US010594179B2

(12) United States Patent
Liu et al.

(10) Patent No.: US 10,594,179 B2
(45) Date of Patent: Mar. 17, 2020

(54) **ALTERNATING FLUX BARRIER AIR GAP IN A SPOKE TYPE MACHINE**

(71) Applicant: **Wisconsin Alumni Research Foundation**, Madison, WI (US)

(72) Inventors: **Wenbo Liu**, Madison, WI (US); **Thomas A. Lipo**, Middleton, WI (US)

(73) Assignee: **WISCONSIN ALUMNI RESEARCH FOUNDATION**, Madison, WI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 215 days.

(21) Appl. No.: **15/595,063**

(22) Filed: **May 15, 2017**

(65) **Prior Publication Data**

US 2018/0331591 A1 Nov. 15, 2018

(51) **Int. Cl.**
H02K 1/27 (2006.01)
H02K 21/14 (2006.01)
H02K 1/16 (2006.01)
H02K 1/24 (2006.01)

(52) **U.S. Cl.**
CPC ***H02K 1/2786*** (2013.01); ***H02K 1/2773*** (2013.01); ***H02K 21/14*** (2013.01); *H02K 1/16* (2013.01); *H02K 1/246* (2013.01); *H02K 2213/03* (2013.01)

(58) **Field of Classification Search**
CPC .. H02K 1/00; H02K 1/14; H02K 1/16; H02K 1/24; H02K 1/246; H02K 1/27; H02K 1/277; H02K 1/2773; H02K 1/278; H02K 1/2786; H02K 1/279; H02K 1/2793; H02K 21/12
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,517,478	A	5/1985	Oudet	
7,723,888	B2	5/2010	Petek	
9,595,858	B2	3/2017	Lipo et al.	
2006/0273684	A1 *	12/2006	Ishikawa	H02K 1/278 310/216.004
2009/0096308	A1 *	4/2009	Staudenmann	H02K 1/2773 310/156.08
2014/0084744	A1 *	3/2014	Nakazono	H02K 1/28 310/216.123

OTHER PUBLICATIONS

Du et al., High torque density ferrite permanent magnet vernier motor analysis and design with demagnetization consideration,Energy Conversion Congress and Exposition (ECCE), 2015 IEEE, Sep. 20, 2015, pp. 6082-6089.

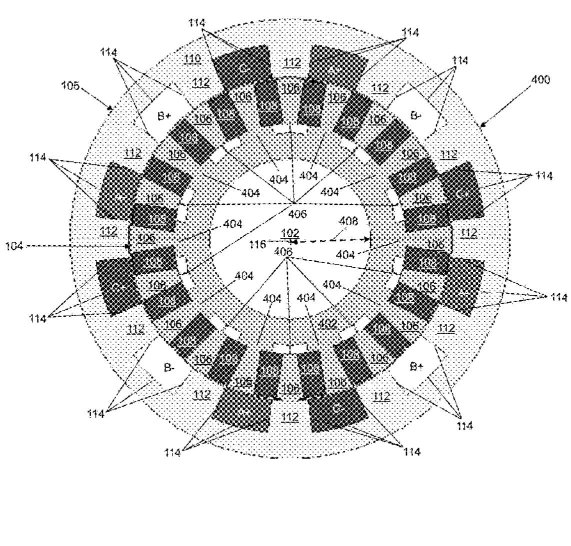
(Continued)

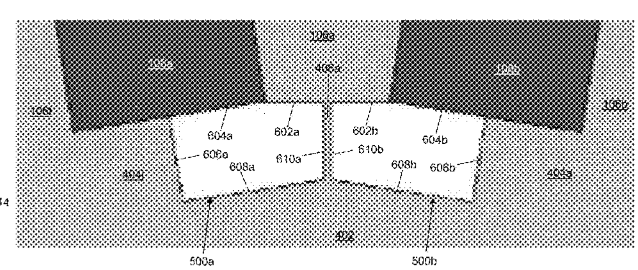
Primary Examiner — Tran N Nguyen
(74) *Attorney, Agent, or Firm* — Bell & Manning, LLC

