different rotational positions of the rotor for each of the motors shown in FIGS. **1**, **2** and **3-4**.

[0016] FIG. **7** is graph illustrating cogging torque at different harmonic orders for each of the motors shown in FIGS. **1**, **2** and **3-4**.

[0017] FIG. **8** is a graph illustrating a back electromotive force (back-emf) constant (Ke) at different rotational positions of the rotor for each of the motors shown in FIGS. **1**, **2** and **3-4**.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

[0018] Referring now to the drawings wherein like reference numerals are used to identify identical components in the various views, FIG. **1** illustrates a prior art brushless synchronous motor **10**. Motor **10** includes a stator **12** and a rotor **14**.

[0019] Stator **12** is provided to generate a rotating magnetic field which interacts with the magnetic field generated by rotor **14** to generate torque and to cause rotation of rotor **14**. Stator **12** is disposed about an axis **16** and may comprise a plurality of laminations that are formed from a material, such as silicon-iron, having a relatively low magnetic reluctance and are stacked along axis **16**. Stator **12** includes a plurality of radially inwardly extending teeth **18**. Teeth **18** are generally rectangular in cross-section and define stator slots **20** between circumferentially adjacent teeth **18** configured to receive coils or other conductors that are wound about the teeth **18** and used to produce magnetic fields and corresponding rotation of rotor **14**. Each tooth **18** may define a stator shoe **22** at a radially inner end projecting in both circumferential directions to support the conductors and configured the magnetic fields. Circumferentially adjacent stator shoes **22** define a stator shoe gap **24** at a radially inner end of each slot **20**. Teeth **18** and shoes **22** define a bore configure to receive rotor **14**.

[0020] Rotor **14** is provided to drive a load (not shown) connected to rotor **14**. Rotor **14** includes a shaft **26** and a plurality of magnet tiles **28** supported on shaft **26**. Shaft **26** is provided to directly or indirectly engage and drive the load. Shaft **26** extends longitudinally along axis **16** and is disposed about, and may be centered about, axis **16**. Shaft **26** may be substantially square in cross-section. Magnet tiles **28** generate magnetic fields that interact with the magnetic fields generated by stator **12** to cause rotation of rotor **14**. Magnet tiles **28** are magnetized and may comprise permanent magnets. Magnet tiles **28** have a “bread-loaf” shape. Each magnet tile **28** has a radially inner surface **30** that is flat and engages one side of shaft **26** and a radially outer surface **32** that is curved such that the radial thickness of the magnet tile **28** varies between a maximum thickness at a circumferential center of the magnet tile **28** and a minimum thickness at each circumferential edge of the magnet tile **28**. Each magnet tile **28** further includes opposed circumferential side surfaces **34**, **36** extending between surfaces **30**, **32** and that are perpendicular to surface **30**. As a result, adjacent magnet tiles **28** define magnet tile gaps **38** having a width that increases moving radially outwardly from shaft **26**. The width of the magnet tile gap **38** at the radially outermost end of the gap is relatively large and, in particular, larger than the stator shoe gap **24**. In motor **10**, the ratio of the pole arc angle τ.sub.a to the pole pitch angle τ.sub.p is between 0.7 and 0.8.

[0021] Referring now to FIG. **2**, another prior art brushless synchronous motor **40** is shown. Motor **40** is substantially similar to motor **10** and like reference numbers are used to identify similar components. Motor **40** differs from motor **10** in that rotor **14** includes magnet tiles **42** that differ from magnet tiles **28** in motor **10**. Magnet tiles **42** again have a radially inner surface **44** that is flat and engages one side of shaft **26** and a radially outer surface **46** that is curved such that the radial thickness of the magnet tile **42** varies between a maximum thickness at a circumferential center of the magnet tile **42** and a minimum thickness at each circumferential edge of the magnet tile **42**. Each magnet tile **42** further includes opposed circumferential side surfaces **48**, **50** extending between surfaces **44**, **46**. In contrast to magnet tile **28** of motor **10**, the radially outer surface **46** of magnet tile **42** in motor **40** has a greater circumferential length than the radially outer surface **32** of magnet tile **28** and the side surfaces **48**, **50** of magnet tile **42** intersect surface **44** of magnet tile **42** at an angle close to ninety mechanical degrees resulting in a nearly complete circle formed by magnet tiles **42** and very narrow magnet tile gaps **52** that have a uniform or constant circumferential width. In motor **40**, the ratio of the pole arc angle τ.sub.a to the pole pitch angle τ.sub.p is between 0.95 and 0.98.

