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(54) **VERNIER MACHINE WITH SHAPED PERMANENT MAGNET GROUPS**

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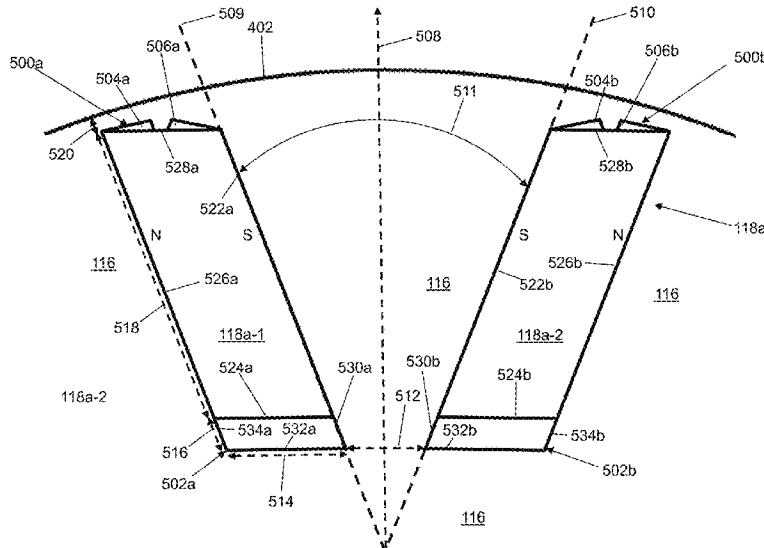
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(57) **ABSTRACT**

An electric machine includes a rotor, permanent magnets, a stator, and a stator winding wound about a plurality of teeth to form a number of stator magnetic poles. The rotor includes a rotor core and a plurality of walls that form openings in the rotor core. A permanent magnet is mounted in each of the openings formed in the rotor core. The plurality of permanent magnets are arranged to form a plurality of groups of permanent magnets that are equally circumferentially distributed around the rotor core with an interior polarity on a side of each permanent magnet facing other permanent magnets of the group of permanent magnets to which the permanent magnet is associated that is the same for all of the permanent magnets. Each permanent magnet is arranged to form a rotor pole, wherein a number of rotor poles is greater than the number of stator magnetic poles.

20 Claims, 8 Drawing Sheets



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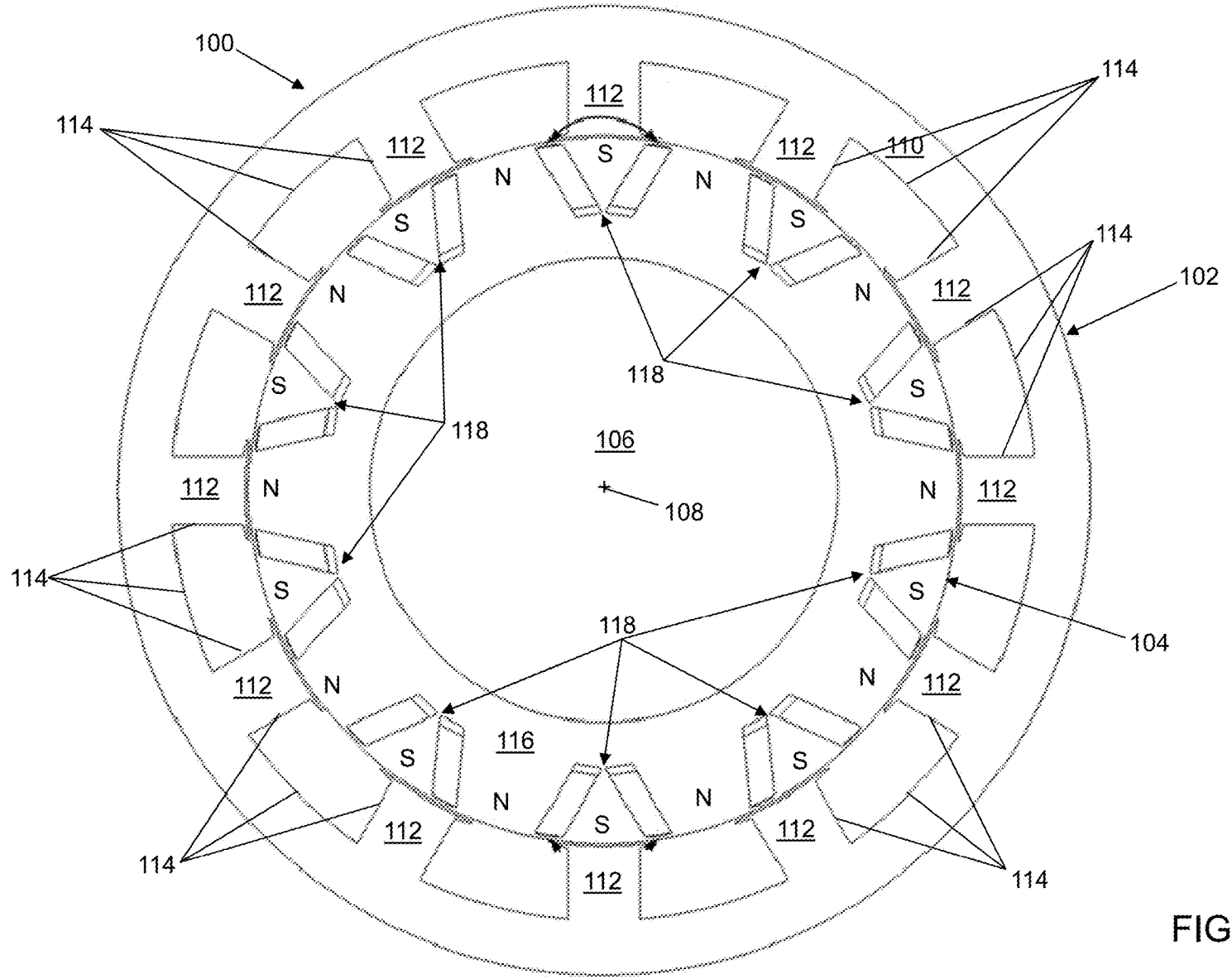
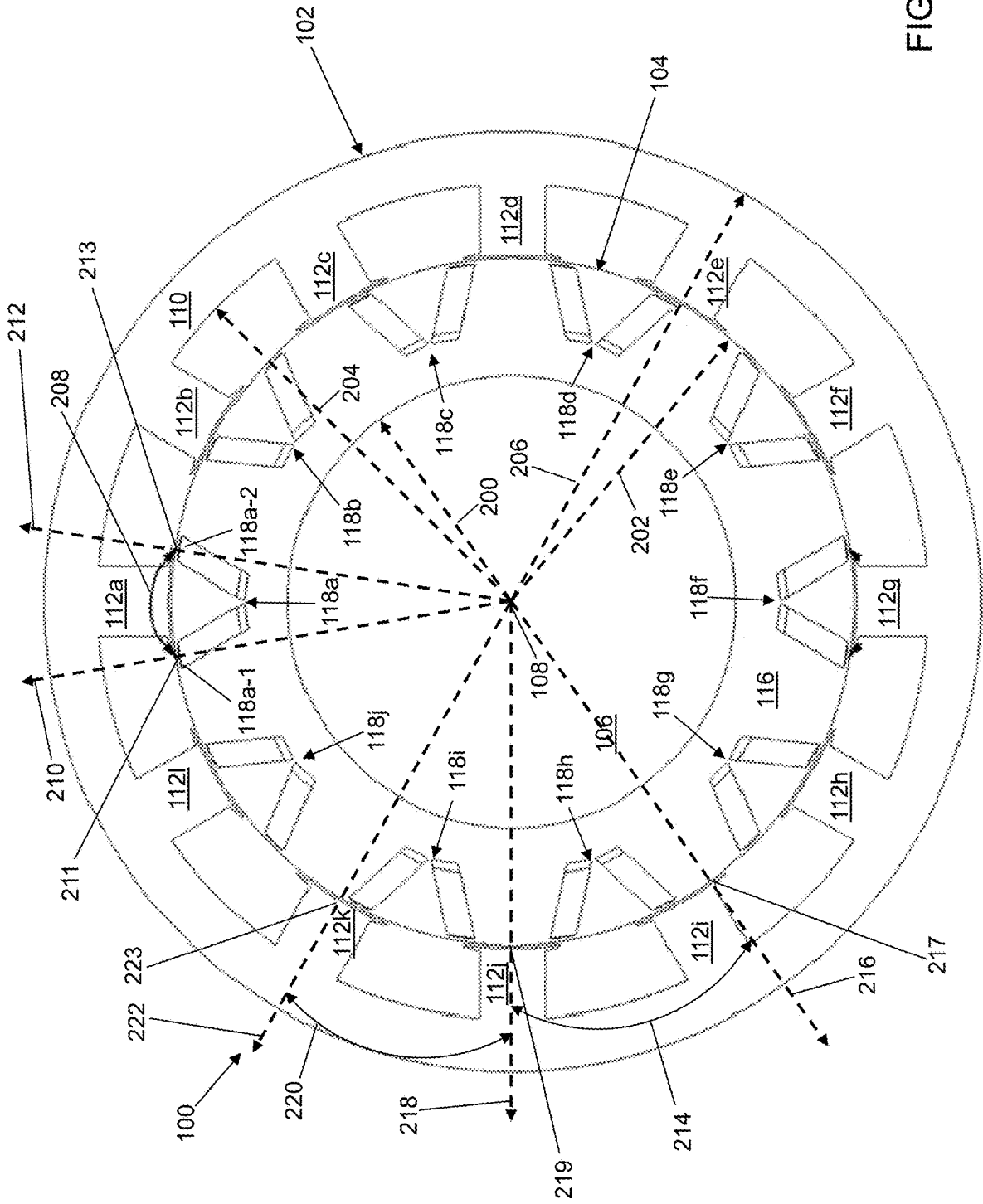


