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Sarlioglu et al.

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(54) **AXIAL FLUX SWITCHING PERMANENT MAGNET MACHINE**

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H02K 16/02	(2006.01)
H02K 16/04	(2006.01)
H02K 1/17	(2006.01)
H02K 3/28	(2006.01)

(52) **U.S. Cl.**

CPC ***H02K 21/44*** (2013.01); *H02K 1/146* (2013.01); *H02K 1/17* (2013.01); *H02K 3/28* (2013.01)

(58) **Field of Classification Search**

CPC H02K 1/146; H02K 1/17; H02K 1/182; H02K 1/223; H02K 3/28; H02K 19/06; H02K 21/04; H02K 21/44; H02K 16/00; H02K 16/02; H02K 16/025; H02K 16/04

USPC 310/46, 181, 112, 154.02, 266, 268, 310/216.008, 216.009

See application file for complete search history.

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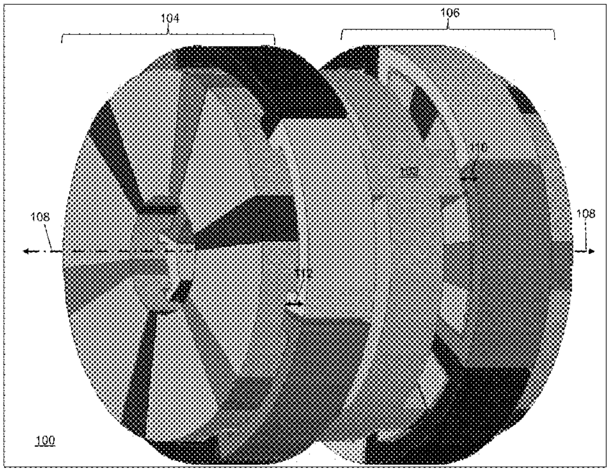
(57) **ABSTRACT**

An electric machine includes a rotor, a first and second stator, a first and second plurality of permanent magnets, a first and second winding, a third and fourth winding. The first stator and the second stator are mounted axially relative to the rotor. A first permanent magnet and a second permanent magnet of the first plurality of permanent magnets have opposite polarities. A first permanent magnet and a second permanent magnet of the second plurality of permanent magnets have opposite polarities. The first winding, the second winding, the third winding, and the fourth winding are connected in series. An absolute value of an angle offset between the first winding and the third winding and between closest poles of the first plurality of poles and the second plurality of poles is 180 electrical degrees.

20 Claims, 15 Drawing Sheets



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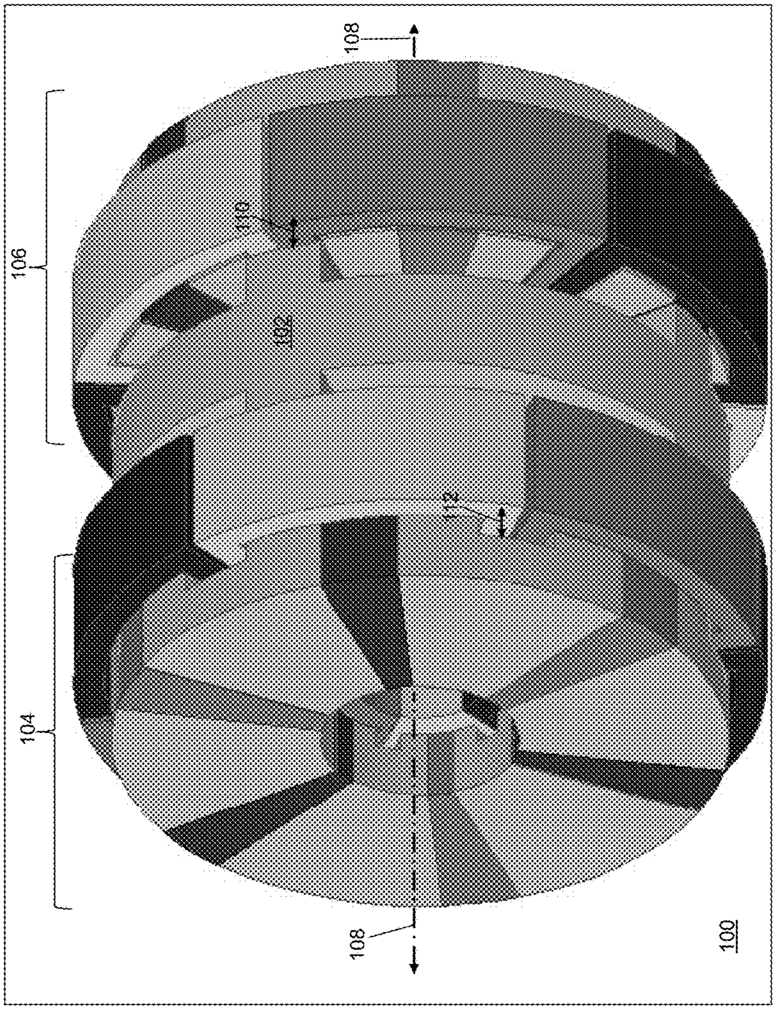
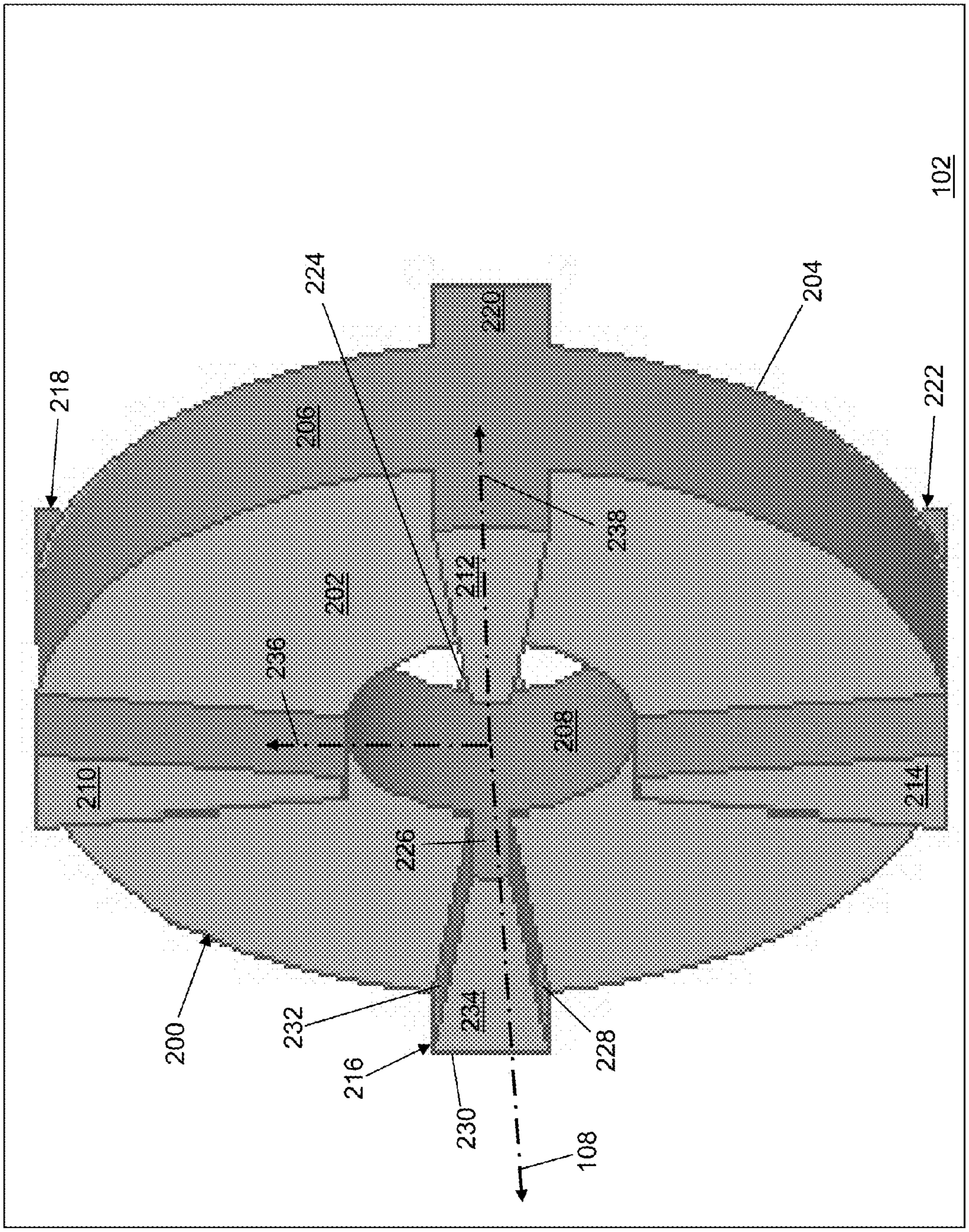


Fig. 1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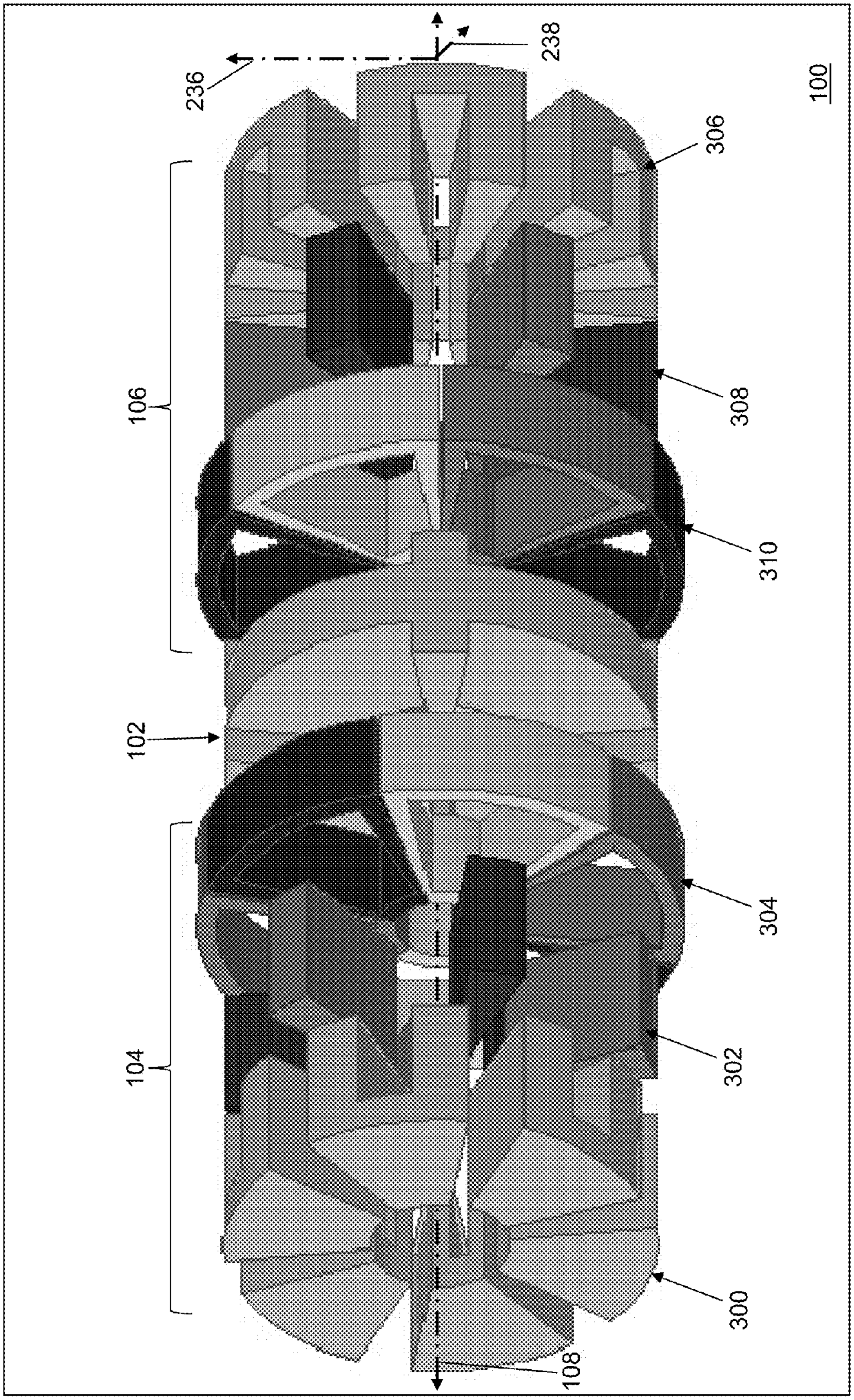
230
108

Fig. 2



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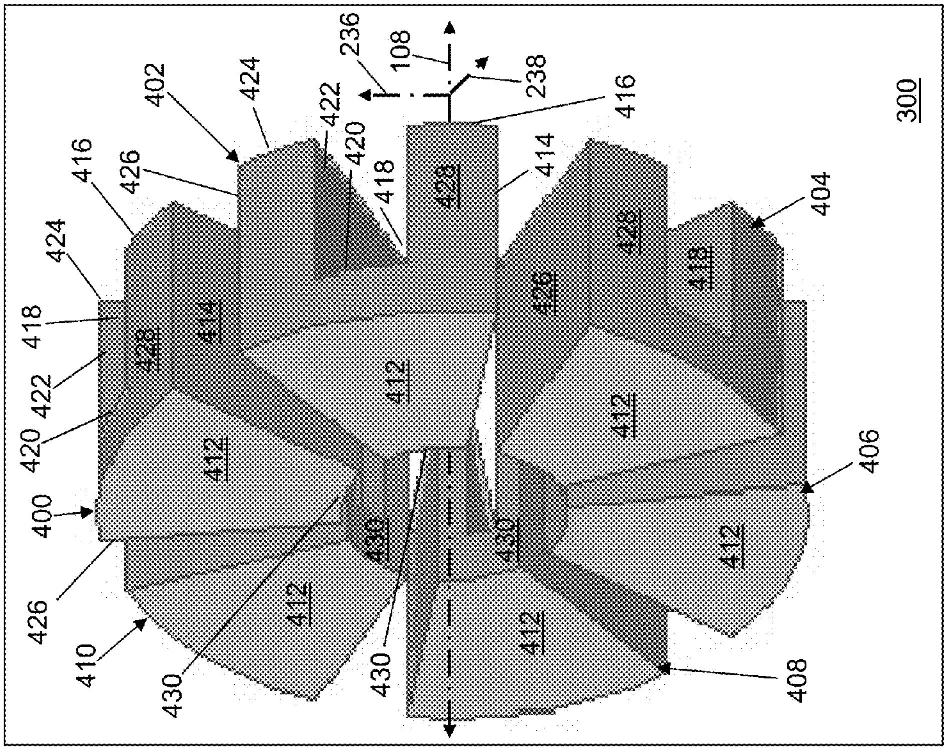
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426
426
428
428
428
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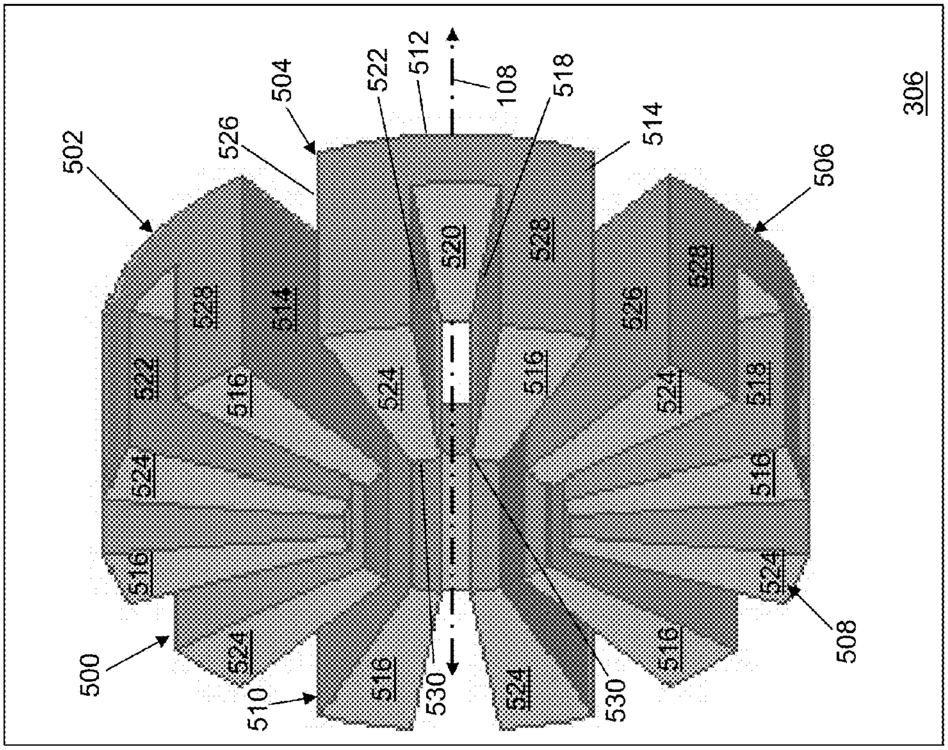
430
430
430
108
236
238
300