(57) **ABSTRACT**

The rotor includes ribs and permanent magnets mounted as spokes in pole pairs. A second wall of each rotor air gap of a plurality of rotor air gaps is parallel to an edge of a permanent magnet of the permanent magnets. A length of the second wall is less than 80% of a length of the edge. A fifth wall of each rotor air gap of the rotor air gaps is formed by a first side of a rib. Each pair of permanent magnets has an associated pair of rotor air gaps of the rotor air gaps. A first rotor air gap of each pair of rotor air gaps of the rotor air gaps is a mirror image of a second rotor air gap of each pair of rotor air gaps. Each pair of rotor air gaps is separated by an associated rib of the plurality of ribs.

20 Claims, 17 Drawing Sheets





(56) **References Cited**

OTHER PUBLICATIONS

Qu et al., Relationship between Magnetic Gears and Vernier Machines, 2011 International Conference on Electrical Machines and Systems (ICEMS), Beijing, Aug. 20-23, 2011, pp. 1-6.
Toba et al., Generic Torque-Maximizing Design Methodology of Permanent Magnet Vernier Machine, 1999, IEEE, pp. 522-524.
Toba et al., Novel Dual-Excitation Permanent Magnet Vernier Machine, 1999.
J. Li, Design, analysis and control of permanent-magnet vernier machines, 2012, pp. 1-177.
Kakihata et al., Design of Surface Permanent Magnet-type Vernier Motor, 2012 15th International Conference on Electrical Machines and Systems (ICEMS), Sapporo, Oct. 21-24, 2012, pp. 1-6.
Zhao et al., Magnet Flux Focusing Design of Double Stator Permanent Magnet Vernier Machine, Compumag 2013, Budapest, Hungary, Jun. 30, 2013.
Boughrara et al., Analytical Calculation of Parallel Double Excitation and Spoke-Type Permanent-Magnet Motors; Simplified Versus Exact Model, Progress in Electromagnetics Research B, vol. 47, 2013, pp. 145-178.
Li et al., High-Power-Factor Vernier Permanent-Magnet Machines, IEEE Trans. Ind. Appl., vol. 50, No. 6, Nov. 2014, pp. 3664-3674.
Kim et al., Operation and Design Principles of a PM Vernier Motor, IEEE Trans. Ind. Appl., vol. 50, No. 6, Nov. 2014, pp. 3656-3663.
Zhao et al., A Novel Dual-Stator Axial-Flux Spoke-Type Permanent Magnet Vernier Machine for Direct-Drive Applications, IEEE Transactions on Magnetics, vol. 50, No. 11, Nov. 2014.
Zhang et al., A Novel Triple-Rotor Axial-Flux Vernier Permanent Magnet Machine, IEEE Transactions on Applied Superconductivity, vol. 26, No. 7, Oct. 2016.
Zou et al., Analysis of a Dual-Rotor, Toroidal-Winding, Axial-Flux Vernier Permanent Magnet Machine, DOI 10.1109/TIA.2017.2657493, IEEE Transactions on Industry Applications, Jan. 24, 2017.
Ge et al., A Spoke-Type IPM Machine With Novel Alternate Airspace Barriers and Reduction of Unipolar Leakage Flux by Step-Staggered Rotor, IEEE Transactions on Industry Applications, vol. 52, No. 6, Nov. 2016, pp. 4789-4797.
Ge et al., A Spoke-Type IPM Machine With Novel Alternate Airspace Barriers and Reduction of Unipolar Leakage Flux by Step-Staggered Rotor, 2015 IEEE Electric Machines & Drives Conference, May 10, 2015.