FIG. 1



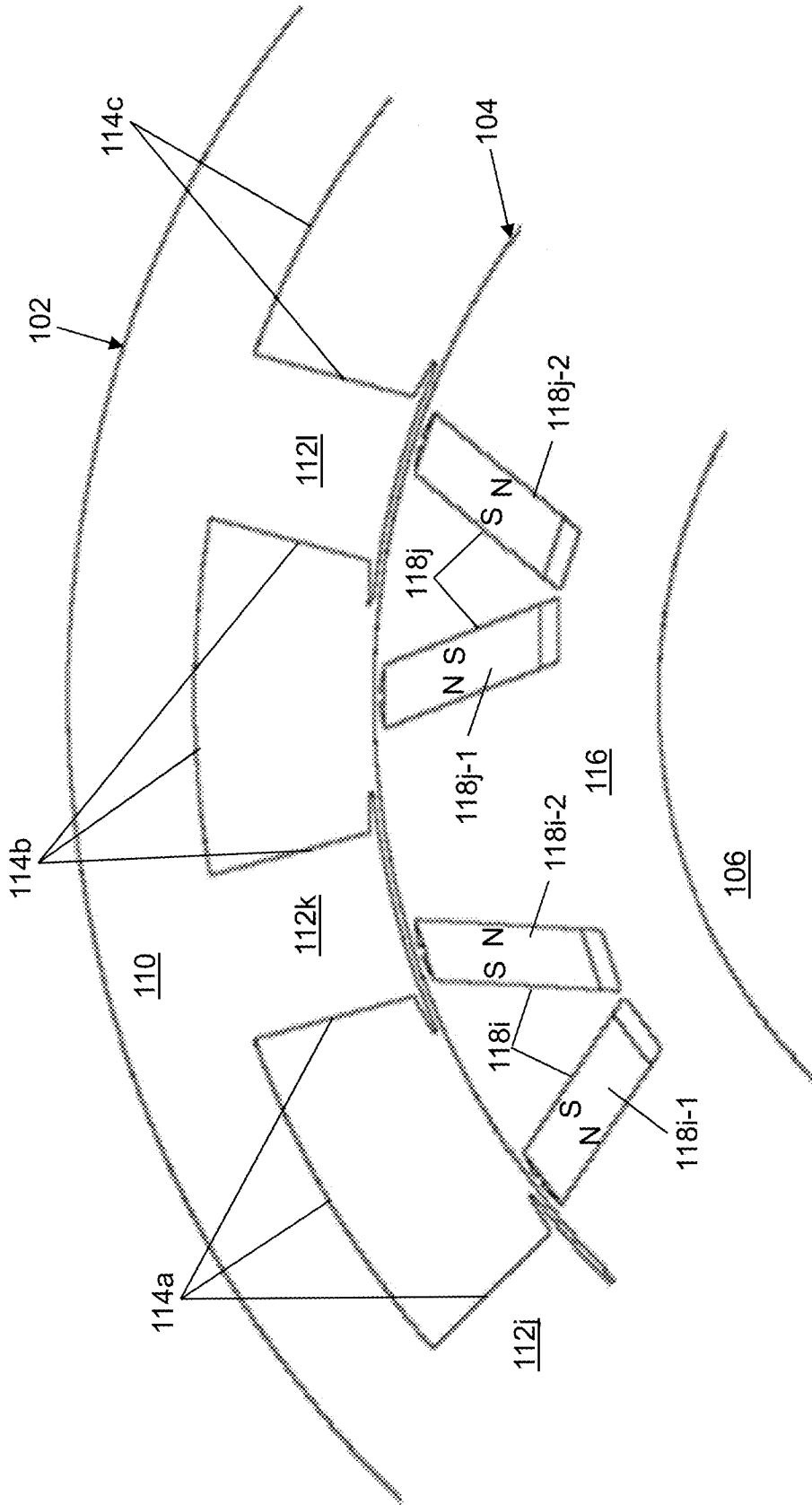


FIG. 3

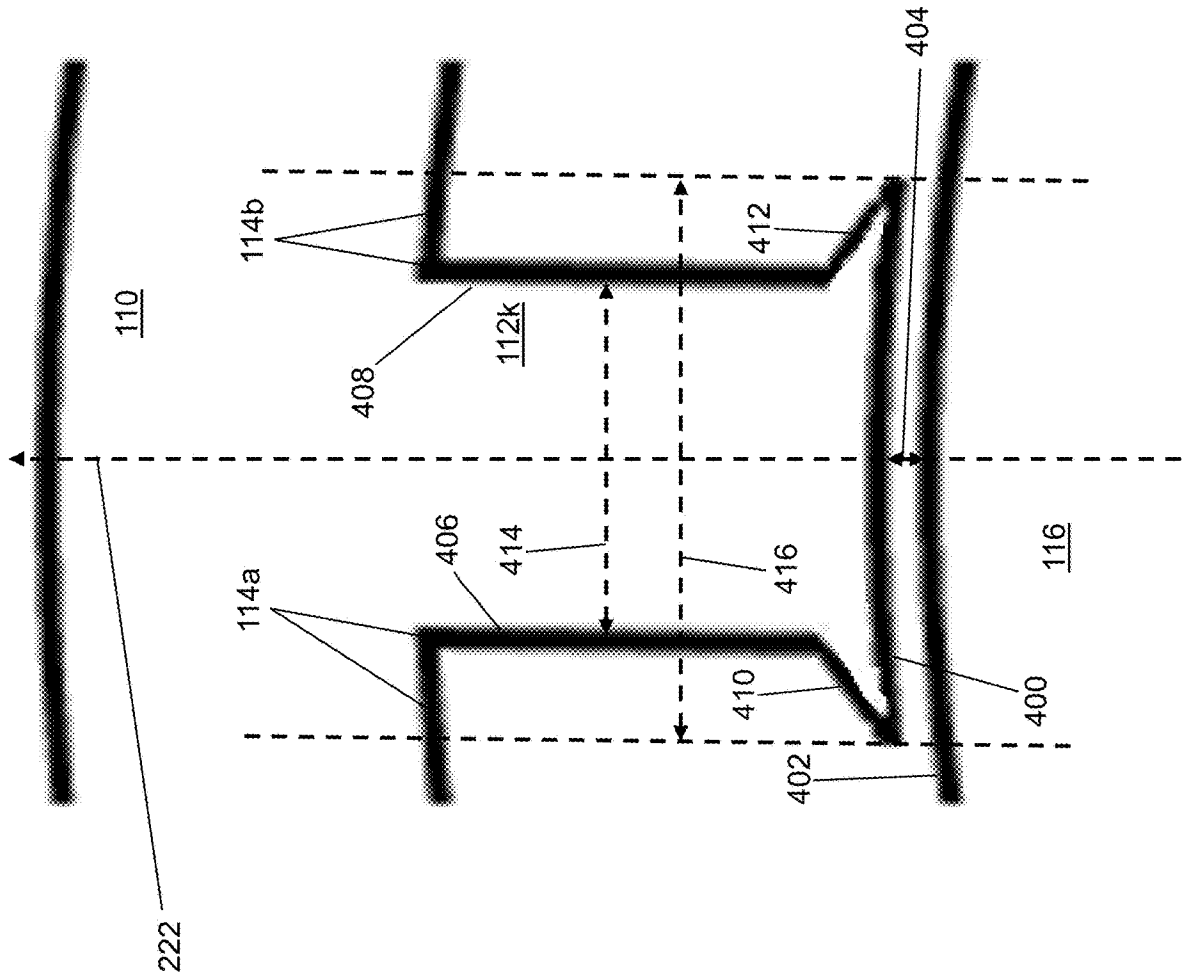


FIG. 4

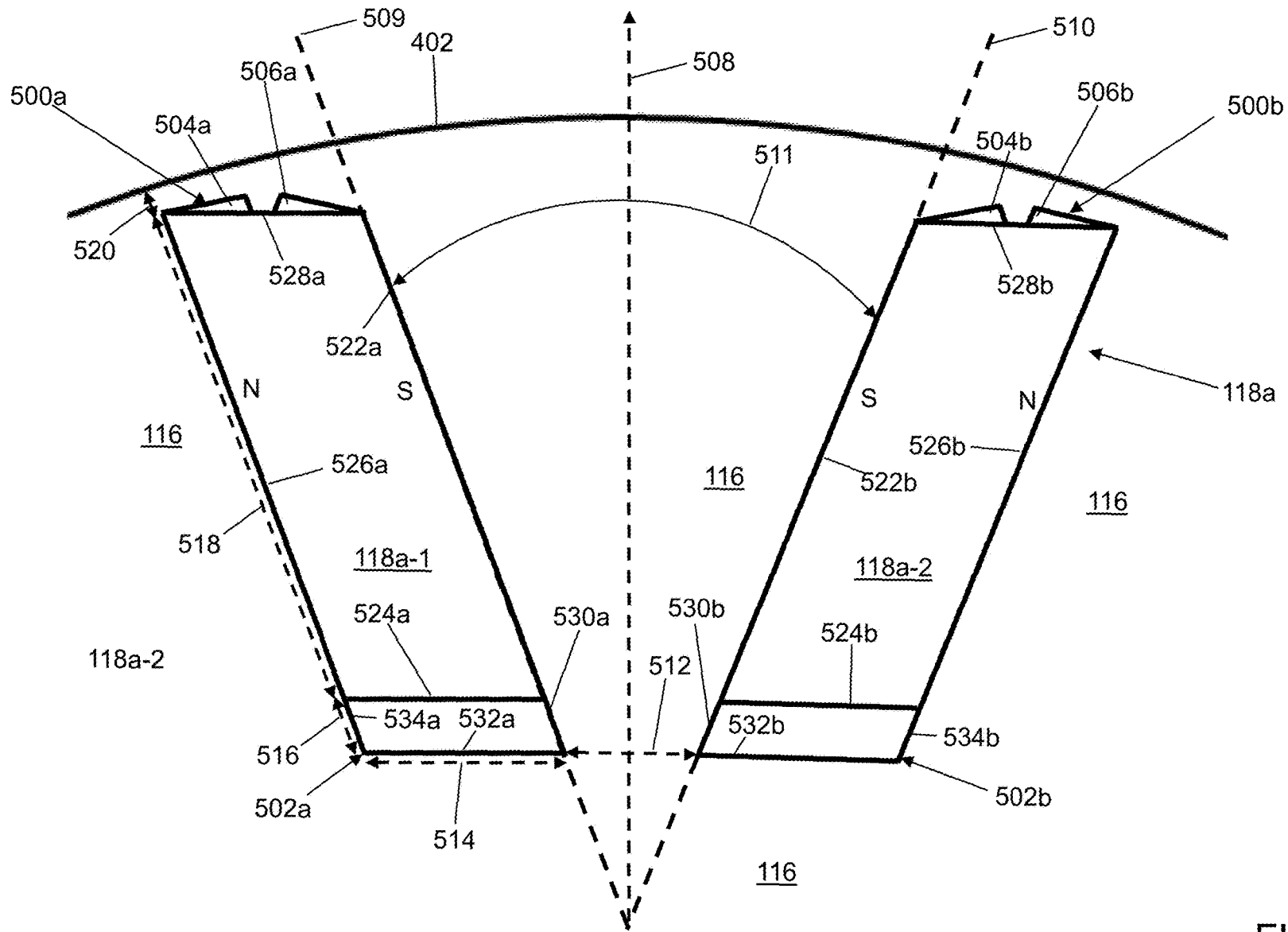


FIG. 5

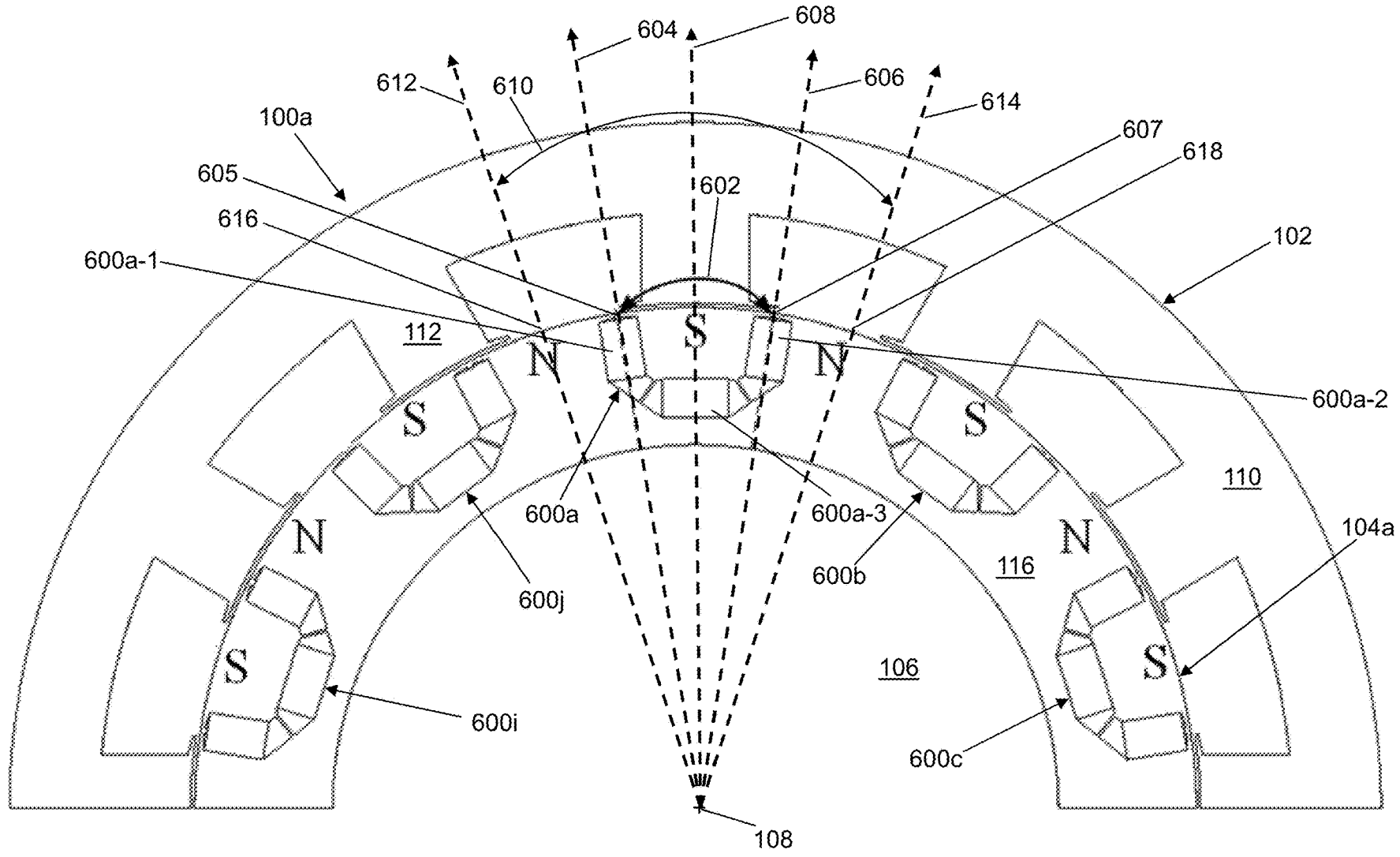


FIG. 6

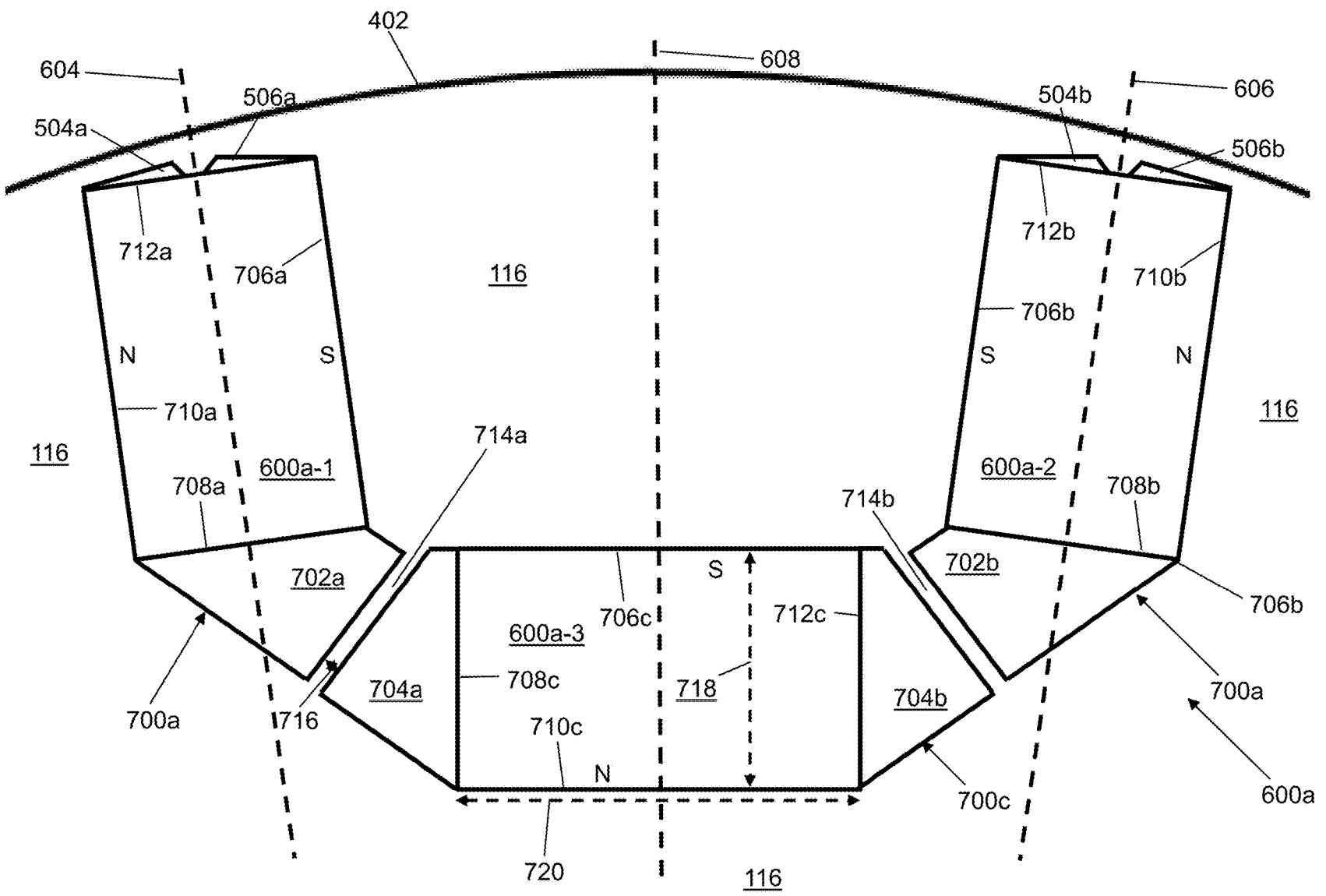


FIG. 7

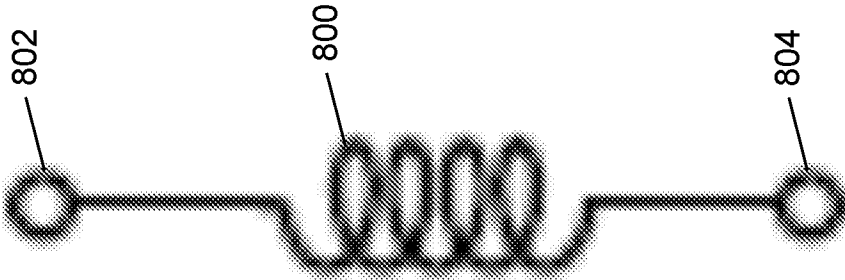


FIG. 8

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VERNIER MACHINE WITH SHAPED PERMANENT MAGNET GROUPS

BACKGROUND

The Vernier machine (VM) is a type of synchronous reluctance machine where the rotor rotates relatively slowly, and only at a fraction of the angular velocity of the stator's rotating field. The torque is developed based on an interaction between stator current and magnetic flux contributed by rotor mounted permanent magnets. In VMs, the machine torque steps up as the rotor speed steps down, creating an electric gearing effect. This makes the VM an attractive topology for direct-drive applications. Direct-drives are ideal as they eliminate the need for gear boxes, which add system complexity and reduce reliability due to increased parts. One disadvantage of a Vernier permanent magnet machine (VPMM) is that it retains a low power factor because the permanent magnets added to the rotor create additional harmonic flux leakage in the air gap between the stator and the rotor.

SUMMARY

In an example embodiment, an electric machine is provided. The electric machine includes, but is not limited to, a rotor, a plurality of permanent magnets, a stator, and a stator winding. The stator includes, but is not limited to, a stator core and a plurality of teeth that extend outward from the stator core. A slot of a plurality of slots is positioned between a pair of the plurality of teeth. The stator winding is wound about the plurality of teeth to form a number of stator magnetic poles between a set of connectors.

The rotor includes, but is not limited to, a rotor core and a plurality of walls that form openings in the rotor core that are separated from each other by rotor core. The stator is mounted on a first side of the rotor separated by an air gap between a surface of the rotor core and a tooth of the plurality of teeth.

A permanent magnet is mounted in each of the openings formed in the rotor core. The plurality of permanent magnets are arranged to form a plurality of groups of permanent magnets that are equally circumferentially distributed around the rotor core. Each permanent magnet has an interior polarity and an exterior polarity, wherein the interior polarity has an opposite polarity relative to the exterior polarity. The interior polarity is on a side of each permanent magnet facing other permanent magnets of the group of permanent magnets to which the permanent magnet is associated. The interior polarity is the same for all of the permanent magnets.

The openings further include a first flux barrier formed by a first plurality of walls of each opening on a first side of each permanent magnet and a second flux barrier formed by a second plurality of walls of each opening on a second side of each permanent magnet, wherein the first side is opposite the second side. Each permanent magnet is arranged to form a rotor pole, wherein a number of rotor poles is greater than the number of stator magnetic poles.

Other principal features of the disclosed subject matter will become apparent to those skilled in the art upon review of the following drawings, the detailed description, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Illustrative embodiments of the disclosed subject matter will hereafter be described referring to the accompanying drawings, wherein like numerals denote like elements.