Fig. 4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528
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528
530
530
108
306

Fig. 5

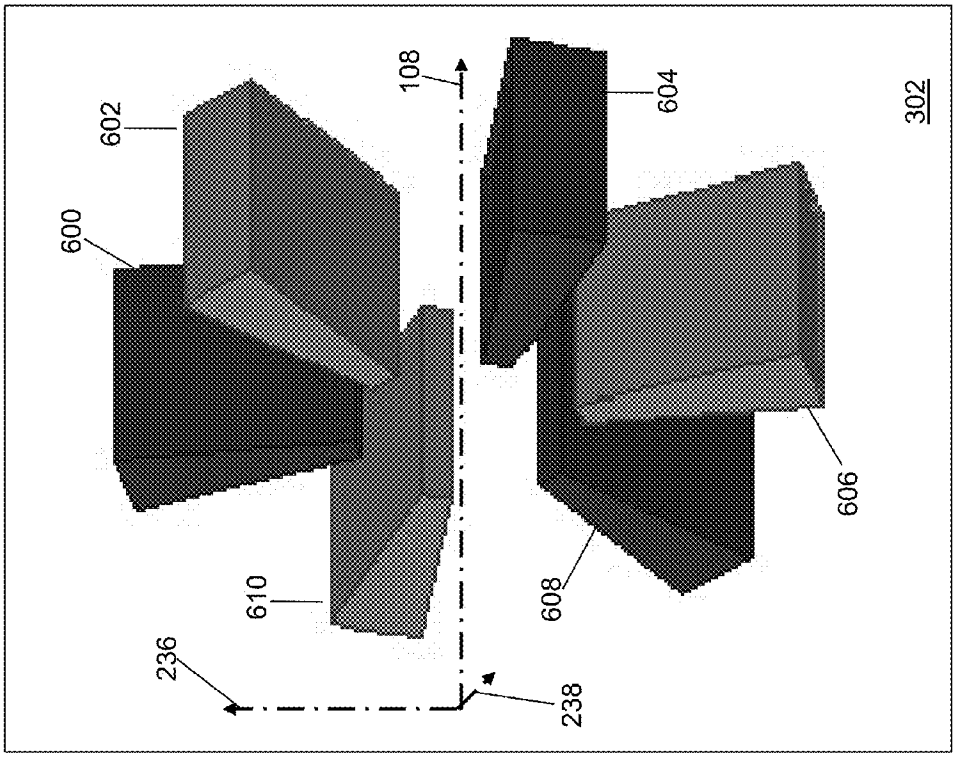
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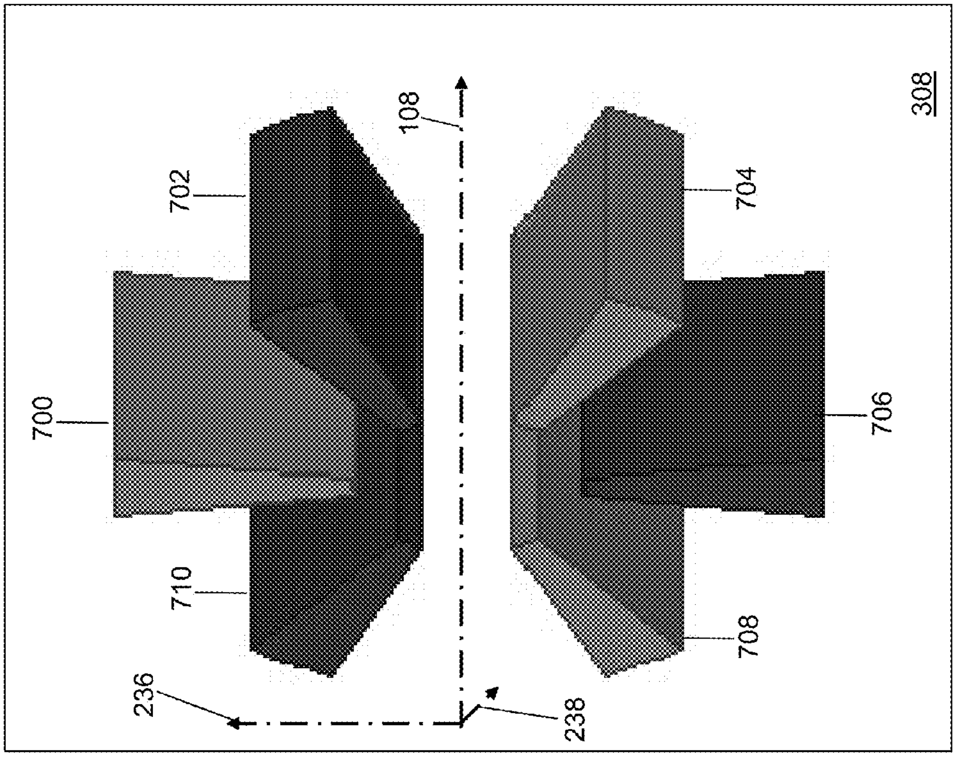
Fig. 6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236
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Fig. 7

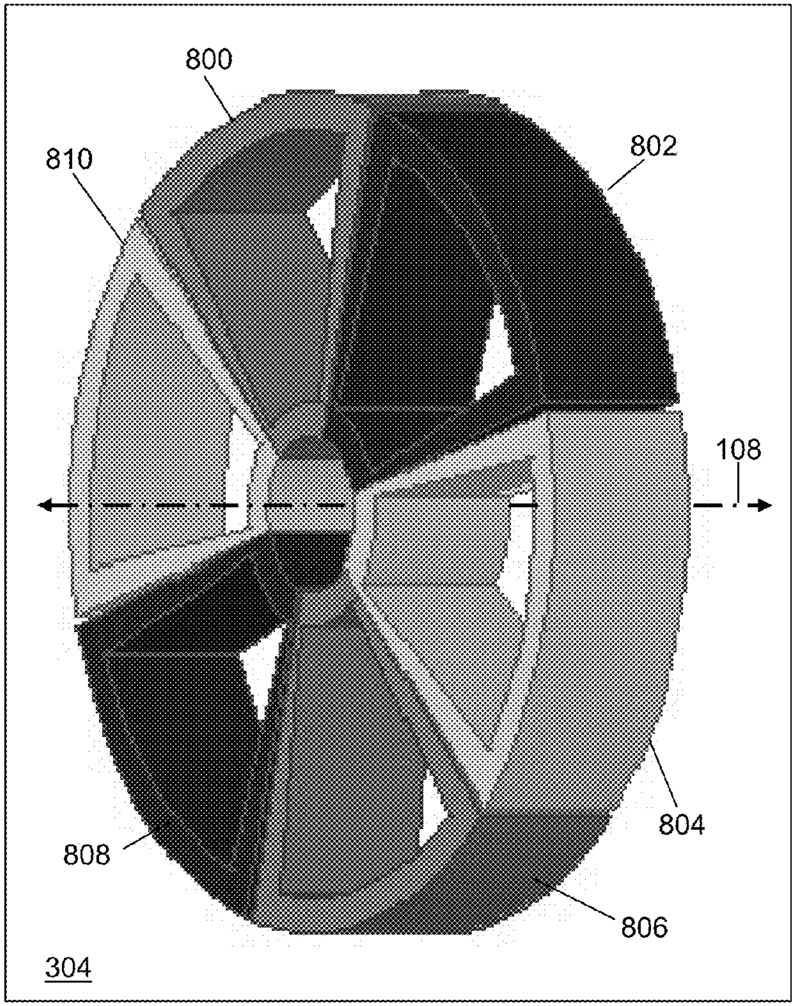
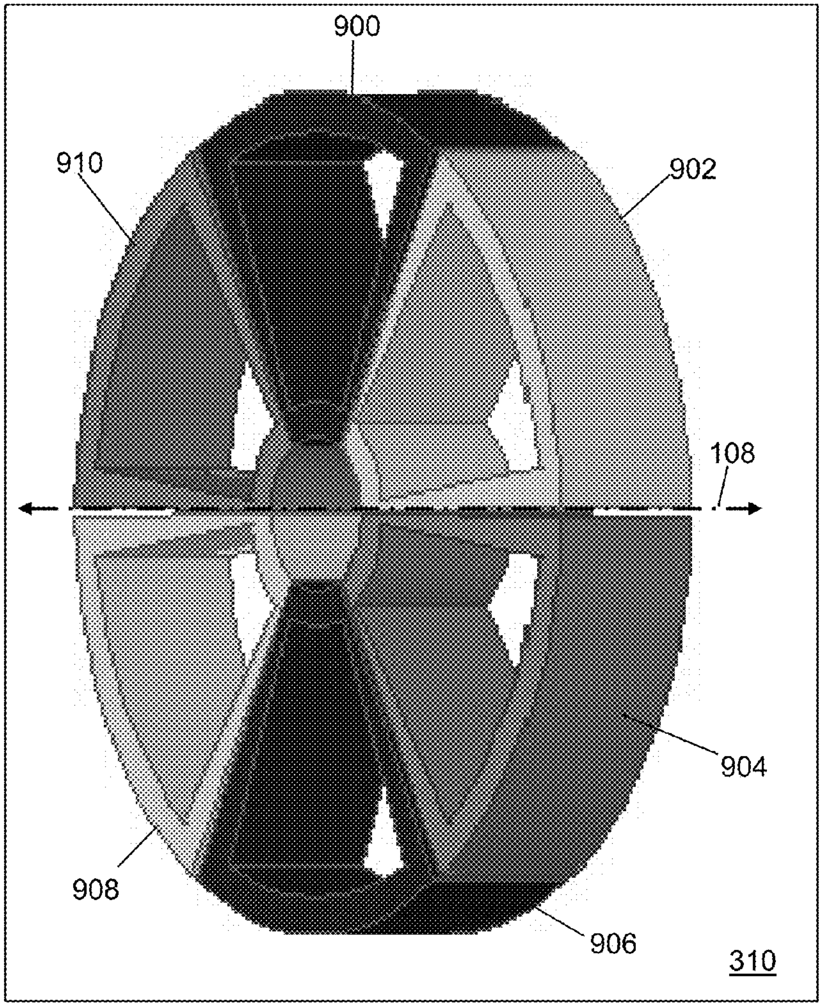