[0022] Motors **10**, **40** continue to generate an undesirable amount of cogging torque. As discussed hereinabove, the cogging torque can be further mitigated by skewing the stator **12** or rotor **14** or my optimizing the ratio of the pole arc angle to pole pitch angle. In motors having a relative high ratio of the active length of the motor to the outer diameter of the motor, however, these methods of reducing cogging torque may create other problems or may not be feasible. Referring now to FIGS. **3-4**, motor **54** has been developed to overcome these issues.

[0023] Motor **54** is a brushless synchronous motor. Motor **54** is relatively small and long and is configured for use in applications such as medical shavers in which both motor performance and ergonomics/ease of handling are important factors in designing the device. Due to the intended application, motor **54** is configured as a relatively long, but small motor and, in particular, a motor having an active length LA along the rotational axis **56** of motor **54** that is at least four times as large as the diameter D of the motor **54**. As discussed hereinabove, traditional methods for reducing cogging torque in motors have limitations in motors with such a configuration. Motor **54** includes a motor housing **58**, a stator **60**, a rotor **62** and a rotor position feedback system **64**.

[0024] Motor housing **58** is provided to position and orient the other components of motor **54** and to protect those components from foreign objects and elements. Housing **58** may be made from non-magnetic stainless steel. Housing **58** may include multiple members **66**, **68**. Member **66** is disposed about, and may be centered about axis **56**. Member **66** is tubular in shape and is configured to receive stator **60** and rotor **62** therein. Member **66** defines an endbell at one axial end of motor **54** configured to receive a bearing **70**. Member **68** is also disposed about, and may be centered about axis **56**. Member **68** is disposed at the opposite axial end of motor **54** and defines another endbell configured to receive a bearing **72**. Member **68** is configured to receive rotor position feedback system **64** and to isolate rotor position feedback system **64** from stator **60**. Member **68** may define passages for routing wires from stator **60** to external devices (e.g., a motor controller).

[0025] Stator **60** is provided to generate a rotating magnetic field that interacts with a magnetic field generated by rotor **62** to develop a torque and to cause rotation of rotor **62**. Stator **60** is disposed about, and may be centered about, axis **56** and may comprise a plurality of laminations that are formed from a material, such as silicon-iron, having a relatively low magnetic reluctance and are stacked along axis **56**. Stator **60** is preferably not skewed. Referring to FIG. **4**, stator **60** includes a plurality of radially inwardly extending teeth **74**. In the illustrated embodiment, stator **60** includes twelve teeth **74**, but it should be understood that the number of teeth may vary. Teeth **74** are generally rectangular in cross-section and define stator slots **76** between circumferentially adjacent teeth **74** configured to receive coils or other conductors **78** (see FIG. **3**) that are wound about the teeth **74** and used to produce magnetic fields and corresponding rotation of rotor **62**. The conductors **78** are wound about teeth **74** in a distributed winding layout to define multiple motor phases (e.g., three motor phases; it should be understood, however, that the number of motor phases may vary). Further, the ratio of the number of slots **76** relative to the number of poles times the number of motors phases may be one. Each tooth **74** may define a stator shoe **80** at a radially inner end projecting in both circumferential directions to support the conductors **78** and configure the magnetic fields generated by stator **60**. Each stator shoe **80** is spaced from a circumferentially adjacent stator shoe **80** of a circumferentially adjacent stator tooth **74** by a stator shoe gap **82** formed at a radially inner end of each slot **76**. Teeth **74** and shoes **80** define a bore configure to receive rotor **62**.

[0026] Rotor **62** is provided to move a load (not shown) connected to rotor **62** such as a cutting tool for shaving bone. Rotor **62** is disposed within stator **60** and configured for rotation relative to stator **60** about axis **56**. Rotor **62** is preferably not skewed. Rotor **62** includes a shaft **84**, a plurality of magnet tiles **86** supported on shaft **84**, and a magnet tile retention sleeve **88** (FIG. **3**) disposed about magnet tiles **86** and configured to maintain the position of magnet tiles **86**.

[0027] Shaft **84** is provided to directly or indirectly engage and drive the load such as a cutting tool in a medical shaver. Referring to FIG. **3**, shaft **84** extends longitudinally along axis **56** and is disposed about, and may be centered about, axis **56**. Shaft **84** is supported within motor housing **58** and, in particular, within the opposed endbells of motor housing **58** by bearings **70**, **72**. One axial end of shaft **84** extends outward from motor housing **58** for direct or indirect connection to the load. The other axial end of shaft **84** is disposed proximate rotor position feedback system **64** and may support elements of a conventional encoder to allow rotor position feedback system **64** to monitor the position of rotor **62**. Referring again to FIG. **4**, shaft **84** may be square or substantially square in cross-section.