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FIG. 1 depicts a radial type Vernier permanent magnet machine (VPMM) with a stator and a rotor positioned radially adjacent to each other in accordance with an illustrative embodiment with pairs of magnets that form a V-shape.

FIG. 2 depicts the VPMM of FIG. 1 illustrating various physical characteristics in accordance with an illustrative embodiment.

FIG. 3 depicts a zoomed portion of the VPMM of FIG. 1 in accordance with an illustrative embodiment.

FIG. 4 depicts a second zoomed portion of the VPMM of FIG. 1 in accordance with an illustrative embodiment.

FIG. 5 depicts a second zoomed portion of a rotor of the VPMM of FIG. 1 in accordance with an illustrative embodiment.

FIG. 6 depicts a radial type Vernier permanent magnet machine (VPMM) with a stator and a rotor positioned radially adjacent to each other in accordance with an illustrative embodiment with a group of magnets that form a U-shape.

FIG. 7 depicts a second zoomed portion of a rotor of the VPMM of FIG. 6 in accordance with an illustrative embodiment.

FIG. 8 depicts a stator winding of the VPMM of FIG. 1 in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

A Vernier permanent magnet (PM) machine (VPMM) is an electromechanical device wherein a number of rotor magnetic poles pairs is much greater than a number of stator winding magnetic pole pairs rather than equal to the number of stator winding magnetic pole pairs as in a conventional PM machine. Though the number of stator and rotor poles is unequal, the VPMM machine achieves smooth torque by synchronizing the space harmonics of the stator magnetomotive force (MMF) with the MMF of the rotor magnets modulated by the stator teeth.

The increase in torque over a conventional PM machine results because two components of torque are produced in a VPMM rather than one component as in a conventional PM machine. The first component is a synchronous reaction torque produced by the PMs and the fundamental component of the stator MMF in which the MMF rotates at synchronous speed defined by the pole pitch of the stator winding (synchronous speed is determined by the stator and rotor pole number combination). The second component is produced by a reluctance torque produced by the PMs and the fundamental slot harmonic component of MMF in which this MMF component rotates at a higher synchronous speed than that defined by the coil pitch of the stator winding (reluctance torque is produced by the stator MMF and rotor reluctance caused by rotor saliency, which rotate at the same speed as the rotor). As understood by a person of skill in the art, the VPMM may be used as a generator or as a motor. The VPMM functions similar to an electric gear in which rotor torque is produced at a different frequency from a rotating frequency of the rotor. Since the rotor flux is spatially modulated by a pulsating toothed stator permeance, the operating principle is analogous to frequency modulation in communication theory.

Referring to FIG. 1, a radial type VPMM 100 is shown in accordance with an illustrative embodiment. VPMM 100 may include a stator 102, a rotor 104, and a shaft 106 positioned radially adjacent to each other. In the illustrative embodiment of FIG. 1, rotor 104 is mounted to shaft 106 interior of stator 102 though stator 102 could be mounted