Fig. 8



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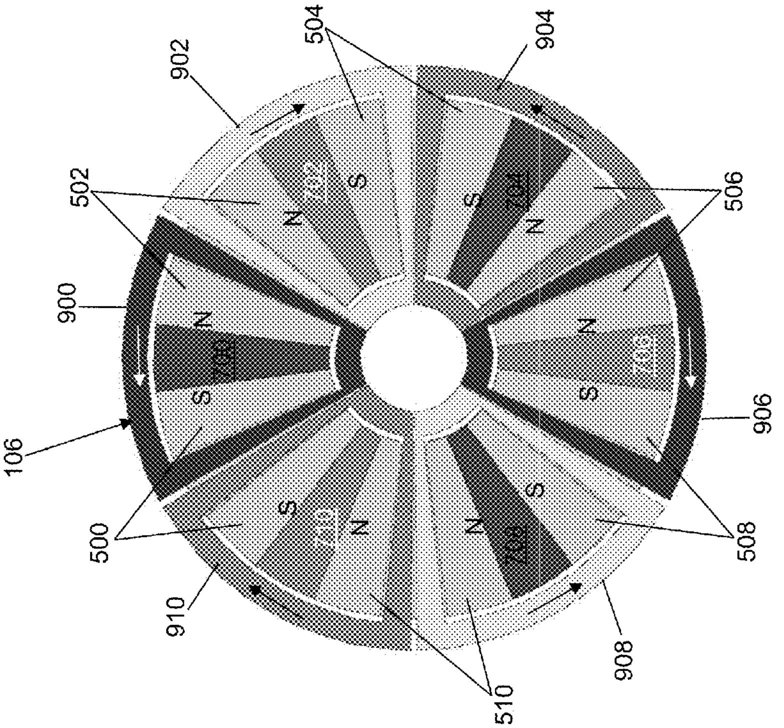
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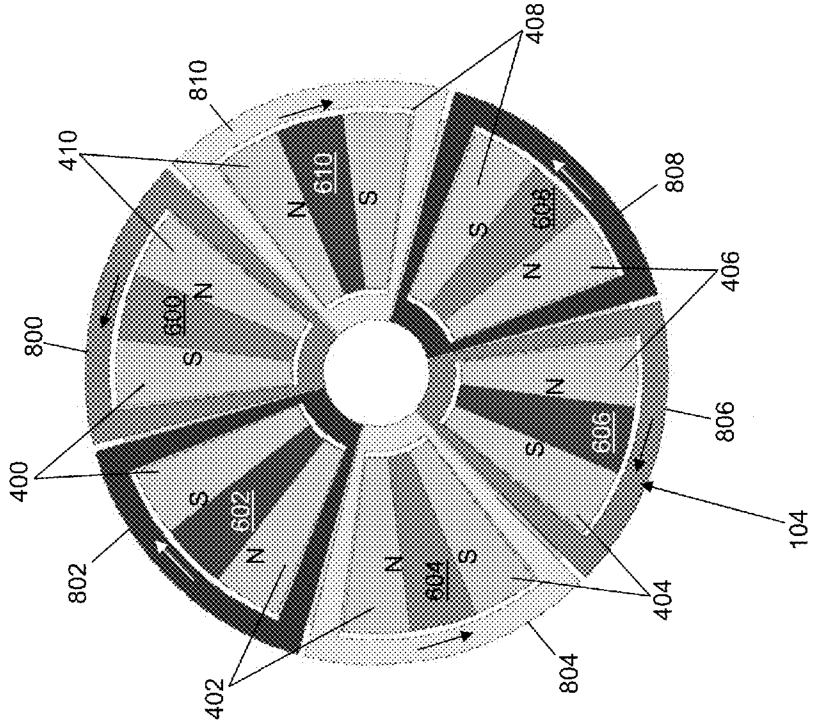
Fig. 11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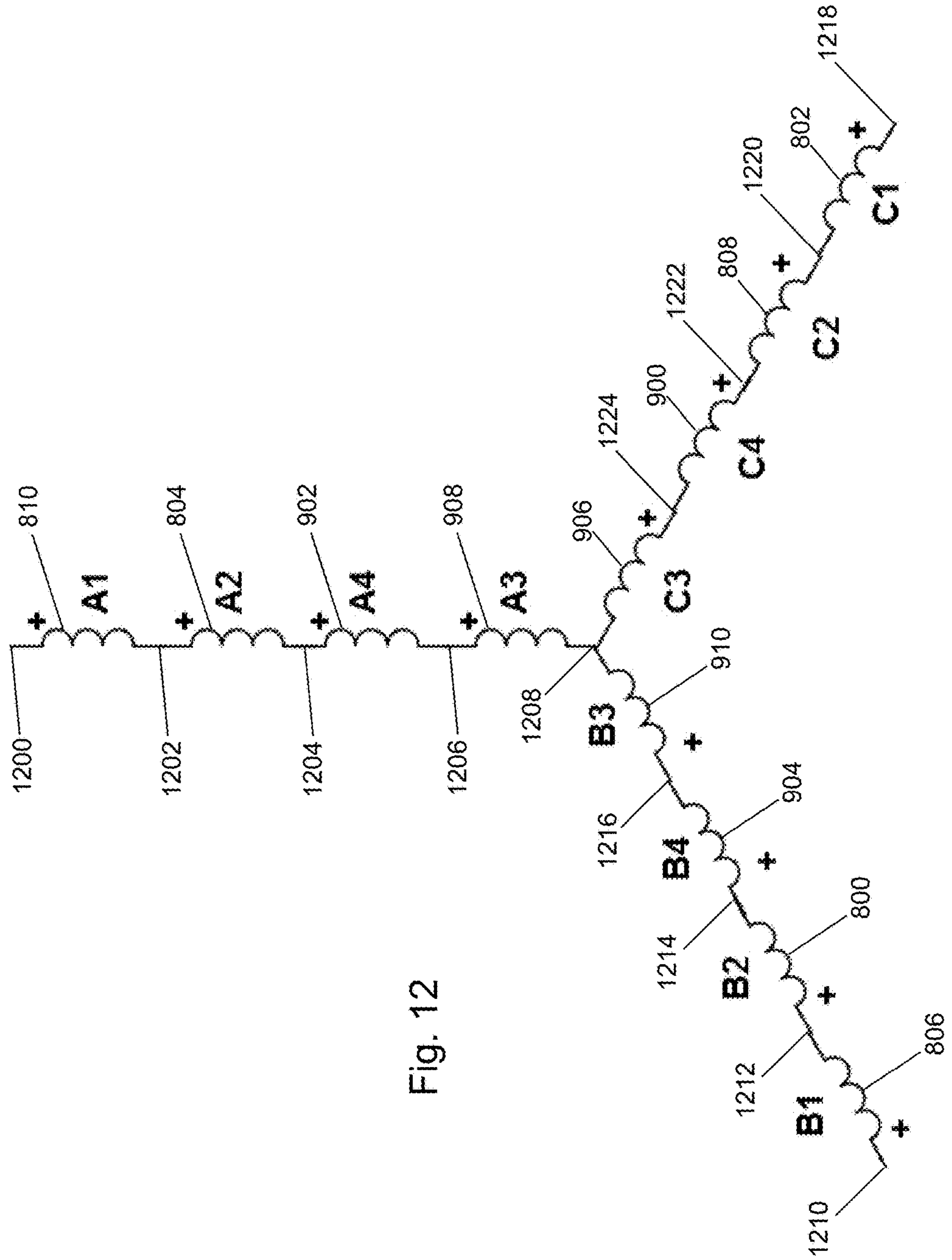
404
402
804

Fig. 10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B2
B1
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C4
C2
C1
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906
1224
900
1222
808
1220
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1218
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1204
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1208
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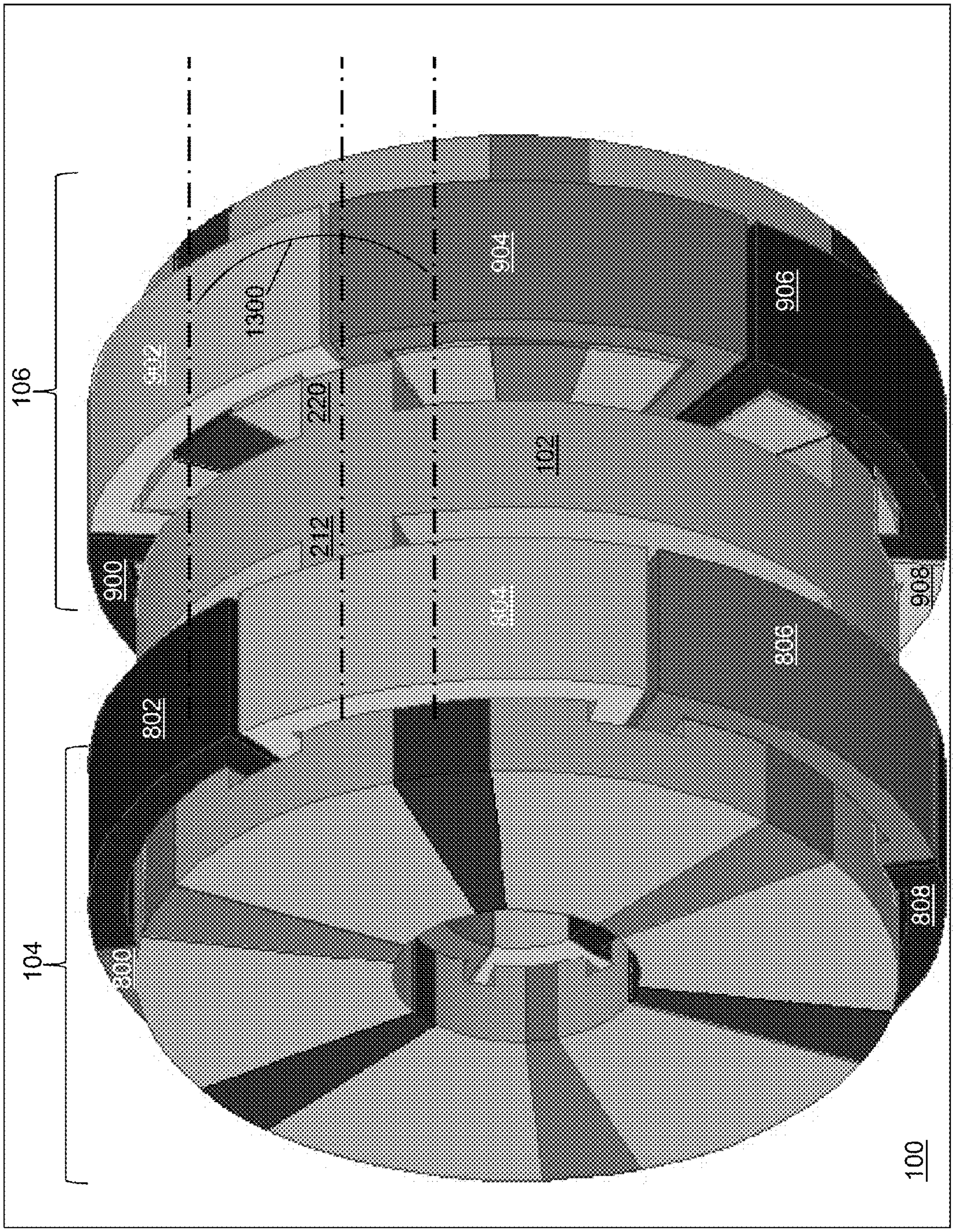
1216
904
1214
800
1212
806
1210

Fig. 12



104
106
800
802
804
806
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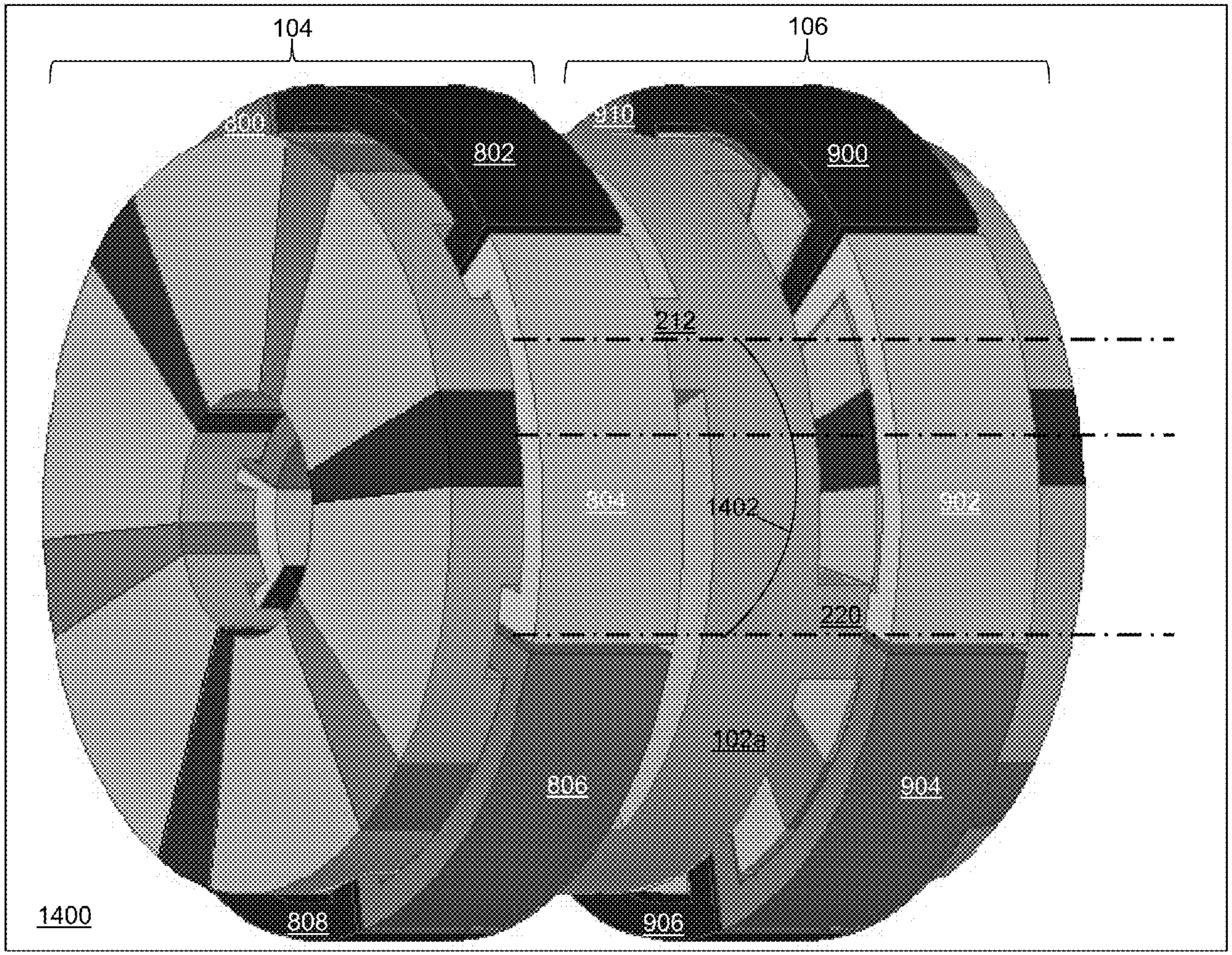
900
904
906
908
912
1300
220
212
102
100

Fig. 13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900
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1402
902
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102a
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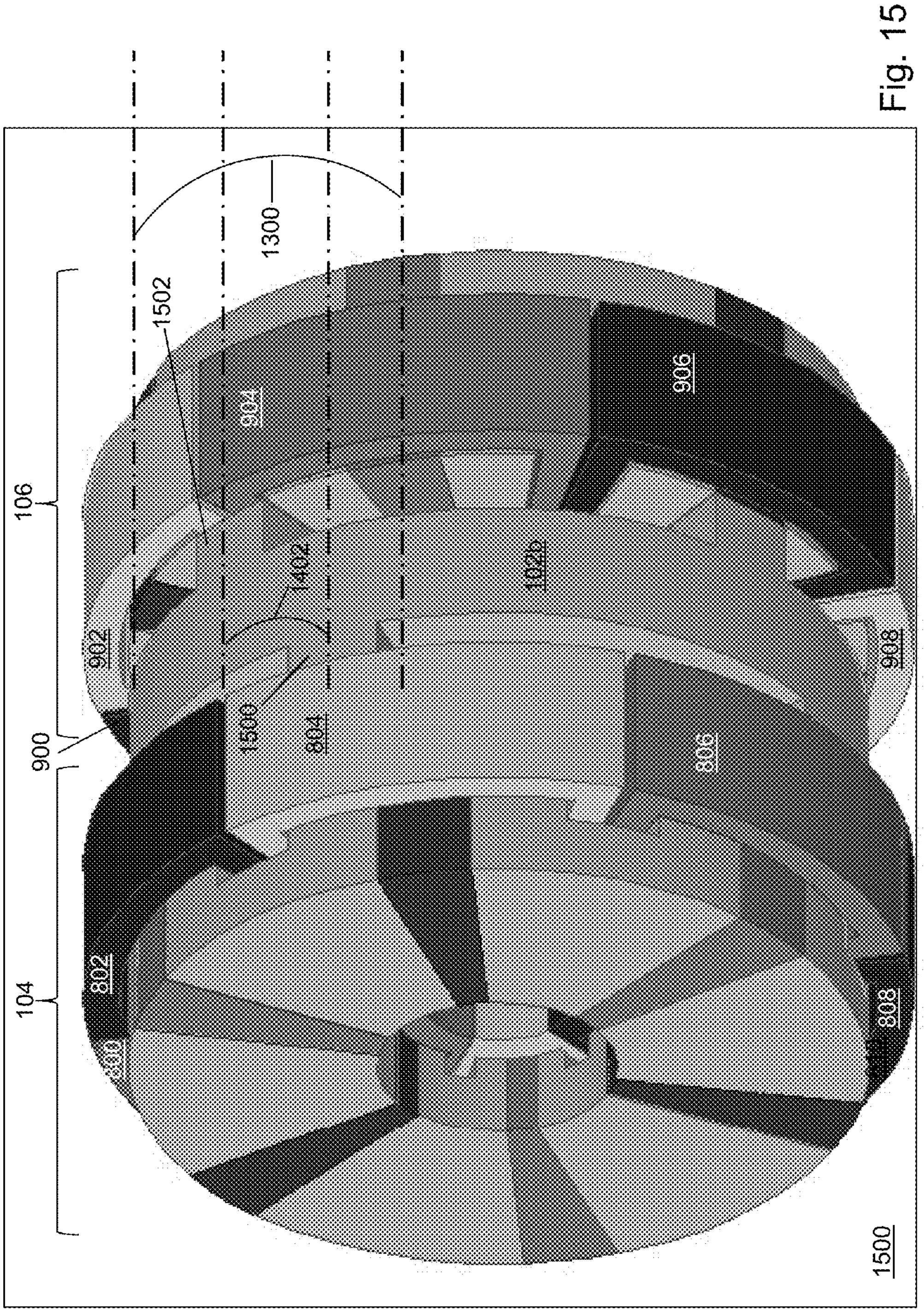
904
1400
808
906