[0028] Magnet tiles **86** generate magnetic fields that interact with the magnetic fields generated by stator **60** to cause rotation of rotor **62**. In the illustrated embodiment, rotor **62** includes four magnet tiles **86**, but it should be understood that the number of magnet tiles **86** may vary. Magnet tiles **86** are magnetized and may comprise permanent magnets. In accordance with one aspect of the teachings disclosed herein, magnet tiles **86** are magnetized in a direction parallel to a thickness of the magnet title. Each magnet tile **86** has a radially inner surface **90** that is flat and engages one side of shaft **84**. A width of surface **90** is less than the width of shaft **84** and each circumferential end of surface **90** is located inward from the corresponding circumferential end of the side of shaft **84** on which the magnet tile **86** is mounted. Each magnet tile **86** has a radially outer surface **92** that is curved in a circular arc. Referring to FIG. **5**, the radial thickness of the magnet tile **86** between surfaces **90**, **92** varies between a maximum thickness t.sub.mm at a circumferential center of the magnet tile **86** and a minimum thickness t.sub.me at each circumferential edge of the magnet tile **86**. The width of surface **92** is greater than the width of surface **90** and the width t.sub.s of shaft **84** such that each circumferential end of surface **92** is located outward from the corresponding circumferential end of the side of shaft **84** on which the magnet tile **86** is mounted and the width W.sub.m of magnet tile **86** at its greatest extent is greater than the width t.sub.s of shaft **84**. Each magnet tile **86** further includes opposed circumferential side surfaces **94**, **96** extending between surfaces **90**, **92**. Because of the shape and length of inner and outer surfaces **90**, **92**, side surfaces **94**, **96** project in a generally radial direction and the circumferential width of magnet tile **86** tapers moving from radially outer surface **92** to radially inner surface **90** and along surfaces **94**, **96**. Further, and because magnet titles **86** are magnetized in a direction parallel to the thickness of the magnet title **86**, each magnet tile **86** produces a magnetization vector having a length that varies from a maximum length at a circumferential center of the magnet tile **86** to a minimum length at each circumferential end of the magnet tile **86**.

[0029] In accordance with one aspect of the motor **54** disclosed herein, the configuration of magnet tile **86** results in a ratio of a pole arc angle τ.sub.a to a pole pitch angle τ.sub.p between 0.8 and 0.9. In accordance with another aspect of the disclosed motor **54**, magnet tile **86** is configured in accordance the formula W.sub.m=D.sub.m×sin(τ.sub.a/2) in which W.sub.m is a maximum width of the magnet tile **86**, D.sub.m is a diameter measured from a radially outer surface of the magnet tile **86** to a radially outer surface of a diametrically opposite magnet title **86** (D.sub.m is typically about one half of the outer diameter Do of the stator **60** lamination stack) and ta is the pole arc angle of the magnet tile **86**. In accordance with another aspect of the disclosed motor **54**, magnet tile **86** is configured in accordance with the formula t.sub.me=[tan((180°/P)+(180°/P)−(Ta/2)]*(t.sub.s/2)−(t.sub.s/2) where t.sub.me is a thickness of the magnet tile **86** at a circumferential end of the magnet tile **86**, P is the number of magnet tiles **86**, τ.sub.a is a pole arc angle of the magnet tile **86** and t.sub.s is thickness of the shaft **84**.

[0030] Referring again to FIG. **4**, the configuration or profile of magnet tiles **86** results in magnet tile gaps **98** between circumferentially adjacent magnet tiles **86**. Each magnet tile gap **98** tapers moving from a radially outer end of the magnet tile gap **98** to a radially inner end of the magnet tile gap **98** such that the width of the magnet tile gap **98** is greatest at the radially outer end of the magnet tile gap **98** and least at the radially inner end of the magnet tile gap **98**. In addition, the width of the magnet tile gap **98** at the radially outer end of the magnet tile gap **98** is less than or equal to the width of the stator shoe gap **82**.