interior of rotor **104**. In alternative embodiments, radial type VPMM **100** could include a plurality of stators and/or a plurality of rotors mounted radially relative to each other in an alternating manner. Shaft **106**, rotor **104**, and stator **102** have generally circular cross sections as shown with reference to FIG. **1**. Rotor **104** is mounted to shaft **106** for rotation with shaft **106**. When VPMM **100** is operating as a motor, electrical energy provided to stator **102** rotates rotor **104** and thereby shaft **106**. When VPMM **100** is operating as a generator, shaft **106** is rotated to generate electrical energy from VPMM **100**.

As used in this disclosure, the term “mount” includes join, unite, connect, couple, associate, insert, hang, hold, affix, attach, fasten, bind, paste, secure, bolt, screw, rivet, solder, weld, glue, adhere, form over, layer, and other like terms. The phrases “mounted on” and “mounted to” include any interior or exterior portion of the element referenced. These phrases also encompass direct mounting (in which the referenced elements are in direct contact) and indirect mounting (in which the referenced elements are not in direct contact). Elements referenced as mounted to each other herein may further be integrally formed together, for example, using a molding process as understood by a person of skill in the art. As a result, elements described herein as being mounted to each other need not be discrete structural elements. The elements may be mounted permanently, removably, or releasably.

Use of directional terms, such as top, bottom, right, left, front, back, upper, lower, horizontal, vertical, behind, etc. are merely intended to facilitate reference to the various surfaces of the described structures relative to the orientations illustrated in the drawings and are not intended to be limiting in any manner unless otherwise indicated.

As used in this disclosure, the term “connect” includes join, unite, mount, couple, associate, insert, hang, hold, affix, attach, fasten, bind, paste, secure, bolt, screw, rivet, pin, nail, clasp, clamp, cement, fuse, solder, weld, glue, form over, slide together, layer, and other like terms. The phrases “connected on” and “connected to” include any interior or exterior portion of the element referenced. Elements referenced as connected to each other herein may further be integrally formed together. As a result, elements described herein as being connected to each other need not be discrete structural elements. The elements may be connected permanently, removably, or releasably.

Stator **102** may be formed of a ferromagnetic material such as iron, cobalt, nickel, etc. Stator **102** may include a stator core **110** and a plurality of teeth **112**. In the illustrative embodiment, the plurality of teeth **112** extend from stator core **110** towards a center **108** of an interior of shaft **106**. A plurality of slot walls **114** define walls of the stator slots. A slot is positioned between a pair of the plurality of teeth **112**. In the illustrative embodiment, the plurality of teeth **112** of stator **102** includes 12 teeth that define 12 stator slots $N_s = N_T = 12$, where N_s is a number of stator slots and N_T is a number of stator teeth of the plurality of teeth **112** of stator **102**. As understood by a person of skill in the art, stator **102** may be formed of laminations mounted closely together in an axial direction and cut to define a shape and a size of stator core **110** and the plurality of teeth **112**.