Fig. 14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1402
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102b
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800
808
1500

Fig. 15

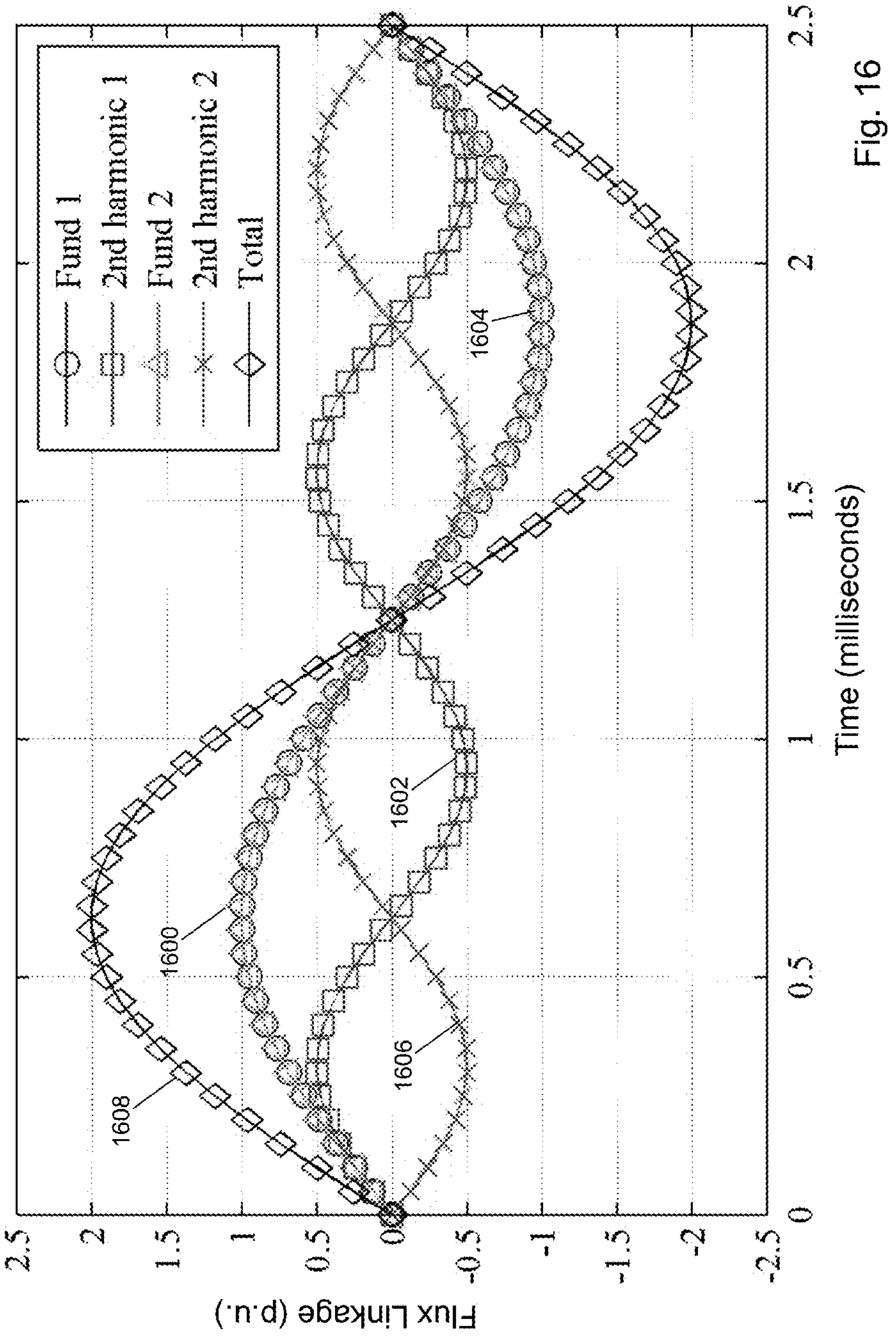

Fund 1
2nd harmonic 1
Fund 2
2nd harmonic 2
Total
1600
1602
1604
1606
1608
Flux Linkage (p.u.)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Time (milliseconds)
0
0.5
1
1.5
2
2.5

Fig. 16

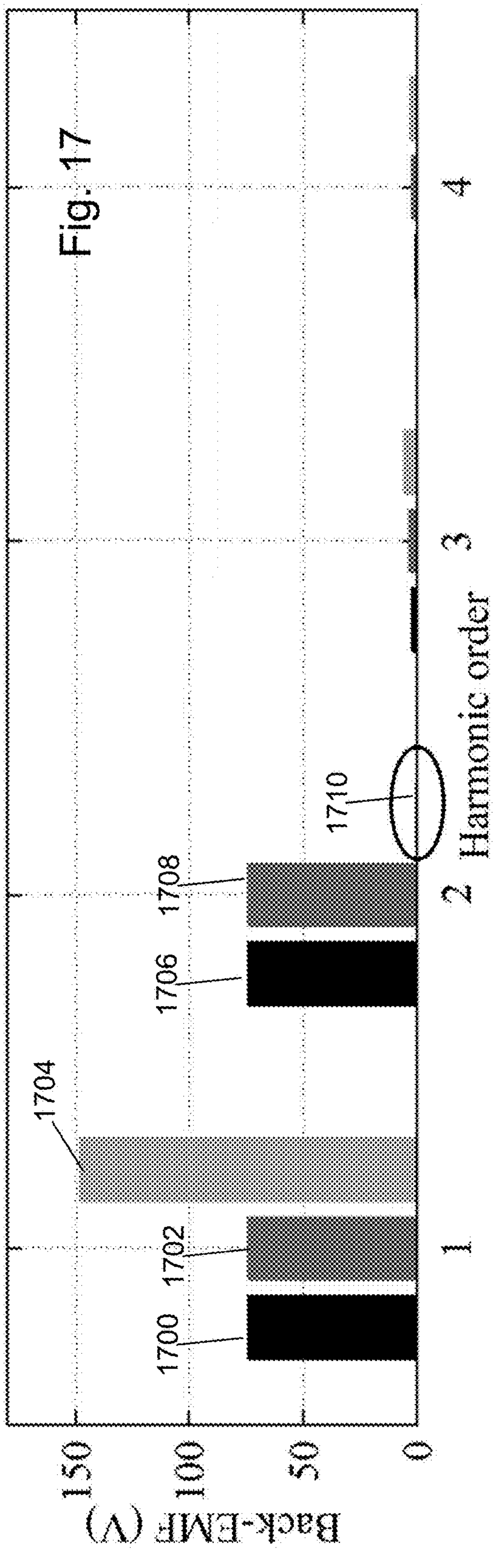


Fig. 17

1700
1702
1704
1706
1708
1710
Back-EMF (V)
0
50
100
150
1
2
3
4
Harmonic order

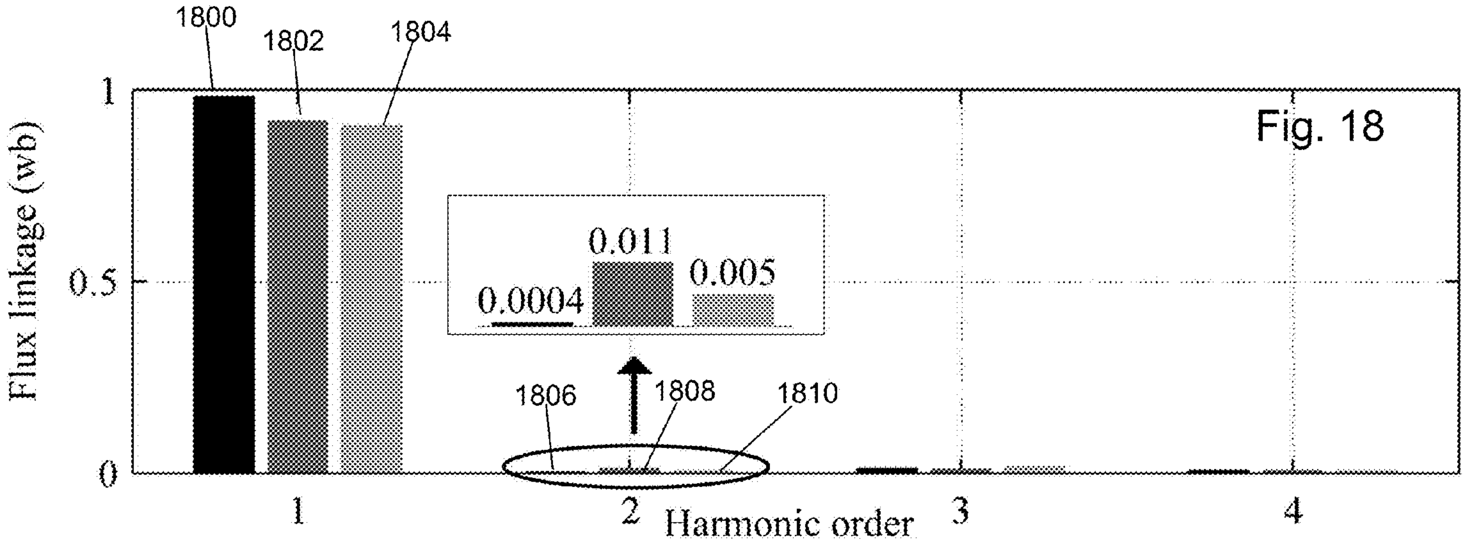


Fig. 18

1800
1802
1804
1
0.5
0
Flux linkage (wb)
0.0004
0.011
0.005
1806
1808
1810
1
2
3
4
Harmonic order

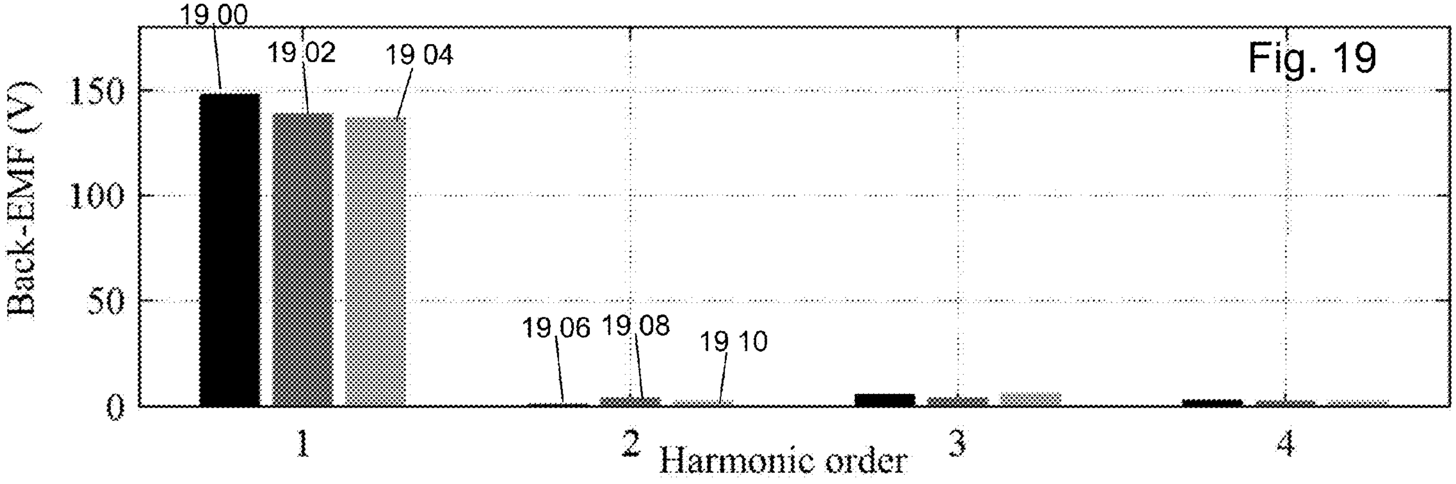
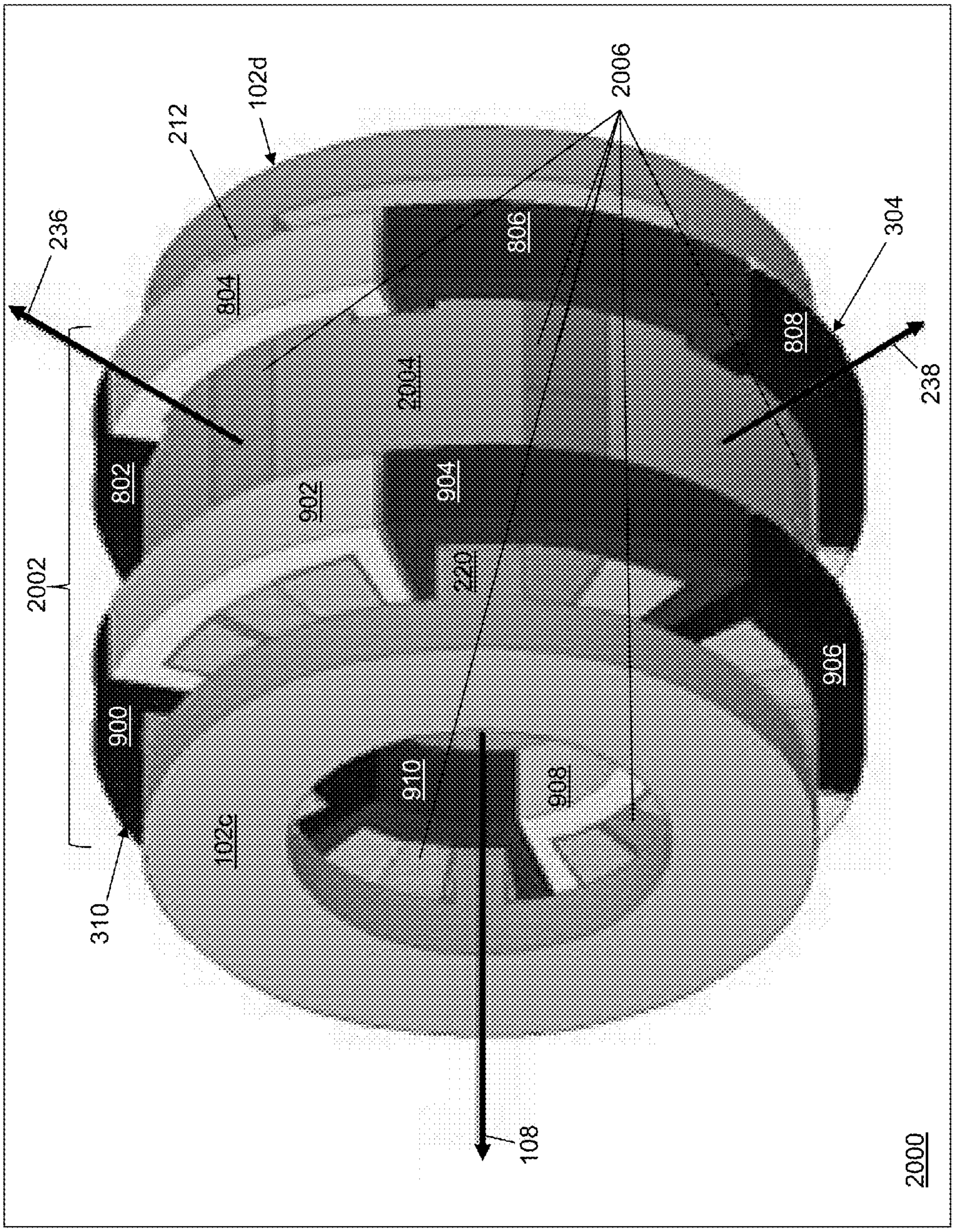


Fig. 19

19 00
19 02
19 04
150
100
50
0
Back-EMF (V)
19 06
19 08
19 10
1
2
3
4
Harmonic order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102c
808
304
238

Fig. 20

AXIAL FLUX SWITCHING PERMANENT MAGNET MACHINE

BACKGROUND

The excitation frequency, f_e, of a flux switching permanent magnet (FSPM) machine is proportional to the number of rotor poles (p_r), $f_e=np_r/60$, and not pole pairs, where n is the rotational speed in revolutions per minute (rpm). A typical FSPM machine has 12 stator slots and 10 rotor poles resulting in a high fundamental excitation frequency when operated at high-speed. For some high speeds, the fundamental frequency may not be attainable with today's power electronic converters.