[0031] The configuration of the magnet titles **86** and magnet tile gaps **98** reduces variation in airgap reluctance with respect to the position of rotor **62** and results in a significant reduction in cogging torque and other benefits. Because cogging torque is defined as

[00001]$T_{cogging} = \frac{1}{2}\varnothing^2 \frac{dR}{d}$ [0032] if the variation in airgap reluctance with respect to rotor position is minimized, cogging torque is also minimized. Referring to FIG. **6**, the configuration of magnet tiles **86** and motor **54** generate a significant reduction in cogging torque relative to prior art motors **10** and **40** at all rotational positions of rotor **62**. Further, and with reference to FIG. **7**, the configuration of magnet tiles **86** and motor **54** generate a significant reduction in cogging torque relative to prior art motors **10** and **40** in each harmonic order. Referring to FIG. **8**, in addition to a reduction in cogging torque the configuration of magnet tiles **86** and motor **54** produces a back

electromotive force constant (Ke) waveform that is substantially sinusoidal in shape.
[0033] A brushless synchronous motor **54** in accordance with the teachings herein is advantageous relative to conventional brushless synchronous motors. In particular, the motor **54** produces less cogging torque than conventional motors and is particularly useful for motors having a relatively large ratio of the active length LA of the motor **54** to the outer diameter D of the motor **54** in which conventional methods for reducing cogging torque are impractical. Further, the motor **54** enables a reduction in cogging torque without negatively impacting other performance factors associated with the motor such as back-emf constant, torque to weight ratio and thermal performance.
[0034] While the invention has been shown and described with reference to one or more particular embodiments thereof, it will be understood by those of skill in the art that various changes and modifications can be made without departing from the spirit and scope of the invention.

Claims

1. A brushless synchronous motor, comprising: a stator disposed about a rotational axis, the stator defining a plurality of radially inwardly extending teeth about which conductors are wound in a distributed winding layout to define multiple motor phases, each tooth of the plurality of teeth defining a shoe at a radially inner end of the tooth and spaced from a circumferentially adjacent shoe of a circumferentially adjacent tooth by a stator shoe gap; a rotor disposed within the stator and configured for rotation relative to the stator about the rotational axis, the rotor including a shaft; and; a plurality of magnet tiles supported on the shaft; wherein each magnet tile of the plurality of magnet tiles is spaced from a circumferentially adjacent magnet tile by a magnet tile gap, the magnet tile gap tapering moving from a radially outer end of the magnet tile gap to a radially inner end of the magnet tile gap and a width of the magnet tile gap at the radially outer end of the magnet tile gap less than or equal to a width of the stator shoe gap.
2. The brushless synchronous motor of claim 1 wherein an active length of the motor along the rotational axis is at least four times as large as a diameter of the motor.
3. The brushless synchronous motor of claim 1 wherein the stator is not skewed.
4. The brushless synchronous motor of claim 1 wherein the rotor is not skewed.
5. The brushless synchronous motor of claim 1 wherein each magnet tile of the plurality of tiles is magnetized in a direction parallel to a thickness of the magnet title.
6. The brushless synchronous motor of claim 1 wherein each magnet tile of the plurality of magnet tiles has radially outer surface that is curved.
7. The brushless synchronous motor of claim 1 wherein each magnet tile of the plurality of magnet tiles tapers from a radially outer surface of the magnet tile to a radially inner surface of the magnet tile.
8. The brushless synchronous motor of claim 1 wherein each magnet tile of the plurality of magnet tiles has a maximum thickness at a circumferential center of the magnet and a minimum thickness at each circumferential end of the magnet tile.
9. The brushless synchronous motor of claim 1 wherein each magnet tile of the plurality of magnet tiles produces a magnetization vector having a length that varies from a maximum length at a circumferential center of the magnet tile to a minimum length at each circumferential end of the magnet tile.
10. The brushless synchronous motor of claim 1 wherein a ratio of a pole arc angle for each magnet tile of the plurality of magnet tiles to a pole pitch angle between circumferentially adjacent magnet tiles of the plurality of magnet tiles is between 0.8 and 0.9.
11. The brushless synchronous motor of claim 1 wherein rotation of the rotor generates a back electromotive force constant (Ke) waveform that is sinusoidal in shape.
12. The brushless synchronous motor of claim 1 wherein each magnet tile of the plurality of magnet tiles is configured in accordance with the formula W.sub.m=D.sub.m×sin(τ.sub.a/2) in

which W.sub.m is a maximum width of the magnet tile, D.sub.m is a diameter of the magnet tile and τ.sub.a is a pole arc angle of the magnet tile.

13. The brushless synchronous motor of claim 1 wherein each magnet tile of the plurality of magnet tiles is configured in accordance with the formula t.sub.me=[tan((180°/P)+(180°/P)−(τ.sub.a/2)]*(t.sub.s/2)−(t.sub.s/2) where t.sub.me is a thickness of the magnet tile at a circumferential end of the magnet tile, P is the number of magnet tiles, τ.sub.a is a pole arc angle of the magnet tile and t.sub.s is thickness of the shaft.

14. The brushless synchronous motor of claim 1 wherein the stator defines exactly twelve radially inwardly extending teeth, the distributed winding layout defines exactly three motor phases and exactly four magnet tiles are supported on the rotor.