Referring to FIG. **8**, a stator winding **800** is shown between a first connector **802** and a second connector **804**. Stator windings are wound around the plurality of teeth **112** and held within the plurality of stator slots. The stator windings carry a current between a plurality of connectors that may be provided to have one or more phases. In the illustrative embodiment, VPMM **100** is a three-phase

machine, $N_{ph} = 3$, with windings that are connected to provide three-phases. The windings are wound about the plurality of teeth **112** using various techniques to form a number of magnetic poles N_{SMP} between a set of connectors, such as first connector **802** and second connector **804**, that may be associated with each phase depending on the winding technique. In an illustrative embodiment, the windings are concentrated windings such that N_s is defined by a number of stator magnetic poles N_{SMP} , where $N_s = N_{ph} N_{SMP}$. In the illustrative embodiment of FIG. **1**, VPMM **100** is wound to form four stator magnetic poles $N_{SMP} = N_s / M_{ph} = 12/3 = 4$.

Rotor **104** may be formed of a ferromagnetic material such as iron, cobalt, nickel, etc. Rotor **104** may include a rotor core **116** and a plurality of permanent magnet pairs **118** mounted within rotor core **116**. As understood by a person of skill in the art, rotor core **116** may be formed of laminations mounted closely together in the axial direction. The permanent magnets of the plurality of permanent magnet pairs **108** are electrically isolated from each other. Openings are formed in rotor core **116** that are sized and shaped to hold the plurality of permanent magnet pairs **118**.

Each permanent magnet of each pair of the plurality of permanent magnet pairs **118** is magnetized to form a south pole “S” (indicated with “S” in the figures) on a first side and a north pole “N” (indicated with “N” in the figures) on a second side opposite the first side in a rotational direction of rotor **104**. The plurality of permanent magnet pairs **118** are mounted with N poles facing N poles and S poles facing S poles to form pole pairs. As indicated referring to FIG. **1**, the magnets within each pair of the plurality of permanent magnet pairs **118** is magnetized with S poles facing each other. N poles of each pair of the plurality of permanent magnet pairs **118** face an adjacent pair of the plurality of permanent magnet pairs **118**. As a result, an interior polarity (e.g., S or N) of each permanent magnet of each pair of the plurality of permanent magnet pairs **118** is the same, while an exterior polarity (e.g., N or S) of each permanent magnet of each pair of the plurality of permanent magnet pairs **118** is the opposite. In the illustrative embodiment of FIG. **1**, VPMM **100** includes ten permanent magnet pole pairs **118** N_{pp} defined using twenty permanent magnets N_{pm} . Each permanent magnet of the plurality of permanent magnet pairs **118** forms a rotor pole such that $N_p = N_{pm}$, where N_p is a number of rotor poles formed by the permanent magnets.

VPMM **100** may be formed using a different number of rotor poles N_p , a different number of stator magnetic poles N_{SMP} , and a different number of phases N_{ph} as long as a Vernier machine is formed such that $N_p \gg N_{SMP}$. For illustration, $N_p = 2N_s \pm N_{SMP}$ can be selected.

Referring to FIG. **2**, various physical characteristics of VPMM **100** are shown in accordance with an illustrative embodiment. In the illustrative embodiment, stator **102** includes a first tooth **112a**, a second tooth **112b**, a third tooth **112c**, a fourth tooth **112d**, a fifth tooth **112e**, a sixth tooth **112f**, a seventh tooth **112g**, an eighth tooth **112h**, a ninth tooth **112i**, a tenth tooth **112j**, an eleventh tooth **112k**, and a twelfth tooth **112l** with associated stator slots formed between adjacent teeth. In the illustrative embodiment, rotor **104** includes a first pair of permanent magnets **118a**, a second pair of permanent magnets **118b**, a third pair of permanent magnets **118c**, a fourth pair of permanent magnets **118d**, a fifth pair of permanent magnets **118e**, a sixth pair of permanent magnets **118f**, a seventh pair of permanent magnets **118g**, an eighth pair of permanent magnets **118h**, a ninth pair of permanent magnets **118i**, and a tenth pair of permanent magnets **118j**. For illustration, the first pair of permanent magnets **118a** includes a first permanent magnet

118a-1 and a second permanent magnet **118a-2** that form a first pole pair having a V-shape that is open towards stator **102**.

Each permanent magnet of the plurality of permanent magnet pairs **118** may be identical (though mounted with an opposing magnetization direction for adjacent magnets to form the pole pairs) and may be formed of rare earth magnets, such as neodymium and dysprosium, of ferrite based magnets, etc. though rare earth magnets are preferred. In the illustrative embodiment of FIGS. 1 and 2, each permanent magnet of the plurality of permanent magnet pairs **118** is rectangular elongated in a radial direction extending from center **108** towards rotor **104**.

Each pole pair formed by each pair of the plurality of permanent magnet pairs **118** also may be identical and formed at a regular pitch circumferentially around rotor **104**. The relative position between rotor **104** and stator **102** changes continuously during use of VPMM **100** because rotor **104** mounts to shaft **106** for rotation as understood by a person of skill in the art. FIGS. 1 and 2 merely show a snapshot in time.

A shaft radius **200** represents a radius R_{sh} of shaft **106** measured from center **108**. An outer rotor radius **202** represents a radius R_r of rotor **104** measured from center **108**. An inner stator core radius **204** represents a radius R_{ist} of stator **102** measured from center **108**. An outer stator core radius **206** represents a radius R_{ost} of stator **102** measured from center **108**. $L_r=R_r-R_{sh}$ is a radial length of rotor core **116**. $L_{SC}=R_{ost}-R_{ist}$ is a radial length of stator core **110**. Though not shown, it is understood by a person of skill in the art that stator **102** and rotor **104** extend respective axial lengths in a perpendicular direction relative to the views shown in FIGS. 1 and 2 and that the stator windings are further wound about the plurality of teeth **112** in the axial direction.

A rotor pole pitch angle **208** represents an angle τ_{pp} between a first axis **210** and a second axis **212**. First axis **210** extends from center axis **108** through a first magnet center **211** of first permanent magnet **118a-1** of the first pair of permanent magnets **118a**. First magnet center **211** of first permanent magnet **118a-1** is positioned at a center of a wall of first permanent magnet **118a-1** closest to stator **102**. Second axis **212** extends from center axis **108** through a second magnet center **213** of second permanent magnet **118a-2** of the first pair of permanent magnets **118a**. Second magnet center **213** of second permanent magnet **118a-2** is positioned at a center of a wall of second permanent magnet **118a-2** closest to stator **102**.

A rotor pole pair pitch angle **214** represents an angle τ_{ppp} between a third axis **216** and a fourth axis **218**. Third axis **216** extends from center axis **108** through a first pole edge **217** that is centered between the seventh pair of permanent magnets **118g** and the eighth pair of permanent magnets **118h**, where the seventh pair of permanent magnets **118g** and the eighth pair of permanent magnets **118h** are adjacent pole pairs. Fourth axis **218** extends from center axis **108** through a second pole edge **219** that is centered between the eighth pair of permanent magnets **118h** and the ninth pair of permanent magnets **118i**, where the eighth pair of permanent magnets **118h** and the ninth pair of permanent magnets **118i** are adjacent pole pairs. Because each pole pair is formed at a regular pitch circumferentially around rotor **104**, $\tau_{ppp}=360/N_{pp}=360/(N_{pm}/2)$ or 36 degrees in the illustrative embodiment.

A stator tooth angle **220** represents an angle τ_s between fourth axis **218** and a fifth axis **222**. In the illustrative embodiment, when rotor **104** is rotated in alignment relative

to stator **102** as shown in FIGS. 1 and 2, fourth axis **218** also extends from center axis **108** through a tooth center of tenth tooth **112j**. Fifth axis **222** extends through a tooth center of eleventh tooth **112k**, where tenth tooth **112j** and eleventh tooth **112k** are adjacent teeth of the plurality of teeth **112**. Because each stator slot and therefore each stator tooth is formed at a regular pitch circumferentially around stator **102**, $\tau_s=360/N_T$ or 30 degrees in the illustrative embodiment.

For further illustration, referring to FIG. 3, the ninth pair of permanent magnets **118i** includes a first permanent magnet **118i-1** and a second permanent magnet **118i-2** that form a ninth pole pair with S poles facing each other and N poles facing the tenth pair of permanent magnets **118j** on a right side and the eighth pair of permanent magnets **118h** (shown referring to FIG. 2) on a left side. The tenth pair of permanent magnets **118j** includes a first permanent magnet **118j-1** and a second permanent magnet **118j-2** that form a tenth pole pair with S poles facing each other and N poles facing the ninth pair of permanent magnets **118i** on a left side and the first pair of permanent magnets **118a** (shown referring to FIG. 2) on a right side.

For illustration, first slot walls **114a** define walls of a first slot formed between tenth tooth **112j**, stator core **110**, and eleventh tooth **112k** in which windings are wound about the plurality of teeth **112** of stator **102** as discussed previously. Second slot walls **114b** define walls of a second slot formed between eleventh tooth **112k**, stator core **110**, and twelfth tooth **112l** in which windings are wound. Third slot walls **114c** (only three are visible in FIG. 3) define walls of a third slot formed between twelfth tooth **112l**, stator core **110**, and first tooth **112a** (shown referring to FIG. 2) in which windings are wound.