To reduce the fundamental frequency for a given rotational speed, the number of rotor poles should be as small as possible. The minimum number of stator slots is six for a three-phase machine since it should be an even number and also a multiple of three. The number of rotor poles can be 4, 5, 7, 8, etc. Previously, not all of these combinations are suitable for practical use due to issues such as an unbalanced back-electromotive force (EMF) and unbalanced rotor force.

SUMMARY

In an example embodiment, an electric machine includes, but is not limited to, a rotor, a first stator, a second stator, a first plurality of permanent magnets, a second plurality of permanent magnets, a first winding, a second winding, a third winding, and a fourth winding. The rotor includes, but is not limited to, a rotor core having a first face and a second face, a first plurality of poles mounted to extend from the first face, and a second plurality of poles mounted to extend from the second face. The second face faces in a direction opposite to the first face. An aperture is formed through the first face and the second face.

The first stator includes, but is not limited to, a first plurality of core pieces, wherein each core piece of the first plurality of core pieces includes a slot having a first sidewall and a second sidewall. The second stator includes, but is not limited to, a second plurality of core pieces, wherein each core piece of the second plurality of core pieces includes a slot having a first sidewall and a second sidewall. A permanent magnet of the first plurality of permanent magnets is mounted between the first sidewall and the second sidewall of adjacent core pieces of the first plurality of core pieces. A permanent magnet of the second plurality of permanent magnets is mounted between the first sidewall and the second sidewall of adjacent core pieces of the second plurality of core pieces.

The first winding is wound over the first sidewall of a first core piece of the first plurality of core pieces, over a first permanent magnet of the first plurality of permanent magnets mounted between the first sidewall of the first core piece and the second sidewall of a second core piece of the first plurality of core pieces, and over the second sidewall of the second core piece of the first plurality of core pieces, wherein the first core piece and the second core piece of the first plurality of core pieces are adjacent to each other. The second winding is wound over the second sidewall of a third core piece of the first plurality of core pieces, over a second permanent magnet of the first plurality of permanent magnets mounted between the second sidewall of the third core piece and the first sidewall of a fourth core piece of the first plurality of core pieces, and over the first sidewall of the fourth core piece of the first plurality of core pieces, wherein the third core piece and the fourth core piece of the first

plurality of core pieces are adjacent to each other. The third winding is wound over the first sidewall of a first core piece of the second plurality of core pieces, over a first permanent magnet of the second plurality of permanent magnets mounted between the first sidewall of the first core piece and the second sidewall of a second core piece of the second plurality of core pieces, and over the second sidewall of the second core piece of the second plurality of core pieces, wherein the first core piece and the second core piece of the second plurality of core pieces are adjacent to each other. The fourth winding is wound over the second sidewall of a third core piece of the second plurality of core pieces, over a second permanent magnet of the second plurality of permanent magnets mounted between the second sidewall of the third core piece and the first sidewall of a fourth core piece of the second plurality of core pieces, and over the first sidewall of the fourth core piece of the second plurality of core pieces, wherein the third core piece and the fourth core piece of the second plurality of core pieces are adjacent to each other. The first winding is closer to the third winding than to the fourth winding.

The first stator is mounted axially relative to the rotor so that a first air gap separates the first plurality of poles from the first winding and the second winding. The second stator is mounted axially relative to the rotor so that a second air gap separates the second plurality of poles from the third winding and the fourth winding. The first permanent magnet of the first plurality of permanent magnets and the second permanent magnet of the first plurality of permanent magnets have opposite polarities. The first permanent magnet of the second plurality of permanent magnets and the second permanent magnet of the second plurality of permanent magnets have opposite polarities. The first winding, the second winding, the third winding, and the fourth winding are connected in series. An absolute value of an angle offset between the first winding and the third winding and between closest poles of the first plurality of poles and the second plurality of poles is 180 electrical degrees.

In another example embodiment, an electric machine includes, but is not limited to, a first rotor, a second rotor, a stator, a plurality of permanent magnets, a first winding, a second winding, a third winding, and a fourth winding. The first rotor includes, but is not limited to, a first rotor core and a first plurality of poles. The first rotor core has a first face and a second face, wherein the second face faces in a direction opposite to the first face. An aperture is formed through the first face and the second face. The first plurality of poles is mounted to extend from the first face of the first rotor core. The second rotor includes, but is not limited to, a second rotor core and a second plurality of poles. The second rotor core has a first face and a second face, wherein the second face faces in a direction opposite to the first face. An aperture is formed through the first face and the second face. The first face of the first rotor core is in a same direction as the first face of the second rotor core. The second plurality of poles is mounted to extend from the second face of the second rotor core.

The stator includes, but is not limited to, a first plurality of core pieces and a second plurality of core pieces. Each core piece of the first plurality of core pieces and of the second plurality of core pieces includes a slot having a first sidewall and a second sidewall. The first plurality of core pieces face towards the first plurality of poles and the second plurality of core pieces face towards the second plurality of poles. A permanent magnet of the plurality of permanent magnets is mounted between the first sidewall and the second sidewall of adjacent core pieces of the first plurality of core pieces and between the first sidewall and the second sidewall of adjacent core pieces of the second plurality of core pieces.

The first winding is wound over the first sidewall of a first core piece of the first plurality of core pieces, over a first permanent magnet of the plurality of permanent magnets mounted between the first sidewall of the first core piece and the second sidewall of a second core piece of the first plurality of core pieces, and over the second sidewall of the second core piece of the first plurality of core pieces, wherein the first core piece and the second core piece of the first plurality of core pieces are adjacent to each other. The second winding is wound over the second sidewall of a third core piece of the first plurality of core pieces, over a second permanent magnet of the plurality of permanent magnets mounted between the second sidewall of the third core piece and the first sidewall of a fourth core piece of the first plurality of core pieces, and over the first sidewall of the fourth core piece of the first plurality of core pieces, wherein the third core piece and the fourth core piece of the first plurality of core pieces are adjacent to each other. The third winding is wound over the first sidewall of a first core piece of the second plurality of core pieces, over the first permanent magnet of the plurality of permanent magnets mounted between the first sidewall of the first core piece and the second sidewall of a second core piece of the second plurality of core pieces, and over the second sidewall of the second core piece of the second plurality of core pieces, wherein the first core piece and the second core piece of the second plurality of core pieces are adjacent to each other. The fourth winding is wound over the second sidewall of a third core piece of the second plurality of core pieces, over the second permanent magnet of the plurality of permanent magnets mounted between the second sidewall of the third core piece and the first sidewall of a fourth core piece of the second plurality of core pieces, and over the first sidewall of the fourth core piece of the second plurality of core pieces, wherein the third core piece and the fourth core piece of the second plurality of core pieces are adjacent to each other. The first winding is closer to the third winding than to the fourth winding;

The stator is mounted axially between the first rotor and the second rotor so that a first air gap separates the first plurality of poles from the first winding and the second winding and a second air gap separates the second plurality of poles from the third winding and the fourth winding. The first permanent magnet of the plurality of permanent magnets and the second permanent magnet of the first plurality of permanent magnets have opposite polarities. The first winding, the second winding, the third winding, and the fourth winding are connected in series. The second plurality of poles is rotated 180 electrical degrees relative to the first plurality of 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.

FIG. **1** depicts a perspective view of an axial flux switching permanent magnet machine (AFSPM) in accordance with an illustrative embodiment.

FIG. **2** depicts a perspective view of a rotor of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **3** depicts an exploded perspective view of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **4** depicts a perspective view of a left stator core of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **5** depicts a perspective view of a right stator core of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **6** depicts a perspective view of a left plurality of magnets of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **7** depicts a perspective view of a right plurality of magnets of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **8** depicts a perspective view of a left plurality of stator windings of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **9** depicts a perspective view of a right plurality of windings of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **10** depicts a right to left side view of a left stator of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **11** depicts a left to right side view of a right stator of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **12** depicts stator winding connections between the left stator and the right stator of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **13** depicts a second perspective view of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **14** depicts a perspective view of a second AFSPM in accordance with an illustrative embodiment.

FIG. **15** depicts a perspective view of a third AFSPM in accordance with an illustrative embodiment.

FIG. **16** depicts a flux linkage in a first pair of stator windings of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **17** depicts a back-electromotive force in the first pair of stator windings of the AFSPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **18** depicts a flux linkage comparison between the AFSPM of FIG. **1**, the second AFSPM of FIG. **14**, and the third AFSPM of FIG. **15** in accordance with an illustrative embodiment.

FIG. **19** depicts a back-electromotive force comparison between the AFSPM of FIG. **1**, the second AFSPM of FIG. **14**, and the third AFSPM of FIG. **15** in accordance with an illustrative embodiment.

FIG. **20** depicts a perspective view of a fourth AFSPM in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

Referring to FIG. **1**, a perspective view of an axial flux switching permanent magnet machine (AFSPM) **100** is shown in accordance with an illustrative embodiment. AFSPM **100** may include a rotor **102**, a left stator **104**, and a right stator **106**. In the illustrative embodiment, AFSPM **100** is a three-phase machine that can be configured as a generator or as a motor as understood by a person of skill in the art. In alternative embodiments, AFSPM **100** can be configured to support a fewer or a greater number of phases.

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 shown in the drawings and are not intended to be limiting in any manner unless otherwise indicated.

AFSPM **100** may be used in various orientations. A shaft (not shown) may be mounted to extend parallel to a center axis **108**. Center axis **108** extends through a center of rotor **102**, left stator **104**, and right stator **106** such that rotor **102**, left stator **104**, and right stator **106** are arranged concentrically around the shaft when AFSPM **100** is mounted to the shaft.

Rotor **102** is mounted to the shaft for rotation as understood by a person of skill in the art. Rotor **102** may be formed of a ferromagnetic material such as lamination steel, iron, cobalt, nickel, etc. as understood by a person of skill in the art. Referring to FIG. **2**, rotor **102** may include a rotor core **200**, a left plurality of poles, and a right plurality of poles. A number of rotor poles, p_{r1}, of the left plurality of poles equals a number of rotor poles, p_{r2}, of the right plurality of poles. The number of rotor poles may depend on the number of phases supported by AFSPM **100**. In the illustrative embodiment, $p_{r1}=p_{r2}=4$, though other numbers of rotor poles are possible. For example, the left plurality of poles may include a first left pole **210**, a second left pole **212**, a third left pole **214**, and a fourth left pole **216**. The right plurality of poles includes the same number of poles as the left plurality of poles. The right plurality of poles may include a first right pole **218**, a second right pole **220**, a third right pole **222**, and a fourth right pole **224**.

Rotor core **200** has a disc shape with an aperture through a center of the disc shape. Rotor core **200** may include a rotor left face **202**, a rotor right face **204**, a rotor exterior face **206**, and a rotor interior face **208**. Rotor left face **202** extends generally perpendicularly from first edges of rotor exterior face **206** and rotor interior face **208**. Rotor right face **204** extends generally perpendicularly from second edges of rotor exterior face **206** and rotor interior face **208**. Rotor left face **202** faces in a direction opposite rotor right face **204**. Rotor left face **202** and rotor right face **204** are generally parallel to each other, flat, and disc-shaped such that the shaft extends through the aperture through a center of the disc shape formed by rotor interior face **208**.

The left plurality of poles is distributed evenly around rotor left face **202**, and the right plurality of poles is distributed evenly around rotor right face **204**. As understood by a person of skill in the art, rotor core **200**, the left plurality of poles, and the right plurality of poles may be laminations stacked in a radial direction. The laminations may be punched or laser cut.

The left plurality of poles extends generally perpendicularly outward from rotor left face **202**. The right plurality of poles extends generally perpendicularly outward from rotor right face **204**. The left and right pluralities of poles extend in alignment from rotor interior face **208** and from rotor exterior face **206**. In the illustrative embodiment of FIG. **2**, each pole of the left plurality of poles is aligned with a respective pole of the right plurality of poles. “Aligned with” indicates that each pair of left and right poles extends from the same point around the circumference of rotor **102** though the left and right poles extend in opposite directions.

The left plurality of poles and the right plurality of poles are distributed at equal angles around the circumference of rotor **102**. For example, in the illustrative position shown in FIG. **2**, first left pole **210** and first right pole **218** are positioned at 90 degrees, second left pole **212** and second right pole **220** are positioned at 0 degrees, third left pole **214** and third right pole **222** are positioned at −90 degrees, and fourth left pole **216** and fourth right pole **224** are positioned at 180 degrees relative to a vertical axis **236** that is perpendicular to center axis **108** and a third axis **238** that is perpendicular to both center axis **108** and vertical axis **236**.

In the illustrative embodiment, each pole of the left and right pluralities of poles has the same shape and size and is formed of the same material. For illustration, fourth left pole **216** may include a pole interior face **226**, a pole bottom face **228**, a pole exterior face **230**, a pole upper face **232** and a stator facing face **234**. Pole interior face **226** extends from rotor interior face **208**. Pole exterior face **230** extends from rotor exterior face **206**. Stator facing face **234** is generally flat and parallel to rotor left face **202**. Pole bottom face **228** extends between pole exterior face **230** and pole interior face **226**, and pole top face **232** extends between pole exterior face **230** and pole interior face **226**. Fourth left pole **216** has a truncated pie shape though other polygonal and or elliptical shapes may be used.

The components of rotor **102** may be integrally formed together or formed of one or more separate pieces that are mounted to each other. As used in this disclosure, the term “mount” further includes join, unite, connect, 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 “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, but are mounted together via intermediate elements). 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.