* cited by examiner

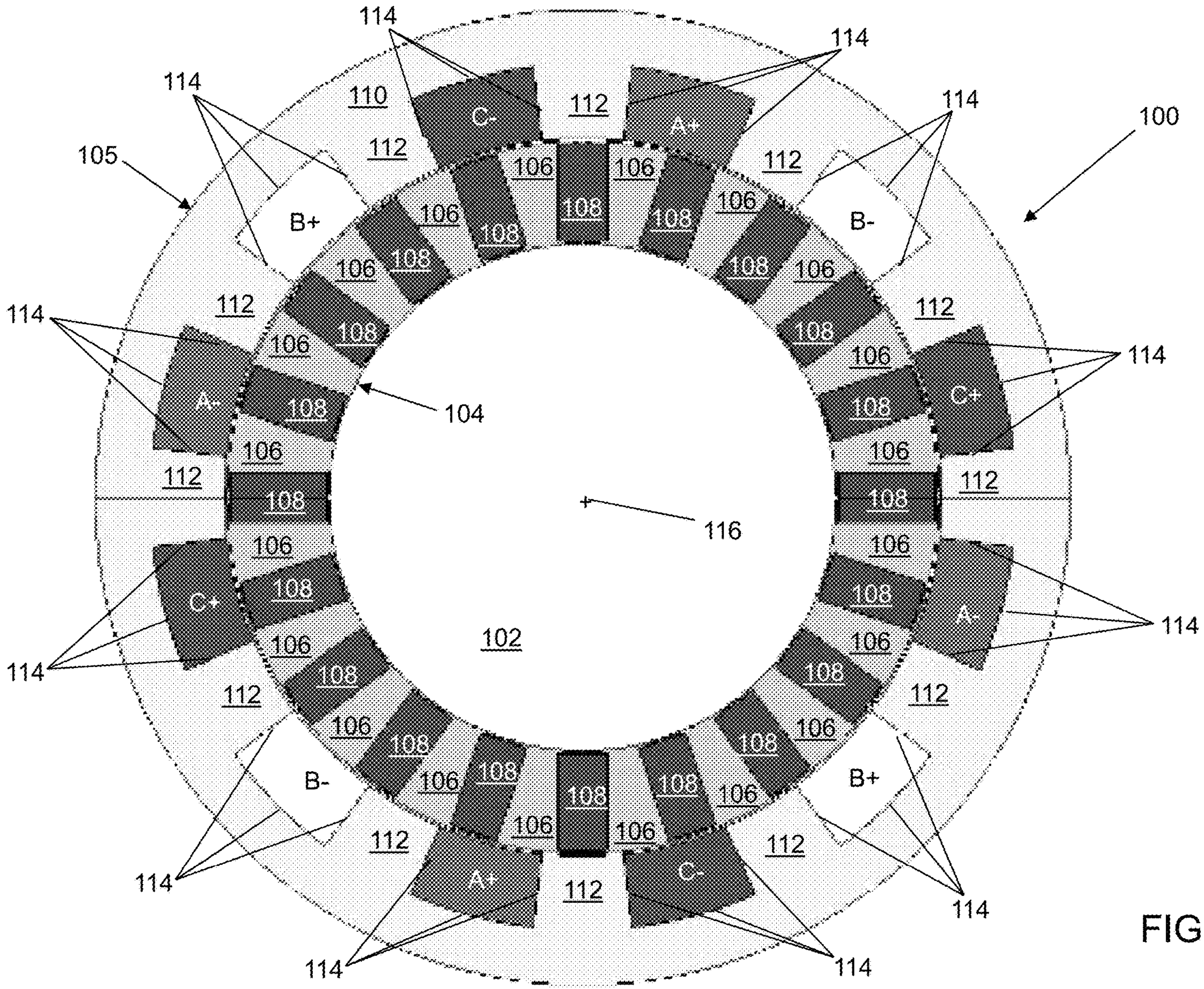


FIG. 1

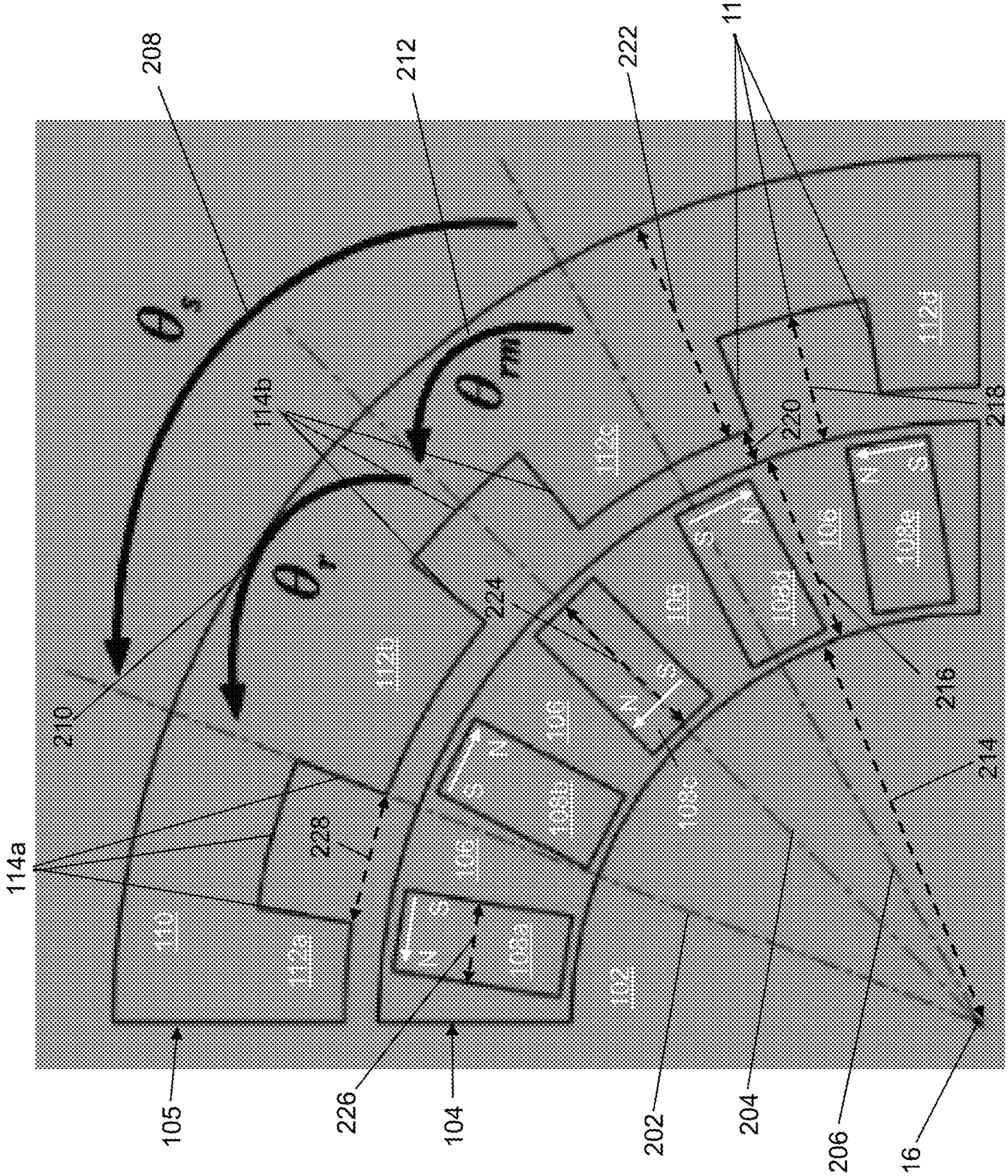

208
212
222
114c
114b
114a
210
224
220
218
216
214
228
226
105
104
202
204
206
116
110
112a
112b
112c
112d
106
108a
108b
108c
108d
108e
102
N
S