Referring to FIG. 4, a zoomed portion of VPMM **100** is shown in accordance with an illustrative embodiment to show a relationship between an interior tooth surface **400** of each stator tooth of the plurality of stator teeth **112** and an exterior surface **402** of rotor **104**. The interior tooth surface **400** of each of the plurality of teeth **112** of stator **102** is separated from exterior surface **402** of rotor **104** by an air gap. Stator **102** is mounted relative to rotor **104** such that they are separated by the air gap at a closest point of contact. An air gap length **404** represents a length L_{ag} of the air gap measured between to interior tooth surface **400** of eleventh tooth **112k** along fifth axis **222**.

Eleventh tooth **112k** shown in the illustrative embodiment of FIG. 4 has a left sidewall **406** that forms a wall of first slot walls **114a** and a right sidewall **408** that forms a wall of second slot walls **114b**. Eleventh tooth **112k** can have various shapes. In the illustrative embodiment, eleventh tooth **112k** also includes a left transition wall **410** and a right transition wall **412**. Left transition wall **410** is formed between left sidewall **406** and interior tooth surface **400** and extends away from left sidewall **406** towards an interior of the first slot formed by first slot walls **114a**. Right transition wall **412** is formed between right sidewall **408** and interior tooth surface **400** and extends away from right sidewall **408** towards an interior of the second slot formed by second slot walls **114b**. A first tooth width **414** represents a width W_{T1} of eleventh tooth **112k** measured perpendicular to fifth axis **222** between left sidewall **406** and right sidewall **408**. A second tooth width **416** represents a width W_{T2} of eleventh tooth **112k** measured perpendicular to fifth axis **222** between left transition sidewall **410** and right transition sidewall **412**.

Referring to FIG. 5, the first pair of permanent magnets **118a** is shown in accordance with an illustrative embodiment. First permanent magnet **118a-1** is rectangular with a

first interior wall **522a**, a first lower wall **524a**, a first exterior wall **526a**, and a first upper wall **528a**. Second permanent magnet **118a-2** is rectangular with a second interior wall **522b**, a second lower wall **524b**, a second exterior wall **526b**, and a second upper wall **528b**.

Again, each permanent magnet of the plurality of permanent magnet pairs **118a** is mounted in an opening formed in rotor core **116** of rotor **104**. The opening is sized and shaped such that the permanent magnet can be mounted within the opening between a lower flux barrier and a pair of upper flux barriers. The lower flux barrier and the pair of upper flux barriers may be filled with air or other material with a permeability approximately equal to air. For illustration, a first opening **500a** within which first permanent magnet **118a-1** of the first pair of permanent magnets **118a** is mounted includes a first lower flux barrier **502a**, a first upper flux barrier **504a**, a second upper flux barrier **506a**, and the opening sized and shaped to accommodate first permanent magnet **118a-1**. For further illustration, a second opening **500b** within which second permanent magnet **118a-2** of the first pair of permanent magnets **118a** is mounted includes a second lower flux barrier **502b**, a third upper flux barrier **504b**, a fourth upper flux barrier **506b**, and the opening sized and shaped to accommodate second permanent magnet **118a-2**.

A sixth axis **508** extends from center **108** (not shown) and bisects the first pair of permanent magnets **118a**. Thus, sixth axis **508** extends midway between first permanent magnet **118a-1** and second permanent magnet **118a-2** measured perpendicular to sixth axis **508**. Second permanent magnet **118a-2** is a mirror image of first permanent magnet **118a-1** relative to sixth axis **508**.

A magnet pair angle **511** represents an angle T_M between a seventh axis **509** and an eighth axis **510**. Seventh axis **509** is parallel to first interior wall **522a** of first permanent magnet **118a-1** that faces second interior wall **522b** of second permanent magnet **118a-2**. Eighth axis **510** is parallel to second interior wall **522b** of second permanent magnet **118a-2** that faces first interior wall **522a** of first permanent magnet **118a-1**. Sixth axis **508** bisects magnet pair angle **511**.

First lower flux barrier **502a** is rectangular and defined by first lower wall **524a** of first permanent magnet **118a-1**, a first interior barrier wall **530a**, a first lower barrier wall **532a**, and a first exterior barrier wall **534a**. Second lower flux barrier **502b** is rectangular and defined by second lower wall **524b** of second permanent magnet **118a-2**, a second interior barrier wall **530b**, a second lower barrier wall **532b**, and a second exterior barrier wall **534b**. A distance **512** represents a distance D_B measured perpendicular to sixth axis **508** between a first corner and a second corner. The first corner is between first interior barrier wall **530a** and first lower barrier wall **532a** of first lower flux barrier **502a**. The second corner is between second interior barrier wall **530b** and second lower barrier wall **532b** of second lower flux barrier **502b**.

A magnet width **514** represents a width W_m measured perpendicular to sixth axis **508** between first interior barrier wall **530a** and first exterior barrier wall **534a** and between first interior wall **522a** and first exterior wall **526a**. A lower barrier length **516** represent a length L_B measured parallel to seventh axis **509** between first lower wall **524a** and first lower barrier wall **532a**. A magnet length **518** represent a length L_M measured parallel to seventh axis **509** between first lower wall **524a** and first upper wall **528a** of first permanent magnet **118a-1**. A mounting distance **520** represent a distance D_M measured parallel to seventh axis **509**

between exterior surface **402** of rotor **104** and a third corner formed by first upper wall **528a** and first exterior wall **526a** of first permanent magnet **118a-1**. Like rotor **104** and stator **102**, each permanent magnet of the plurality of permanent magnet pairs **118** has a depth (not shown) that extends in an axial direction perpendicular relative to the view shown in FIG. 5.

First upper flux barrier **504a**, second upper flux barrier **506a**, third upper flux barrier **504b**, and fourth upper flux barrier **506b** are triangular and approximately equal in size and with a similar shape. First upper flux barrier **504a** is formed by first upper wall **528a** of first permanent magnet **118a-1** and two walls that extend away from first upper wall **528a** toward exterior surface **402** of rotor **104**. Second upper flux barrier **506a** is formed by first upper wall **528a** of first permanent magnet **118a-1** and two walls that extend away from first upper wall **528a** toward exterior surface **402** of rotor **104**. Third upper flux barrier **504b** is formed by second upper wall **528b** of second permanent magnet **118a-2** and two walls that extend away from second upper wall **528b** toward exterior surface **402** of rotor **104**. Fourth upper flux barrier **506b** is formed by second upper wall **528b** of second permanent magnet **118a-2** and two walls that extend away from second upper wall **528b** toward exterior surface **402** of rotor **104**. Rotor core **116** fills a space between first upper flux barrier **504a** and second upper flux barrier **506a** and between third upper flux barrier **504b** and fourth upper flux barrier **506b**. Rotor core **116** further fills a space between each of first upper flux barrier **504a**, second upper flux barrier **506a**, third upper flux barrier **504b**, and fourth upper flux barrier **506b** and exterior surface **402** of rotor **104**.

Given a selected outer stator core radius **206** R_{ost} , the other dimensions of VPMM **100** can be defined. Outer rotor radius **202** R_r is selected to have a value between ~10% and ~95% of R_{ost} . The radial length of rotor core **116** L_r is selected to have a value between ~5% and ~95% of R_{ost} . Magnet length **518** L_M is selected to have a value between ~0.1% and 100% of L_r . Magnet width **514** W_m is selected to have a value between ~0.1 and ~50 times air gap length **404** L_{ag} . Rotor pole pitch angle **208** τ_{rp} is selected to have a value between ~25% and ~75% of rotor pole pair pitch angle **210** τ_{rpp} that is determined based on N_{pp} . Distance **512** D_B is selected to have a value between ~0.1% and ~25% of magnet width **514** W_m . Lower barrier length **516** L_B is selected to have a value between ~0.1% and ~50% of magnet length **518** L_M .

Referring to FIG. 6, a second radial type VPMM **600** is shown in accordance with an illustrative embodiment. Only an upper half of second radial type VPMM **600** is shown for simplicity. Second radial type VPMM **600** may include stator **102**, a second rotor **104a**, and shaft **106** positioned radially adjacent to each other. Second rotor **104a** is mounted to shaft **106** for rotation with shaft **106**.

Second rotor **104a** is similar to rotor **104** except that each pair of the plurality of permanent magnet pairs **118** is replaced with a group of permanent magnets that are arranged to have a U-shape relative to center axis **108** instead of a V-shape. In the illustrative embodiment, rotor **104** includes a first group of permanent magnets **600a**, a second group of permanent magnets **600b**, a third group of permanent magnets **600c**, a fourth group of permanent magnets (not shown), a fifth group of permanent magnets (not shown), a sixth group of permanent magnets (not shown), a seventh group of permanent magnets (not shown), an eighth group of permanent magnets (not shown), a ninth group of permanent magnets **600i**, and a tenth group of permanent magnets **600j**. For illustration, the first group of

permanent magnets **600a** includes a first permanent magnet **600a-1**, a second permanent magnet **600a-2**, and a third permanent magnet **600a-3** that form a first pole group having a U-shape relative center axis **108**.