Referring to FIG. **3**, left stator **104** may include a left stator core **300**, a left plurality of magnets **302**, and a left plurality of windings **304**. Right stator **106** may include a right stator core **306**, a right plurality of magnets **308**, and a right plurality of windings **310**. Left stator **104** is positioned adjacent the left plurality of poles of rotor **102**. Right stator **106** is positioned adjacent the right plurality of poles of rotor **102**. Left stator **104** and right stator **106** have generally circular cross sections with a hollow core sized to accommodate the shaft that rotates rotor **102**.

Referring again to FIG. **1**, left stator **104** is mounted axially relative to rotor **102** and a first air gap (not shown) separates the left plurality of poles of rotor **102** from left stator **104**. Right stator **106** is mounted axially relative to rotor **102** and a second air gap **110** separates the right plurality of poles of rotor **102** from right stator **106**. The first air gap and second air gap **110** have the same width between the respective poles and stator.

Left stator core **300** and right stator core **306** may be formed of laminations stacked in a radial direction. The laminations may be punched or laser cut. Left stator core **300** and right stator core **306** may be formed of a ferromagnetic material such as lamination steel, iron, cobalt, nickel, etc. Referring to FIG. **4**, left stator core **300** may include a first plurality of core pieces with two core pieces for each phase. In the illustrative three-phase embodiment, the first plurality of core pieces includes a first left core piece **400**, a second left core piece **402**, a third left core piece **404**, a fourth left core piece **406**, a fifth left core piece **408**, and a sixth left core piece **410**.

Referring to FIG. **5**, right stator core **306** is identical to left stator core **300**, but flipped 180 degrees relative to a plane defined by vertical axis **236** and third axis **238** that is perpendicular to center axis **108**. Right stator core **306** may include a second plurality of core pieces, which include a first right core piece **500**, a second right core piece **502**, a third right core piece **504**, a fourth right core piece **506**, a fifth right core piece **508**, and a sixth right core piece **510**.

In the illustrative embodiment, each core piece of the first plurality of core pieces and the second plurality of core pieces has the same size and shape. The first plurality of core pieces and the second plurality of core pieces are arranged around center axis **108**. In the illustrative embodiment, each core piece has a "C"-shape though an "E"-shape may also be used as understood by a person of skill in the art where the outside edges of the "E"-shape are similar to those described for the "C"-shape. The hollow of the C-shape of each core piece defines a stator slot within which the left plurality of windings **304** are mounted as described further below. In the illustrative embodiment, the number of stator slots, p_{s1}, of left stator **104** equals a number of stator slots, p_{s2}, of right stator **106**. In the illustrative embodiment, $p_{s1}=p_{s2}=6$, though other numbers of stator slots are possible. The slots are distributed at equal angles around the circumference of left stator **104** and of right stator **106**. For example, relative to the plane defined by vertical axis **236** and third axis **238**, a center of first left core piece **400** is positioned at 75 degrees, a center of second first left core piece **402** is positioned at 15 degrees, a center of third first left core piece **404** is positioned at −45 degrees, a center of fourth left core piece **406** is positioned at −105 degrees, a center of fifth left core piece **408** is positioned at −165 degrees, and a center of sixth left core piece **410** is positioned at 135 degrees. A center of first right core piece **500** is positioned at 120 degrees, a center of second first right core piece **502** is positioned at 60 degrees, a center of third first right core piece **504** is positioned at 0 degrees, a center of fourth right core piece **506** is positioned at −60 degrees, a center of fifth right core piece **508** is positioned at −120 degrees, and a center of sixth right core piece **510** is positioned at 180 degrees.

Referring again to FIG. **4**, second left core piece **402** may include a left exterior face **412**, a bottom exterior face **414**, a bottom, right exterior face **416**, a bottom, top face **418**, a right center face **420**, a top, bottom face **422**, a top, right exterior face **424**, a top exterior face **426**, an exterior circumferential face **428**, and an interior circumferential face **430**. The dimensions of the faces of second left core piece **402** may be relatively wider or narrower than that shown in FIG. **4**. Exterior circumferential face **428** and interior circumferential face **430** have the C-shape and are curved circumferentially relative to center axis **108** though exterior circumferential face **428** and interior circumferential face **430** may have be flat in other embodiments. Exterior circumferential face **428** and interior circumferential face **430** further extend in the direction of the shaft about which AFSPM is mounted. Left exterior face **412**, bottom, right exterior face **416**, and top, right exterior face **424** extend generally parallel to each other and perpendicular to center axis **108** between exterior circumferential face **428** and interior circumferential face **430**.

Bottom exterior face **414** extends between edges of interior circumferential face **430**, left exterior face **412**, exterior circumferential face **428**, and bottom, right exterior face **416**. Top exterior face **426** extends between edges of interior circumferential face **430**, left exterior face **412**, exterior circumferential face **428**, and top, right exterior face **424**. Bottom, right exterior face **416** extends between edges of interior circumferential face **430**, bottom exterior face **414**, exterior circumferential face **428**, and bottom, top face **418**. Top, right exterior face **424** extends between edges of interior circumferential face **430**, top exterior face **426**, exterior circumferential face **428**, and top, bottom face **422**. Right center face **420** extends between edges of interior circumferential face **430**, bottom, top face **418**, exterior circumferential face **428**, and top, bottom face **422**. Left exterior face **412**, bottom, right exterior face **416**, top, right exterior face **424**, and right center face **420** are parallel and extend generally perpendicular from exterior circumferential face **428** and interior circumferential face **430**. Left exterior face **412**, bottom, right exterior face **416**, top, right exterior face **424**, and right center face **420** have a truncated pie shape though other polygonal and or elliptical shapes may be used. Bottom, right exterior face **416**, top, right exterior face **424**, and right center face **420** face outwards from left stator core **300** in an opposite direction to left exterior face **412**. Bottom, right exterior face **416** and top, right exterior face **424** face the left plurality of poles of rotor **102** when AFSPM **100** is formed. Bottom exterior face **414**, bottom, top face **418**, top, bottom face **422**, and top exterior face **426** are generally rectangular.

Referring again to FIG. **5**, third right core piece **504** of right stator core **306** similarly may include a right exterior face **512**, a bottom exterior face **514**, a bottom, left exterior face **516**, a bottom, top face **518**, a left center face **520**, a top, bottom face **522**, a top, left exterior face **524**, a top exterior face **526**, an exterior circumferential face **528**, and an interior circumferential face **530**.

Bottom, top face **418**, right center face **420**, and top, bottom face **422** form a slot. Top, bottom face **422**, top, right exterior face **424**, and top exterior face **426** form a first sidewall of the slot formed by each core piece of the first plurality of core pieces. Bottom exterior face **414**, a bottom, right exterior face **416**, a bottom, top face **418** form a second sidewall of the slot formed by each core piece of the first plurality of core pieces.

Bottom, top face **518**, left center face **520**, and top, bottom face **522** form a slot. Top, bottom face **522**, top, left exterior face **524**, and top exterior face **526** form a first sidewall of the slot formed by each core piece of the second plurality of core pieces. Bottom exterior face **514**, a bottom, left exterior face **516**, a bottom, top face **518** form a second sidewall of the slot formed by each core piece of the second plurality of core pieces.

Referring to FIG. **6**, the left plurality of magnets **302** includes two magnets for each phase. In the illustrative three-phase embodiment, the left plurality of magnets **302** includes a first left magnet **600**, a second left magnet **602**, a third left magnet **604**, a fourth left magnet **606**, a fifth left magnet **608**, and a sixth left magnet **610**. Each magnet of the left plurality of magnets **302** and the right plurality of magnets **308** is magnetized to form a south (S) pole on a first side and a north (N) pole on a second side opposite the first side, wherein the magnetization direction is in a radial direction from the first side to the second side of the magnet. The left plurality of magnets **302** are mounted with N poles adjacent N poles and S poles adjacent S poles to form pole pairs. Thus, first left magnet **600**, third left magnet **604**, and fifth left magnet **608** have an opposite N-S polarity relative to second left magnet **602**, fourth left magnet **606**, and sixth left magnet **610**. For illustration, first left magnet **600** and second left magnet **602** form a first pole pair. The pole pairs are formed at a regular pitch circumferentially around left stator **104**. In the illustrative embodiment, first left magnet **600**, third left magnet **604**, and fifth left magnet **608** have N-S polarity and second left magnet **602**, fourth left magnet **606**, and sixth left magnet **610** have S-N polarity.

First left magnet **600**, second left magnet **602**, third left magnet **604**, fourth left magnet **606**, fifth left magnet **608**, and sixth left magnet **610** have a truncated pie shape that is sized to fit in slots formed between adjacent core pieces of the first plurality of core pieces. First left magnet **600**, second left magnet **602**, third left magnet **604**, fourth left magnet **606**, fifth left magnet **608**, and sixth left magnet **610** may have other polygonal and or elliptical shapes in alternative embodiments. For example, second left magnet **602** is mounted in a slot formed between first left core piece **400** and second left core piece **402**, more specifically between top exterior face **426** of second left core piece **402** and bottom exterior face **414** of first left core piece **400**. Similarly, third left magnet **604** is mounted in a slot formed between second left core piece **402** and third left core piece **404**; fourth left magnet **606** is mounted in a slot formed between third left core piece **404** and fourth left core piece **406**; fifth left magnet **608** is mounted in a slot formed between fourth left core piece **406** and fifth left core piece **408**; sixth left magnet **610** is mounted in a slot formed between fifth left core piece **408** and sixth left core piece **410**; and first left magnet **600** is mounted in a slot formed between sixth left core piece **410** and first left core piece **400**. For example, relative to the plane defined by vertical axis **236** and third axis **238**, a center of first left magnet **600** is positioned at 105 degrees, a center of second left magnet **602** is positioned at 45 degrees, a center of third left magnet **604** is positioned at −15 degrees, a center of fourth left magnet **606** is positioned at −75 degrees, a center of fifth left magnet **608** is positioned at −135 degrees, and a center of sixth left magnet **610** is positioned at 165 degrees.

Similarly, referring to FIG. 7, the right plurality of magnets **308** includes two magnets for each phase. In the illustrative three-phase embodiment, the right plurality of magnets **308** includes a first right magnet **700**, a second right magnet **702**, a third right magnet **704**, a fourth right magnet **706**, a fifth right magnet **708**, and a sixth right magnet **710**. The right plurality of magnets **308** are mounted with N poles adjacent N poles and S poles adjacent S poles to form pole pairs. Thus, first right magnet **700**, third right magnet **704**, and fifth right magnet **708** have an opposite N-S polarity relative to second right magnet **702**, fourth right magnet **706**, and sixth right magnet **710**. For illustration, first right magnet **700** and second right magnet **702** form a first pole pair. The pole pairs are formed at a regular pitch circumferentially around right stator **106**. In the illustrative embodiment, first right magnet **700**, third right magnet **704**, and fifth right magnet **708** have S-N or opposite N-S polarity and second right magnet **702**, fourth right magnet **706**, and sixth right magnet **710** have N-S polarity.

First right magnet **700**, second right magnet **702**, third right magnet **704**, fourth right magnet **706**, fifth right magnet **708**, and sixth right magnet **710** have a truncated pie shape that is sized to fit between adjacent core pieces of the second plurality of core pieces. First right magnet **700**, second right magnet **702**, third right magnet **704**, fourth right magnet **706**, fifth right magnet **708**, and sixth right magnet **710** may have other polygonal and or elliptical shapes in alternative embodiments. For example, second right magnet **702** is mounted in a slot formed between second right core piece **502** and third right core piece **504**, more specifically between top exterior face **526** of third right core piece **504** and bottom exterior face **514** of second right core piece **502**. Similarly, third right magnet **704** is mounted in a slot formed between third right core piece **504** and fourth right core piece **506**; fourth right magnet **706** is mounted in a slot formed between fourth right core piece **506** and fifth right core piece **508**; fifth right magnet **708** is mounted in a slot formed between fifth right core piece **508** and sixth right core piece **510**; sixth right magnet **710** is mounted in a slot formed between sixth right core piece **510** and first right core piece **500**; and first right magnet **700** is mounted in a slot formed between first right core piece **500** and second right core piece **502**. For example, relative to the plane defined by vertical axis **236** and third axis **238**, a center of first right magnet **700** is positioned at 90 degrees, a center of second right magnet **702** is positioned at 30 degrees, a center of third right magnet **704** is positioned at −30 degrees, a center of fourth right magnet **706** is positioned at −90 degrees, a center of fifth right magnet **708** is positioned at −150 degrees, and a center of sixth right magnet **710** is positioned at 150 degrees.

In the arrangement shown in the illustrative embodiment of FIG. **1**, first left magnet **600** has an opposite N-S polarity relative to first right magnet **700**. The left plurality of magnets **302** and the right plurality of magnets **308** are permanent magnets that may be formed of rare earth magnets, such as neodymium and dysprosium, of ferrite based magnets, etc. The left plurality of magnets **302** and the right plurality of magnets **308** are electrically isolated from each other. First left magnet **600** may have the same N-S polarity relative to first right magnet **700** if current direction on the right plurality of windings **310** is reversed relative to that shown in FIG. **12**.

Referring to FIG. **8**, the left plurality of windings **304** includes two windings for each phase. In the illustrative embodiment, each winding of the left plurality of windings **304** is trapezoidal and concentrated though other winding configurations may be used. In the illustrative three-phase embodiment, the left plurality of windings **304** includes a first left winding **800**, a second left winding **802**, a third left winding **804**, a fourth left winding **806**, a fifth left winding **808**, and a sixth left winding **810**. First left winding **800** and fourth left winding **806** are connected to receive a second phase. Second left winding **802** and fifth left winding **808** are connected to receive a third phase. Third left winding **804** and sixth left winding **810** are connected to receive a first phase. The first phase, the second phase, and the third phase are separated by 360/N or 120 degrees in the illustrative three-phase embodiment, where N is the number of phases. The first phase may be denoted as an “A”-phase; the second phase may be denoted as a “B”-phase; and the third phase may be denoted as a “C”-phase.

The left plurality of windings **304** mount through the slot formed by the hollow part of the C-shape of two adjacent core pieces such that each winding extends over a different magnet of the left plurality of magnets **302**. As an example, second left winding **802** is wound over a bottom portion of interior circumferential face **430**, over bottom, top face **418**, and over a bottom portion of exterior circumferential face **428** of first core piece **400**, over an exterior facing side of second left magnet **602**, over a top portion of exterior circumferential face **428**, over top, bottom face **422**, and over a top portion of interior circumferential face **430** of second core piece **402**, and over an interior facing side of second left magnet **602**. Thus, second left winding **802** is wound over the second sidewall of the slot formed by first core piece **400**, over second left magnet **602**, and over the first sidewall of the slot formed by second core piece **402**.

Each additional winding is similarly wound around respective core pieces and magnets. For example, third left winding **804** is similarly wound over second core piece **402**, third left magnet **604**, and third core piece **404**; fourth left winding **806** is similarly wound over third core piece **404**, fourth left magnet **606**, and fourth core piece **406**; fifth left winding **808** is similarly wound over fourth core piece **406**, fifth left magnet **608**, and fifth core piece **408**; sixth left winding **810** is similarly wound over fifth core piece **408**, sixth left magnet **610**, and sixth core piece **410**; and first left winding **800** is similarly wound over sixth core piece **410**, first left magnet **600**, and first core piece **400**.