Each permanent magnet of each group of a plurality of groups of permanent magnets **600** is magnetized to form a south pole “S” on a first side and a north pole “N” on a second side opposite the first side. The plurality of groups of permanent magnets **600** are mounted with N poles facing N poles and S poles facing S poles to form pole groups as further described referring to FIG. 7. As indicated referring to FIG. 6, the magnets within each group of the plurality of groups of permanent magnets **600** is magnetized with S poles facing each other. N poles of each group of the plurality of groups of permanent magnets **600** face an adjacent group of the plurality of groups of permanent magnets **600**. In the illustrative embodiment of FIG. 1, VPMM **100** includes ten permanent magnet pole groups **600** N_{pG} defined using thirty permanent magnets N_{pm} . Second VPMM **600** may be formed using a different number of rotor poles N_p , a different number of stator magnetic poles N_{SMP} , and a different number of phases N_{ph} as long as a Vernier machine is formed such that $N_p \gg N_{SMP}$. Each permanent magnet of the plurality of groups of permanent magnets **600** form a rotor pole such that $N_p = N_{pm}$, where N_p is a number of rotor poles formed by the permanent magnets.

A rotor pole pitch angle **602** represents an angle τ_{rp} between a first axis **604** and a second axis **606**. First axis **604** extends from center axis **108** through a first magnet center **605** of first permanent magnet **600a-1** of the first group of permanent magnets **600a**. First magnet center **605** of first permanent magnet **600a-1** is positioned at a center of a wall of first permanent magnet **600a-1** closest to stator **102**. Second axis **606** extends from center axis **108** through a second magnet center **607** of second permanent magnet **600a-2** of the first group of permanent magnets **600a**. Second magnet center **607** of second permanent magnet **600a-2** is positioned at a center of a wall of second permanent magnet **600a-2** closest to stator **102**.

A third axis **608** extends from center **108** and bisects the first group of permanent magnets **600a**. Thus, third axis **608** extends midway between first permanent magnet **600a-1** and second permanent magnet **600a-2** measured perpendicular to third axis **608** and through a center of third permanent magnet **600a-3**. Second permanent magnet **600a-2** is a mirror image of first permanent magnet **600a-1** relative to third axis **608**.

A rotor pole pair pitch angle **610** represents an angle τ_{rpp} between a fourth axis **612** and a fifth axis **614**. Fourth axis **612** extends from center axis **108** through a first pole edge **616** that is centered between the tenth group of permanent magnets **600j** and the first group of permanent magnets **600a**, where the tenth group of permanent magnets **600j** and the first group of permanent magnets **600a** are adjacent pole groups. Fifth axis **614** extends from center axis **108** through a second pole edge **618** that is centered between the first group of permanent magnets **600a** and the second group of permanent magnets **600b**, where the first group of permanent magnets **600a** and the second group of permanent magnets **600b** are adjacent pole groups. Because each pole group is formed at a regular pitch circumferentially around rotor **104**, $\tau_{rpp} = 360/N_{pG} = 360/(N_{pm}/3)$ or 36 degrees in the illustrative embodiment. In an illustrative embodiment, rotor pole pitch angle **602** τ_{rp} is selected to have a value between -0.1% and 100% of rotor pole pair pitch angle **610** τ_{rpp} that is determined based on N_{pG} .

Referring to FIG. 7, similar to each permanent magnet of the plurality of permanent magnet pairs **118a**, each permanent magnet of the first group of permanent magnets **600a** is mounted in an opening formed in rotor core **116** of second rotor **104a**. First permanent magnet **600a-1** and second permanent magnet **600a-2** include a lower flux barrier and a pair of upper flux barriers similar to first permanent magnet **118a-1** and second permanent magnet **118a-2** though the lower flux barriers may have a different size and shape. For illustration, a first opening **700a** within which first permanent magnet **600a-1** of the first group of permanent magnets **600a** is mounted includes a first lower flux barrier **702a**, first upper flux barrier **504a**, second upper flux barrier **506a**, and the opening sized and shaped to accommodate first permanent magnet **600a-1**. For further illustration, a second opening **700b** within which second permanent magnet **600a-2** of the second group of permanent magnets **600a** is mounted includes a second lower flux barrier **702b**, third upper flux barrier **504b**, fourth upper flux barrier **506b**, and the opening sized and shaped to accommodate second permanent magnet **600a-2**.

Third permanent magnet **600a-3** includes a left flux barrier and a right flux barrier. For illustration, a third opening **700c** within which third permanent magnet **600a-3** of the first group of permanent magnets **600a** is mounted includes a left flux barrier **704a**, a right flux barrier **704b**, and the opening sized and shaped to accommodate third permanent magnet **600a-3**. Third permanent magnet **600a-3** is positioned between first permanent magnet **600a-1** and second permanent magnet **600a-2** to form a base of the U-shape that is open towards stator **102**.

First permanent magnet **600a-1** is rectangular with a first interior wall **706a**, a first lower wall **708a**, a first exterior wall **710a**, and a first upper wall **712a**. First interior wall **706a** and first exterior wall **710a** may be parallel to first axis **604**. Second permanent magnet **600a-2** is rectangular with a second interior wall **706b**, a second lower wall **708b**, a second exterior wall **710b**, and a second upper wall **712b**. Second interior wall **706b** and second exterior wall **710b** may be parallel to second axis **606**. First permanent magnet **600a-1** and second permanent magnet **600a-2** may be sized similar to first permanent magnet **118a-1** and second permanent magnet **118a-2**.

Third permanent magnet **600a-3** is rectangular with a third interior wall **706c**, a left wall **708c**, a third exterior wall **710c**, and a right wall **712c**. Third interior wall **706c** and third exterior wall **710c** may be perpendicular to third axis **608**. A magnet length **718** of third permanent magnet **600a-3** represents a length L_{M3} measured parallel to third axis **608** between third interior wall **706c** and third exterior wall **710c** of first third permanent magnet **600a-3**. A magnet width **720** of third permanent magnet **600a-3** represents a width W_{m3} measured perpendicular to third axis **608** between left wall **708** and right wall **712c**. Length L_{M3} may be approximately equal to a magnet width of first permanent magnet **600a-1** measured perpendicular to first axis **604** between first interior wall **706a** and first exterior wall **710a**.

First lower flux barrier **702a** and left flux barrier **704a** are separated by a first gap **714a** of rotor core **116**. Second lower flux barrier **702b** and right flux barrier **704b** are similarly separated by a second gap **714b** of rotor core **116**. A gap width **716** represents a width W_{FBG} measured across first gap **714a** that is the same for second gap **714b**.

The walls of first lower flux barrier **702a**, left flux barrier **704a**, second lower flux barrier **702b**, and right flux barrier **704b** may be curved in alternative embodiments.

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The illustrative dimensions described above relative to rotor **104** and the plurality of permanent magnet pairs **118a** may be determined in a similar manner given the selected outer stator core radius **206** R_{ost} . Magnet width **720** of third permanent magnet **600a-3** W_{m3} is selected to have a value between $\sim 0.1\%$ and $\sim 100\%$ of rotor pole pitch angle **602** τ_{rp} . Gap width **716** W_{FBG} measured across first gap **714a** and second gap **714b** is selected to have a value between $\sim 0.1\%$ and $\sim 25\%$ of magnet width **720** of third permanent magnet **600a-3** W_{m3} .

A comparison between VPMM **100** and second VPMM **600** and a benchmark interior PM machine (IPMM) was performed. A performance comparison is tabulated in Table 1 below. Neodymium, iron and boron alloy rare earth PMs were used for each of IPMM, VPMM **100**, and second VPMM **600**.

TABLE 1

	IPMM	VPMM 100	VPMM
N_{SM}/N_{pm}	4/4	4/20	4/20
J_S [A/mm ²]	4.6	4.6	4.6
Excitation frequency [Hz]	13.33	66.67	66.67
PM mass/% total weight [kg]	11.3/3.6%	11.5/3.7%	11.9/3.8%
Torque [Nm]	534	912	946
Torque density (over total volume) [Nm/L]	17.3	29.4	30.5
Power factor (lagging)	0.8	0.83	0.83
R_{ost} [mm]	355.6	355.6	355.6
Stack length [mm]	311	311	311

VPMM **100** and second VPMM **600** provide an $\sim 80\%$ torque improvement with a comparable power factor. VPMM **100** and second VPMM **600** include alternating rotor leakage flux blocking topologies, which enable use in low and medium speed applications as a motor or generator. An alternating flux barrier (e.g. first lower flux barrier **502a** and second lower flux barrier **502b**) is placed at bottom of each permanent magnet of the plurality of pairs of permanent magnets **118** on rotor **104**.

Many industries require high torque, low speed motors/generators at the power level ranging from kilowatts to megawatts, which can be provided by VPMM **100** and second VPMM **600**. VPMM **100** and second VPMM **600** can be used in a direct drive configuration, which helps reduce machine complexity and cost and improves reliability. VPMM **100** and second VPMM **600** are ideal for low speed, high torque applications such as wind turbines, industrial automation, and marine propulsion and for higher speeds, similar to conditions motors in the wheels of electric vehicles encounter.

The word “illustrative” is used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as “illustrative” is not necessarily to be construed as preferred or advantageous over other aspects or designs. Further, for the purposes of this disclosure and unless otherwise specified, “a” or “an” means “one or more”. Still further, using “and” or “or” in the detailed description is intended to include “and/or” unless specifically indicated otherwise.

The foregoing description of illustrative embodiments of the disclosed subject matter has been presented for purposes of illustration and of description. It is not intended to be exhaustive or to limit the disclosed subject matter to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the disclosed subject matter. The embodiments were chosen and described in order to explain the

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principles of the disclosed subject matter and as practical applications of the disclosed subject matter to enable one skilled in the art to utilize the disclosed subject matter in various embodiments and with various modifications as suited to the particular use contemplated. It is intended that the scope of the disclosed subject matter be defined by the claims appended hereto and their equivalents.