Referring to FIG. **9**, similar to the left plurality of windings **302**, the right plurality of windings **310** includes two windings for each phase where each winding is trapezoidal and concentrated. In the illustrative three-phase embodiment, the right plurality of windings **310** includes a first right winding **900**, a second right winding **902**, a third right winding **904**, a fourth right winding **906**, a fifth right winding **908**, and a sixth right winding **910**. In the illustrative embodiment, first right winding **900** and fourth right winding **906** are connected to receive the third phase; second right winding **902** and fifth right winding **908** are connected to receive the first phase; and third right winding **904** and sixth right winding **910** are connected to receive the second phase.

The right plurality of windings **310** mount through the slot formed by the hollow part of the C-shape of two adjacent core pieces such that each winding extends over a different magnet of the right plurality of magnets **308**. As an example, second right winding **902** is wound over a bottom portion of interior circumferential face **530**, over bottom, top face **518**, and over a bottom portion of exterior circumferential face **528** of second core piece **502**, over an exterior facing side of second right magnet **702**, over a top portion of exterior circumferential face **528**, over top, bottom face **522**, and over a top portion of interior circumferential face **530** of third core piece **504**, and over an interior facing side of second right magnet **702**. Thus, second right winding **902** is wound over the second sidewall of the slot formed by second core piece **502**, over second right magnet **702**, and over the first sidewall of the slot formed by third core piece **504**.

Each additional winding is similarly wound over respective core pieces and magnets. For example, third right winding **904** is similarly wound over third core piece **504**, third right magnet **704**, and fourth core piece **506**; fourth right winding **906** is similarly wound over fourth core piece **506**, fourth right magnet **706**, and fifth core piece **508**; fifth right winding **908** is similarly wound over fifth core piece **508**, fifth right magnet **708**, and sixth core piece **510**; sixth right winding **910** is similarly wound over sixth core piece **510**, sixth right magnet **710**, and first core piece **500**; and first right winding **900** is similarly wound over first core piece **500**, first right magnet **700**, and second core piece **502**.

Referring again to FIG. **1**, an insulation gap **112** may separate the left plurality of windings **304** from the first plurality of core pieces of left stator **104**. Insulation may be mounted within insulation gap **112**. Similar insulation gaps may be formed between each winding of the left plurality of windings **304** and respective core pieces of the first plurality of core pieces of left stator **104**. Similarly, insulation gaps may be formed between each winding of the right plurality of windings **310** and respective core pieces of the second plurality of core pieces of right stator **106**.

Referring to FIG. **10**, a right to left view of left stator **104** is shown in accordance with an illustrative embodiment. For illustration, a N-S polarity is indicated for each magnet of the left plurality of magnets **302**. For illustration, an arrow also shows a direction of positive current in each winding of the left plurality of windings **304**. Referring to FIG. **11**, a left to right view of right stator **106** is shown in accordance with an illustrative embodiment. For illustration, a N-S polarity is indicated for each magnet of the right plurality of magnets **308**. For illustration, an arrow also shows a direction of positive current in each winding of the right plurality of windings **310**.

In the illustrative embodiment, AFSPM **100** includes three-phase windings that are tied together. For example, referring to FIG. **12**, in an illustrative embodiment, the left plurality of windings **304** and the right plurality of windings **310** are tied together at a central connection point **1208** to form a "Y" configuration. Sixth left winding **810** is connected between a first connection point **1200** and a second connection point **1202**. Third left winding **804** is connected between second connection point **1202** and a third connection point **1204**. Second right winding **902** is connected between third connection point **1204** and a fourth connection point **1206**. Fifth right winding **908** is connected between fourth connection point **1206** and central connection point **1202**. Thus, sixth left winding **810**, third left winding **804**, second right winding **902**, and fifth right winding **908** are connected in series between first connection point **1200** and central connection point **1208**, where the "+" indicates positive current flow with the first phase from first connection point **1200** to central connection point **1208** such that each of sixth left winding **810**, third left winding **804**, second right winding **902**, and fifth right winding **908** can be referred to as a positive winding.

Fourth left winding **806** is connected between a fifth connection point **1210** and a sixth connection point **1212**. First left winding **800** is connected between sixth connection point **1212** and a seventh connection point **1214**. Third right winding **904** is connected between seventh connection point **1214** and an eighth connection point **1216**. Sixth right winding **910** is connected between eighth connection point **1216** and central connection point **1208**. Thus, fourth left winding **806**, first left winding **800**, third right winding **904**, and sixth right winding **910** are connected in series between fifth connection point **1210** and central connection point **1208**, where the "+" indicates positive current flow with the second phase from fifth connection point **1210** to central connection point **1202** such that each of fourth left winding **806**, first left winding **800**, third right winding **904**, and sixth right winding **910** can be referred to as a positive winding.

Second left winding **802** is connected between a ninth connection point **1218** and a tenth connection point **1220**. Fifth left winding **808** is connected between tenth connection point **1220** and an eleventh connection point **1222**. First right winding **900** is connected between eleventh connection point **1222** and a twelfth connection point **1224**. Fourth right winding **906** is connected between twelfth connection point **1224** and central connection point **1208**. Thus, second left winding **802**, fifth left winding **808**, first right winding **900**, and fourth right winding **906** are connected in series between ninth connection point **1218** and central connection point **1202**, where the "+" indicates positive current flow with the third phase from ninth connection point **1218** to central connection point **1208** such that each of second left winding **802**, fifth left winding **808**, first right winding **900**, and fourth right winding **906** can be referred to as a positive winding.

Referring to FIG. **13**, a perspective view of AFSPM **100** is shown again in accordance with an illustrative embodiment illustrating angles between the poles of rotor **102** and between the windings of left stator **104** and right stator **106**. As stated previously, the left plurality of poles and the right plurality of poles of rotor **102** of AFSPM **100** are aligned so that a rotor angle $\theta_r=0$ in mechanical and electrical degrees. Third left winding **804** and second right winding **902** are offset by a stator angle **1300** of 45 mechanical degrees resulting in a stator shift θ_s of 180 electrical degrees or π electrical radians because $\theta_{mech}=\theta_{elec}/p_{r1}$. Thus, an angular offset $\theta_{off}=|\theta_s-\theta_r|=|\pi-0|=\pi$ exists between the left and right plurality and poles of rotor **102** and the windings of left stator **104** and right stator **106**.

Referring to FIG. **14**, a perspective view of a second AFSPM **1400** is shown in accordance with a second illustrative embodiment. Second AFSPM **1400** may include a second rotor **102***a*, left stator **104**, and right stator **106**. In the illustrative embodiment, second AFSPM **1400** is a three-phase machine that can be configured as a generator or as a motor as understood by a person of skill in the art. In alternative embodiments, second AFSPM **1400** can be configured to support a fewer or a greater number of phases.

Second rotor **102***a* is identical to rotor **102** except that the right plurality of poles are rotated a rotor angle **1402** equal to 45 mechanical degrees or 180 electrical degrees relative to the left plurality of poles.

In comparison with AFSPM **100**, right stator **106** of second AFSPM **1400** has also been rotated relative to left stator **104**. Relative to the plane defined by vertical axis **236** and third axis **238**, a center of first right core piece **500** is positioned at 75 degrees, a center of second first right core piece **502** is positioned at 15 degrees, a center of third first right core piece **504** is positioned at −45 degrees, a center of fourth right core piece **506** is positioned at −105 degrees, a center of fifth right core piece **508** is positioned at −165 degrees, and a center of sixth right core piece **510** is positioned at 135 degrees. Thus, right stator **106** of second AFSPM **1400** is rotated 45 mechanical degrees relative to right stator **106** of AFSPM **100**.

Thus, for second AFSPM **1400**, stator angle $\theta_s=0$ and a rotor angle θ_r equals 180 electrical degrees or π electrical radians. Thus, the angular offset is $\theta_{off}=|\theta_s-\theta_r|=|0-\pi|=\pi$.

Referring to FIG. **15**, a perspective view of a third AFSPM **1500** is shown in accordance with a second illustrative embodiment. Third AFSPM **1500** may include a third rotor **102***b*, left stator **104**, and right stator **106**. In the illustrative embodiment, third AFSPM **1500** is a three-phase machine that can be configured as a generator or as a motor as understood by a person of skill in the art. In alternative embodiments, third AFSPM **1500** can be configured to support a fewer or a greater number of phases.

Third rotor **102***b* is identical to rotor **102** except that the right plurality of poles are rotated a second rotor angle **1500** relative to the left plurality of poles and, relative to AFSPM **100**, right stator **106** of third AFSPM **1500** has been rotated a second stator angle **1502** such that the angular offset remains $\theta_{off}=|\theta_s-\theta_r|=\pi$ in electrical degrees. The left half of third AFSPM **1500** that includes left stator **104** and the left plurality of poles of third rotor **102***b* and the right half of third AFSPM **1500** that includes right stator **106** and the right plurality of poles of third rotor **102***b* can operate separately so that the left half and the right half can be shifted to any degree as long as the relationship $\theta_{off}=|\theta_s-\theta_r|=\pi$ is maintained. In the illustrative example, rotor angle **1402** is 15 mechanical degrees or 60 electrical degrees and stator angle **1300** is 60 mechanical degrees or 240 electrical degrees.

Each of AFSPM **100**, second AFSPM **1400**, and third AFSPM **1500** eliminate even order harmonic components of flux linkage. In a dual stator, single rotor AFSPM machine, a second flux linkage component is introduced because of an additional linkage between the second (right) stator and rotor **102**. The total flux linkage can be defined as:

$$\lambda_a \approx \Lambda_1 \sin(p_r\theta_m)+\Lambda_2 \sin(2p_r\theta_m)+(-1)^k\Lambda_1 \sin(p_r\theta_m+\theta_{off})+(-1)^k\Lambda_2 \sin(2p_r\theta_m+2\theta_{off})$$

where p_r is the number of rotor poles of the left plurality of poles and of the right plurality of poles of rotor **102**, **102***a*, **102***b*. θ_{off} as described above is the electrical offset angle between the two flux linkages in radians and θ_m is the mechanical position of rotor **102**, second rotor **102***a*, or third rotor **102***b*.

The total flux linkage becomes:

$$\lambda_a \approx -2\Lambda_1\cos\left(p_r\theta_m+\frac{\theta_{off}}{2}\right)\sin\left(\frac{\theta_{off}}{2}\right)-2\Lambda_2\cos(2p_r\theta_m+\theta_{off})\sin(\theta_{off})$$

If θ_{off} is set to be π radians electric, the total flux linkage becomes:

$$\lambda_a \approx 2\Lambda_1 \sin(p_r\theta_m)$$

As a result, the second order harmonic component of the total flux linkage is effectively eliminated.

Referring to FIG. **16**, $\theta_{off}=\pi$ is shown in accordance with an illustrative embodiment of AFSPM **100**, second AFSPM **1400**, or third AFSPM **1500**. A first curve **1600** shows a fundamental flux linkage from left stator **104**. A second curve **1602** shows a second harmonic of flux linkage from left stator **104**. A third curve **1604** shows a fundamental flux linkage from right stator **106**. A fourth curve **1606** shows a second harmonic of flux linkage from right stator **106**. A fifth curve **1608** shows a total flux linkage from left stator **104** and from right stator **106**. Second curve **1602** and fourth curve **1606** sum to zero indicating that the second order harmonic component of flux linkage is effectively eliminated. First curve **1600** and third curve **1604** are in phase resulting in a total flux linkage that is doubled at the fundamental frequency. p.u. stands for per unit. A per-unit system is an expression of system quantities as fractions of a defined base unit quantity. Here, the peak value of the fundamental flux linkage defined the base unit quantity so that their peaks become one.

The various dimensions of the elements of rotor **102**, second rotor **102***a*, third rotor **102***b*, left stator **104**, and right stator **106**, including the first air gap and the second air gap **110**, may be determined based on desired rated performance characteristics using analytical sizing equations and finite element analysis using an electromechanical design tool.

The performance of AFSPM **100**, second AFSPM **1400**, and third AFSPM **1500** was evaluated using finite element analysis. A design specification of AFSPM **100**, second AFSPM **1400**, and third AFSPM **1500** is summarized in Table I below.

TABLE I

CALCULATED MACHINE DIMENSIONS

Symbol	Quantity	Size
D_o	Outer diameter	350 mm
D_i	Inner diameter	114 mm
I_{cr}	Rotor core thickness	29 mm
I_{cs}	Stator yoke thickness	58 mm
I_{st}	Stator tooth thickness	84 mm
hpm	Magnet height	84 mm

where D_i is an inner diameter and D_o is an outer diameter of rotor **102**, **102***a*, **102***b* and of left stator core **300**, the left plurality of magnets **302**, right stator core **306**, and the right plurality of magnets **308**, and the stator yoke thickness is a thickness of bottom exterior face **414**, top exterior face **426**, bottom exterior face **514**, and top exterior face **526**.

FIG. **17** shows Fourier transform analysis results calculated for the back-EMF waveforms generated by AFSPM **100** with $\theta_{off}=\pi$. A first curve **1700** shows a fundamental back-EMF value from left stator **104**. A second curve **1702** shows a fundamental back-EMF from right stator **106**. A third curve **1704** shows a total fundamental back-EMF from left stator **104** and from right stator **106**. A fourth curve **1706** shows a second harmonic of back-EMF from left stator **104**. A fifth curve **1708** shows a second harmonic of back-EMF from right stator **106**. A sixth curve **1710** shows a total second harmonic of back-EMF from left stator **104** and from right stator **106**. The total fundamental harmonic is 148 Volts (V). The total second order harmonic is 0.233 V, which is a 99.8% cancellation compare to a conventional dual stator topology.

FIG. **18** shows a comparison between the flux linkage generated by AFSPM **100**, second AFSPM **1400**, and third AFSPM **1500**, with $\theta_{off}=\pi$. A first curve **1800** shows a total fundamental flux linkage value from left stator **104** and from right stator **106** of AFSPM **100**. A second curve **1802** shows a total fundamental flux linkage value from left stator **104** and from right stator **106** of second AFSPM **1400**. A third curve **1804** shows a total fundamental flux linkage value from left stator **104** and from right stator **106** of third AFSPM **1500**. A fourth curve **1806** shows a total second harmonic of flux linkage from left stator **104** and from right stator **106** of AFSPM **100**. A fifth curve **1808** shows a total second harmonic of flux linkage from left stator **104** and from right stator **106** of second AFSPM **1400**. A sixth curve **1810** shows a total second harmonic of flux linkage from left stator **104** and from right stator **106** of third AFSPM **1500**. AFSPM **100** produced a total fundamental flux linkage of 0.98 Weber (wb), while second AFSPM **1400** and third AFSPM **1500** produced 0.916 wb and 0.905 wb respectively. AFSPM **100** produced 6.98% and 8.28% larger total fundamental flux linkage than that of the second AFSPM **1400** and third AFSPM **1500**. The total second order harmonics of AFSPM **100**, second AFSPM **1400**, and third AFSPM **1500** were 0.0004 wb, 0.011 wb, and 0.005 wb. Second AFSPM **1400** had 97.42% of remaining second order harmonic, while AFSPM **100** and third AFSPM **1500** had 99.8% and 98.73% respectively.