What is claimed is:

1. An electric machine comprising:

- a stator comprising
 - a stator core; and
 - a plurality of teeth that extend outward from the stator core, wherein a slot of a plurality of slots is positioned between a pair of the plurality of teeth;
- a stator winding wound about the plurality of teeth to form a number of stator magnetic poles between a set of connectors, wherein the number of stator magnetic poles is equal to a number of the plurality of teeth divided by a number of phases, wherein the number of phases is defined for a current provided to the stator winding when the electric machine is operated;

a rotor comprising

- a rotor core; and
- a plurality of walls that form openings in the rotor core that are separated from each other by the rotor core; and

a plurality of permanent magnets, wherein a permanent magnet is mounted in each of the openings formed in the rotor core, wherein the plurality of permanent magnets are arranged to form a plurality of pairs of permanent magnets that are equally circumferentially distributed around the rotor core, wherein each permanent magnet has an interior polarity and an exterior polarity, wherein the interior polarity has an opposite polarity relative to the exterior polarity, wherein the interior polarity is on a side of each permanent magnet facing other permanent magnets of the group of permanent magnets to which the permanent magnet is associated, wherein the interior polarity is the same for all of the permanent magnets;

wherein the stator is mounted on a first side of the rotor separated by an air gap between a surface of the rotor core and a tooth of the plurality of teeth;

wherein the openings further include a first flux barrier formed by a first plurality of walls of each opening on a first side of each permanent magnet that is closest to the stator, a second flux barrier formed by a second plurality of walls of each opening on the first side of each permanent magnet physically separated from the first flux barrier by the rotor core, and a third flux barrier formed by a third plurality of walls of each opening on a second side of each permanent magnet, wherein the first side is opposite the second side;

wherein each permanent magnet is arranged to form a rotor pole,

wherein a number of rotor poles is greater than the number of stator magnetic poles.

2. The electric machine of claim 1, wherein each pair of permanent magnets of the plurality of pairs of permanent magnets are arranged to form a V-shape open towards the plurality of teeth of the stator.

3. The electric machine of claim 1, wherein the third plurality of walls of each opening form three sides of a parallelogram, wherein a fourth side of the parallelogram is formed by a first face of a respective permanent magnet, wherein a first wall of the third plurality of walls is parallel to a second face of the respective permanent magnet,

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wherein a second wall of the third plurality of walls is parallel to a third face of the respective permanent magnet, wherein the first side is opposite the second side, wherein a third wall of the third plurality of walls connects between the first wall and the second wall and is parallel to the first face of the respective permanent magnet.

4. The electric machine of claim 1, wherein the first plurality of walls of each opening form two sides of a first triangle, wherein a third side of the first triangle is formed by a first portion of a first face of a respective permanent magnet, wherein the second plurality of walls of each opening form two sides of a second triangle, wherein a third side of the second triangle is formed by a second portion of the first face of the respective permanent magnet.

5. The electric machine of claim 1, wherein the number of rotor poles is selected as $N_p = 2N_s \pm N_{SMP}$, where N_p is the number of rotor poles, N_s is the number of the plurality of teeth of the stator, and N_{SMP} is the number of stator magnetic poles.

6. The electric machine of claim 5, wherein the number of rotor poles is twenty, the number of the plurality of teeth of the stator is twelve, and the number of stator magnetic poles is four.

7. The electric machine of claim 1, wherein a rotor pole pitch angle is defined between a first axis and a second axis, wherein the first axis extends radially outward from a radial center of the rotor core through a center of a first wall of a first permanent magnet of each pair of permanent magnets, wherein the first wall is a closest wall of the first permanent magnet to an exterior surface of the rotor core, wherein the second axis extends radially outward from the radial center of the rotor core through a center of a second wall of a second permanent magnet of each pair of permanent magnets, wherein the second wall is a closest wall of the second permanent magnet to the exterior surface of the rotor core, wherein the rotor pole pitch angle is between 25% and 75% of a rotor pole pair pitch angle τ_{rpp} , where $\tau_{rpp} = 360/N_{pG}$, where N_{pG} is a number of the plurality of pairs of permanent magnets.

8. The electric machine of claim 1, wherein each pair of permanent magnets includes a first permanent magnet and a second permanent magnet, wherein the first permanent magnet is mounted in its opening to form a mirror image of the second permanent magnet relative to a first axis that extends radially outward from a radial center of the rotor core through a center of the pair of permanent magnets to which the first permanent magnet and the second permanent magnet are associated.

9. The electric machine of claim 3, wherein a minimum distance is defined between the third flux barrier of a first permanent magnet of each pair of permanent magnets and the third flux barrier of a second permanent magnet of each pair of permanent magnets, wherein the minimum distance is between 0.1% and 25% of a width of each permanent magnet.

10. The electric machine of claim 9, wherein a length of the first wall of the third flux barrier associated with each permanent magnet of the plurality of permanent magnets is between 0.1% and 50% of a length of the second face of each permanent magnet.

11. The electric machine of claim 1, wherein an outer radius of the rotor core is between 10% and 95% of an outer radius of the stator core.

12. The electric machine of claim 1, wherein a radial length of the rotor core is between 5% and 95% of an outer radius of the stator core.

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13. The electric machine of claim 12, wherein a length of each permanent magnet is between 0.1% and 100% of the radial length of the rotor core.

14. The electric machine of claim 1, wherein a width of each permanent magnet is between 0.1 and 50 times a length of the air gap.

15. An electric machine comprising:

a stator comprising

a stator core; and

a plurality of teeth that extend outward from the stator core, wherein a slot of a plurality of slots is positioned between a pair of the plurality of teeth;

a stator winding wound about the plurality of teeth to form a number of stator magnetic poles between a set of connectors, wherein the number of stator magnetic poles is equal to a number of the plurality of teeth divided by a number of phases, wherein the number of phases is defined for a current provided to the stator winding when the electric machine is operated;

a rotor comprising

a rotor core; and

a plurality of walls that form a first plurality of openings and a second plurality of openings in the rotor core that are separated from each other by the rotor core; and

a plurality of permanent magnets, wherein a permanent magnet is mounted in each of the openings formed in the rotor core, wherein the plurality of permanent magnets are arranged to form a plurality of groups of permanent magnets that are equally circumferentially distributed around the rotor core, wherein each permanent magnet has an interior polarity and an exterior polarity, wherein the interior polarity has an opposite polarity relative to the exterior polarity, wherein the interior polarity is on a side of each permanent magnet facing other permanent magnets of the group of permanent magnets to which the permanent magnet is associated, wherein the interior polarity is the same for all of the permanent magnets, wherein each group of permanent magnets of the plurality of groups of permanent magnets includes a first permanent magnet, a second permanent magnet, and a third permanent magnet, wherein the third permanent magnet is between a respective first permanent magnet and a respective second permanent magnet to form a U-shape open towards the plurality of teeth of the stator;

wherein the stator is mounted on a first side of the rotor separated by an air gap between a surface of the rotor core and a tooth of the plurality of teeth;

wherein the first plurality of openings include a first flux barrier formed by a first plurality of walls of each respective opening of the first plurality of openings on a first side of each first permanent magnet and of each second permanent magnet that are closest to the stator, a second flux barrier formed by a second plurality of walls of each respective opening of the first plurality of openings on the first side of each first permanent magnet and on the first side of each second permanent magnet, and a third flux barrier formed by a third plurality of walls of each respective opening of the first plurality of openings on a second side of each first permanent magnet and of each second permanent magnet, wherein the first side is opposite the second side, wherein the first flux barrier of each first permanent magnet and of each second permanent magnet is physically separated from the respective second flux barrier by the rotor core,

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wherein the second plurality of openings include a fourth flux barrier formed by a fourth plurality of walls of each respective opening of the second plurality of openings on a first side of each third permanent magnet and a fifth flux barrier formed by a fifth plurality of walls of each respective opening of the second plurality of openings on a second side of each third permanent magnet, wherein the first side of each third permanent magnet is opposite the second side of each third permanent magnet;

wherein each permanent magnet is arranged to form a rotor pole,

wherein a number of rotor poles is greater than twice the number of stator magnetic poles.

16. The electric machine of claim 15, wherein a minimum distance is defined between the third flux barrier of the first permanent magnet of each group of permanent magnets and the fourth flux barrier of the third permanent magnet of each group of permanent magnets, wherein the minimum distance is between 0.1% and 25% of a width of each permanent magnet.

17. The electric machine of claim 16, wherein the minimum distance is further defined between the third flux

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barrier of the second permanent magnet of each group of permanent magnets and the fifth flux barrier of the third permanent magnet of each group of permanent magnets.

18. The electric machine of claim 15, wherein the first plurality of walls and the second plurality of walls form two sides of a triangle, wherein a third side of the triangle is formed by a portion of a first face of a respective permanent magnet.

19. The electric machine of claim 15, wherein the number of rotor poles is selected as $N_p = 2N_s \pm N_{SMP}$, where N_p is the number of rotor poles, N_s is the number of the plurality of teeth of the stator, and N_{SMP} is the number of stator magnetic poles.

20. The electric machine of claim 15, wherein the first permanent magnet of each group is mounted in its opening to form a mirror image of the second permanent magnet relative to a first axis that extends radially outward from a radial center of the rotor core through a center of the group of permanent magnets to which the first permanent magnet and the second permanent magnet are associated.

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