FIG. **19** shows a comparison between the back-EMF generated by AFSPM **100**, second AFSPM **1400**, and third AFSPM **1500**, with $\theta_{off}=\pi$. A first curve **1900** shows a total fundamental back-EMF value from left stator **104** and from right stator **106** of AFSPM **100**. A second curve **1902** shows a total fundamental back-EMF value from left stator **104** and from right stator **106** of second AFSPM **1400**. A third curve **1904** shows a total fundamental back-EMF value from left stator **104** and from right stator **106** of third AFSPM **1500**. A fourth curve **1906** shows a total second harmonic of back-EMF from left stator **104** and from right stator **106** of AFSPM **100**. A fifth curve **1908** shows a total second harmonic of back-EMF from left stator **104** and from right stator **106** of second AFSPM **1400**. A sixth curve **1910** shows a total second harmonic of back-EMF from left stator **104** and from right stator **106** of third AFSPM **1500**.

The analytical calculations were performed under the assumption that left stator **104** and right stator **106** of AFSPM **100**, of second AFSPM **1400**, and of third AFSPM **1500** were symmetrical and identical.

Instead of using a dual stator configuration, a dual rotor configuration also achieves the balanced flux linkage and back-EMF waveforms as discussed relative to AFSPM **100**, second AFSPM **1400**, and third AFSPM **1500**. Referring to FIG. **20**, a perspective view of a fourth AFSPM **2000** is shown in accordance with an illustrative embodiment. Fourth AFSPM **2000** may include a left rotor **102***c*, a right rotor **102***d*, and a stator **2002**. In the illustrative embodiment, fourth AFSPM **2000** is a three-phase machine that can be configured as a generator or as a motor as understood by a person of skill in the art. In alternative embodiments, fourth AFSPM **2000** can be configured to support a fewer or a greater number of phases. Fourth AFSPM **2000** is essentially a rearrangement of the elements of second AFSPM **1400**.

Left rotor **102***c* may be formed as a first half of second rotor **102***a* that includes half of rotor core **200** and the right plurality of poles. Right rotor **102***d* may be formed as a second half of second rotor **102***a* that includes a remaining half of rotor core **200** and the left plurality of poles. Left rotor **102***c* is mounted axially on a left side of stator **2002** and right rotor **102***d* is mounted axially on a right side of stator **2002**. The first air gap separates stator **2002** from left rotor **102***c* and second air gap **110** (not visible) separates stator **2002** from right rotor **102***d*.

Stator **2002** is similar to left stator **104** and right stator **106** mounted together to form a single stator positioned axially between left rotor **102***c* and right rotor **102***d*. Stator **2002** may include a stator core **2004**, a plurality of magnets **2006**, the left plurality of windings **304**, and the right plurality of windings **310**. Stator core **2004** may include left stator core **300** and right stator core **306**. Left exterior face **412** of each of the first plurality of core pieces of left stator core **300** is mounted to right exterior face **512** of the second plurality of core pieces of right stator core **306** to form stator **2002**.

The left plurality of windings **304** are mounted to the first plurality of core pieces of left stator core **300** that forms a right half of stator **2002**. Second air gap **110** separates the left plurality of poles of right rotor **102***d* from the left plurality of windings **304**. The right plurality of windings **310** are mounted to the second plurality of core pieces of right stator core **306** that forms a left half of stator **2002**. The first air gap separates the right plurality of poles of left rotor **102***c* from the right plurality of windings **310**. Third left winding **804** is aligned with second right winding **902** in the plane defined by vertical axis **236** and third axis **238**. Similarly, fourth left winding **806** is aligned with third right winding **904**; fifth left winding **808** is aligned with fourth right winding **906**; sixth left winding **810** is aligned with fifth right winding **908**; first left winding **800** is aligned with sixth right winding **910**; and second left winding **802** is aligned with first right winding **900**. The left plurality of windings **304** and the right plurality of windings **310** are connected as shown in FIG. **12**.

The plurality of magnets **2006** is similar to the left plurality of magnets **302** and to the right plurality of magnets **308**. The plurality of magnets **2006** are mounted between adjacent core pieces of stator core **2004** with alternating N-S polarity as described with reference to AFSPM **100**.

Similar to second AFSPM **1400**, left rotor **102***c* and right rotor **102***d* are shifted by 45 mechanical degrees resulting in 180 electric degrees shift based on the alignment between the left plurality of windings **304** and the right plurality of windings **310**, which compensate each other as described with reference to second AFSPM **1400**. As a result, the coil flux linkages add up to form a waveform that is very close to sinusoidal so that the three phase back-EMFs are balanced. Fourth AFSPM **2000** then achieves a similar performance to that described for AFSPM **100**, second AFSPM **1400**, and third AFSPM **1500**.

AFSPM **100**, second AFSPM **1400**, third AFSPM **1500**, and fourth AFSPM **2000** use a low number of rotor poles that is amenable particularly for high-speed operation though AFSPM **100**, second AFSPM **1400**, third AFSPM **1500**, and fourth AFSPM **2000** can be used for medium and low speed applications. AFSPM **100**, second AFSPM **1400**, third AFSPM **1500**, and fourth AFSPM **2000** also reduce core losses, copper losses, and inverter switching losses thereby increasing the efficiency and power density. Axial flux machines can be used in many applications including heating, ventilation, and air conditioning systems, industrial systems, flywheels, fans, pumps, traction drives for hybrid and electric vehicles, aircraft and marine applications, etc. AFSPM **100**, second AFSPM **1400**, third AFSPM **1500**, and fourth AFSPM **2000** can be cascaded.

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, in the detailed description, using "and" or "or" 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 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 electrical machine comprising:

a rotor comprising

a rotor core having a first face and a second face, wherein the second face faces in a direction opposite to the first face, wherein an aperture is formed through the first face and the second face;

a first plurality of poles mounted to extend from the first face; and

a second plurality of poles mounted to extend from the second face;

a first stator comprising a first plurality of core pieces, wherein each core piece of the first plurality of core pieces includes a slot having a first sidewall and a second sidewall;

a second stator comprising a second plurality of core pieces, wherein each core piece of the second plurality of core pieces includes a slot having a first sidewall and a second sidewall;

a first plurality of permanent magnets, wherein a permanent magnet of the first plurality of permanent magnets is mounted between the first sidewall and the second sidewall of adjacent core pieces of the first plurality of core pieces;

a second plurality of permanent magnets, wherein a permanent magnet of the second plurality of permanent magnets is mounted between the first sidewall and the second sidewall of adjacent core pieces of the second plurality of core pieces;

a first winding wound over the first sidewall of a first core piece of the first plurality of core pieces, over a first permanent magnet of the first plurality of permanent magnets mounted between the first sidewall of the first core piece and the second sidewall of a second core piece of the first plurality of core pieces, and over the second sidewall of the second core piece of the first plurality of core pieces, wherein the first core piece and the second core piece of the first plurality of core pieces are adjacent to each other;

a second winding wound over the second sidewall of a third core piece of the first plurality of core pieces, over a second permanent magnet of the first plurality of permanent magnets mounted between the second sidewall of the third core piece and the first sidewall of a fourth core piece of the first plurality of core pieces, and over the first sidewall of the fourth core piece of the first plurality of core pieces, wherein the third core piece and the fourth core piece of the first plurality of core pieces are adjacent to each other;

a third winding wound over the first sidewall of a first core piece of the second plurality of core pieces, over a first permanent magnet of the second plurality of permanent magnets mounted between the first sidewall of the first core piece and the second sidewall of a second core piece of the second plurality of core pieces, and over the second sidewall of the second core piece of the second plurality of core pieces, wherein the first core piece and the second core piece of the second plurality of core pieces are adjacent to each other; and

a fourth winding wound over the second sidewall of a third core piece of the second plurality of core pieces, over a second permanent magnet of the second plurality of permanent magnets mounted between the second sidewall of the third core piece and the first sidewall of a fourth core piece of the second plurality of core pieces, and over the first sidewall of the fourth core piece of the second plurality of core pieces, wherein the third core piece and the fourth core piece of the second plurality of core pieces are adjacent to each other;

wherein the first winding is closer to the third winding than to the fourth winding;

wherein the first stator is mounted axially relative to the rotor so that a first air gap separates the first plurality of poles from the first winding and the second winding;

wherein the second stator is mounted axially relative to the rotor so that a second air gap separates the second plurality of poles from the third winding and the fourth winding;

wherein the first permanent magnet of the first plurality of permanent magnets and the second permanent magnet of the first plurality of permanent magnets have opposite polarities;

wherein the first permanent magnet of the second plurality of permanent magnets and the second permanent magnet of the second plurality of permanent magnets have opposite polarities;

wherein the first winding, the second winding, the third winding, and the fourth winding are connected in series; and

wherein an absolute value of an angle offset between the first winding and the third winding and between closest poles of the first plurality of poles and the second plurality of poles is 180 electrical degrees.

2. The electrical machine of claim **1**, wherein a number of the first plurality of core pieces equals a number of the second plurality of core pieces.

3. The electrical machine of claim **2**, wherein a number of poles of the first plurality of poles equals a number of poles of the second plurality of poles.

4. The electrical machine of claim **3**, wherein the number of the first plurality of core pieces is greater than the number of poles.

5. The electrical machine of claim **3**, wherein the number of the first plurality of core pieces equals six, and the number of poles equals four.

6. The electrical machine of claim **1**, wherein a number of the first plurality of core pieces is equal to two and a number of phases of a current of the electrical machine is one.

7. The electrical machine of claim **1**, wherein a first number of the first plurality of core pieces and a second number of the second plurality of core pieces is two, and the third core piece and the second core piece of the first plurality of core pieces are the same core piece, and the first core piece and the fourth core piece of the first plurality of core pieces are the same core piece.

8. The electrical machine of claim **1**, wherein a number of the first plurality of core pieces equals a number of the first plurality of permanent magnets.

9. The electrical machine of claim **1**, wherein the second plurality of poles are aligned with the first plurality of poles.

10. The electrical machine of claim **1**, wherein the second plurality of poles are rotated 180 electrical degrees relative to the first plurality of poles.

11. The electrical machine of claim **1**, wherein the first permanent magnet of the first plurality of permanent magnets and the first permanent magnet of the second plurality of permanent magnets have a common polarity, and further wherein the second permanent magnet of the first plurality of permanent magnets and the second permanent magnet of the second plurality of permanent magnets have a common polarity.

12. The electrical machine of claim **1**, wherein the first permanent magnet of the first plurality of permanent magnets and the first permanent magnet of the second plurality of permanent magnets have an opposite polarity, and further wherein the second permanent magnet of the first plurality of permanent magnets and the second permanent magnet of the second plurality of permanent magnets have the opposite polarity.

13. The electrical machine of claim **1**, wherein the second plurality of poles are rotated θ_r electrical degrees relative to the first plurality of poles and wherein the second plurality of permanent magnets are rotated θ_s electrical degrees relative to the first plurality of permanent magnets, and $\theta_{off}=|\theta_s-\theta_r|=\pi$, where θ_{off} is the angle offset.

14. The electrical machine of claim **1**, wherein each core piece of the first plurality of core pieces is mounted at a regular pitch circumferentially around a first aperture of the first stator.

15. The electrical machine of claim **14**, wherein each core piece of the second plurality of core pieces is mounted at the regular pitch circumferentially around a second aperture of the second stator.

16. The electrical machine of claim **1**, wherein the first winding is connected in series between the second winding and the third winding, and the third winding is connected in series between the first winding and the fourth winding.

17. An electrical machine comprising:

a first rotor comprising

a first rotor core having a first face and a second face, wherein the second face faces in a direction opposite to the first face, wherein an aperture is formed through the first face and the second face; and

a first plurality of poles mounted to extend from the first face of the first rotor core;

a second rotor comprising

a second rotor core having a first face and a second face, wherein the second face faces in a direction opposite to the first face, wherein an aperture is formed through the first face and the second face, wherein the first face of the first rotor core is in a same direction as the first face of the second rotor core; and

a second plurality of poles mounted to extend from the second face of the second rotor core;

a stator comprising a first plurality of core pieces and a second plurality of core pieces, wherein each core piece of the first plurality of core pieces and of the second plurality of core pieces includes a slot having a first sidewall and a second sidewall, wherein the first plurality of core pieces face towards the first plurality of poles and the second plurality of core pieces face towards the second plurality of poles;

a plurality of permanent magnets, wherein a permanent magnet of the plurality of permanent magnets is mounted between the first sidewall and the second sidewall of adjacent core pieces of the first plurality of core pieces and between the first sidewall and the second sidewall of adjacent core pieces of the second plurality of core pieces;

a first winding wound over the first sidewall of a first core piece of the first plurality of core pieces, over a first permanent magnet of the plurality of permanent magnets mounted between the first sidewall of the first core piece and the second sidewall of a second core piece of the first plurality of core pieces, and over the second sidewall of the second core piece of the first plurality of core pieces, wherein the first core piece and the second core piece of the first plurality of core pieces are adjacent to each other;

a second winding wound over the second sidewall of a third core piece of the first plurality of core pieces, over a second permanent magnet of the plurality of permanent magnets mounted between the second sidewall of the third core piece and the first sidewall of a fourth core piece of the first plurality of core pieces, and over the first sidewall of the fourth core piece of the first plurality of core pieces, wherein the third core piece and the fourth core piece of the first plurality of core pieces are adjacent to each other;

a third winding wound over the first sidewall of a first core piece of the second plurality of core pieces, over the first permanent magnet of the plurality of permanent magnets mounted between the first sidewall of the first core piece and the second sidewall of a second core piece of the second plurality of core pieces, and over the second sidewall of the second core piece of the second plurality of core pieces, wherein the first core piece and the second core piece of the second plurality of core pieces are adjacent to each other; and

a fourth winding wound over the second sidewall of a third core piece of the second plurality of core pieces, over the second permanent magnet of the plurality of permanent magnets mounted between the second sidewall of the third core piece and the first sidewall of a fourth core piece of the second plurality of core pieces, and over the first sidewall of the fourth core piece of the second plurality of core pieces, wherein the third core piece and the fourth core piece of the second plurality of core pieces are adjacent to each other;

wherein the first winding is closer to the third winding than to the fourth winding;

wherein the stator is mounted axially between the first rotor and the second rotor so that a first air gap separates the first plurality of poles from the first winding and the second winding, and a second air gap separates the second plurality of poles from the third winding and the fourth winding;

wherein the first permanent magnet of the plurality of permanent magnets and the second permanent magnet of the first plurality of permanent magnets have opposite polarities;

wherein the first winding, the second winding, the third winding, and the fourth winding are connected in series; and

wherein the second plurality of poles is rotated 180 electrical degrees relative to the first plurality of poles.

18. The electrical machine of claim **17**, wherein the slots of the first plurality of core pieces face in a direction opposite to slots of the second plurality of core pieces.

19. The electrical machine of claim **17**, wherein each core piece of the first plurality of core pieces is mounted at a regular pitch circumferentially around a first aperture of the first stator.

20. The electrical machine of claim **19**, wherein each core piece of the second plurality of core pieces is mounted at the regular pitch circumferentially around a second aperture of the second stator.

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