FIG. 2

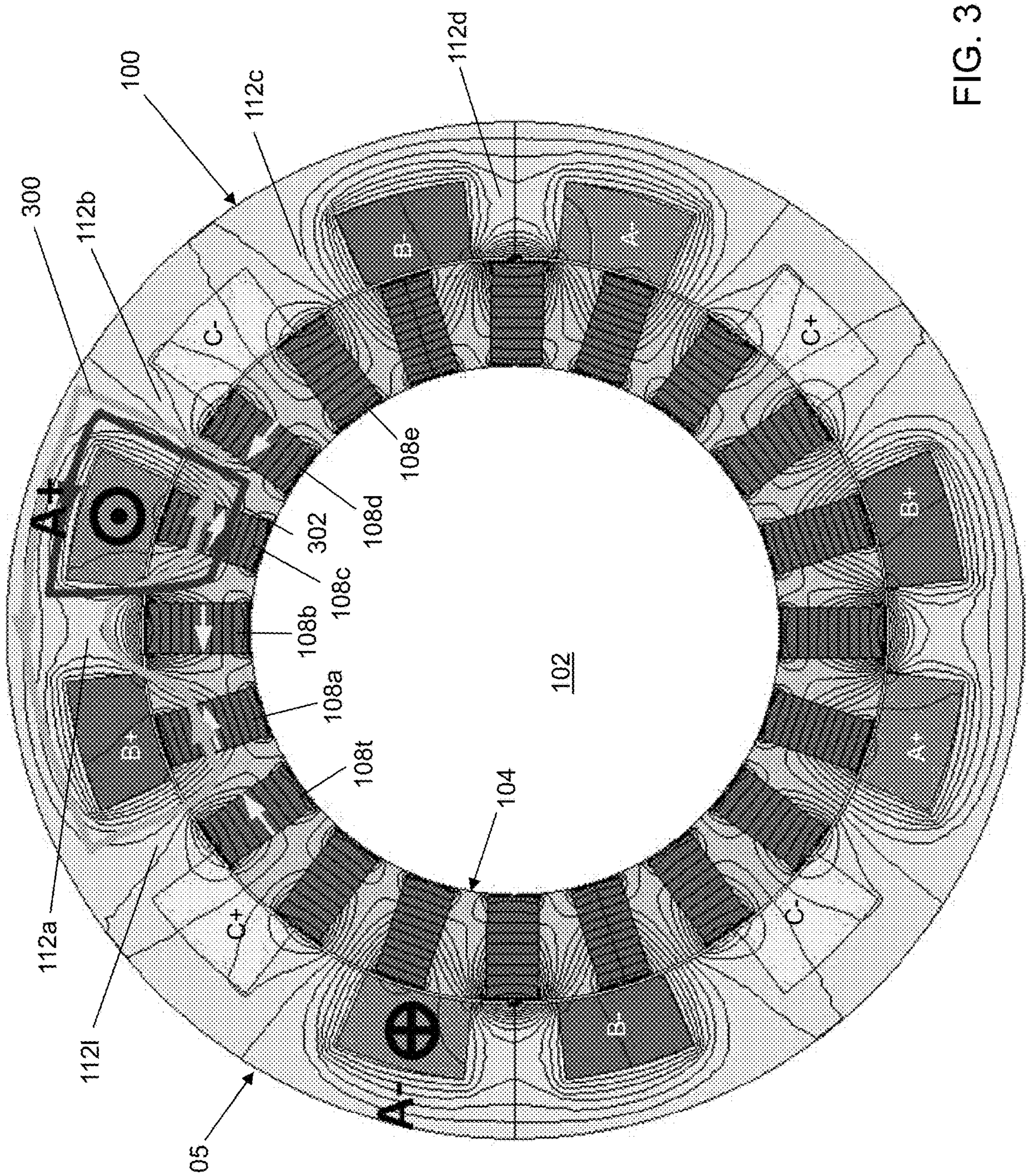
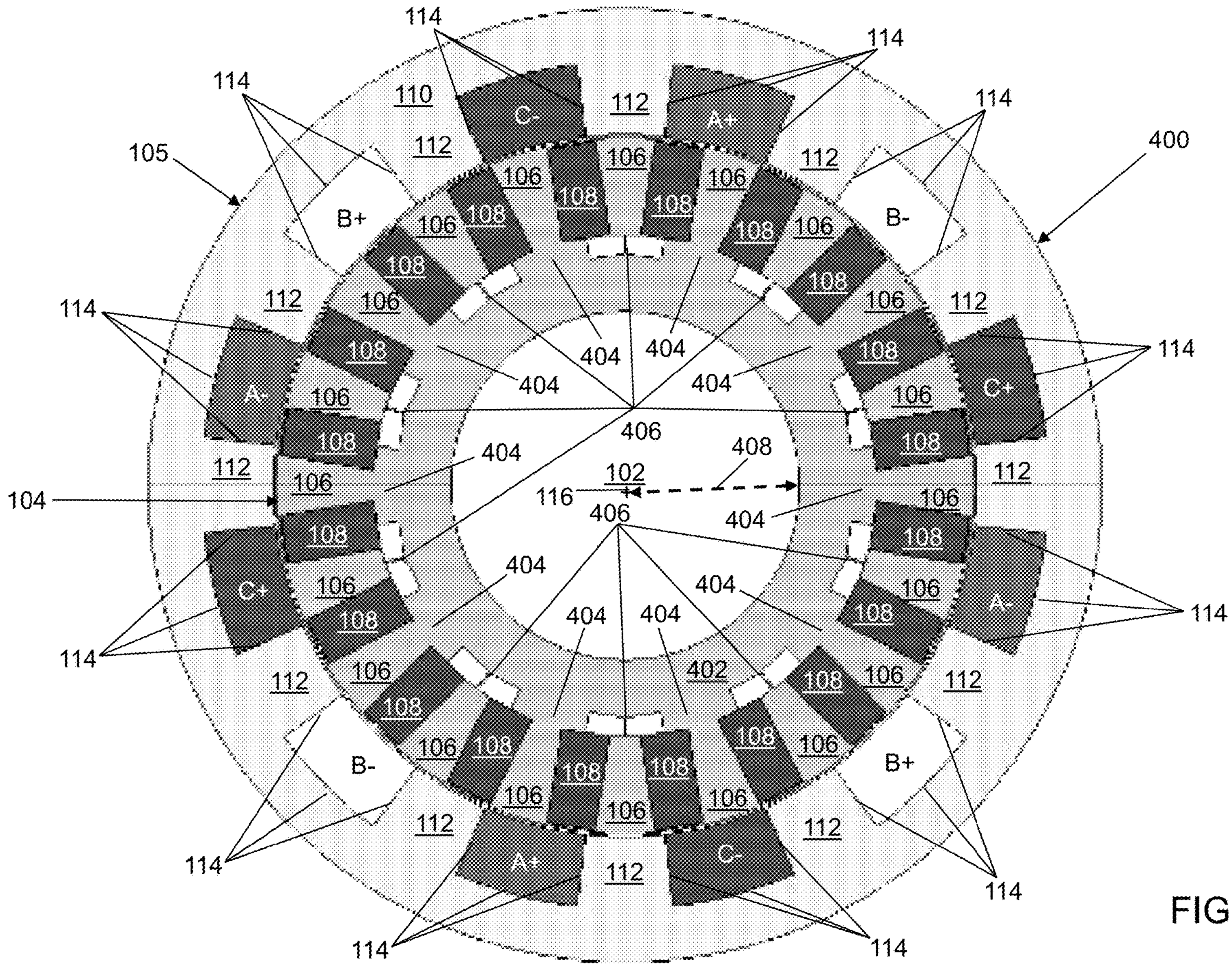

100
300
112b
112c
112d
A+
302
108c
108d
108e
108b
108a
108t
104
102
112a
112l
105
A-
A+
A-
B+
B-
C+
C-

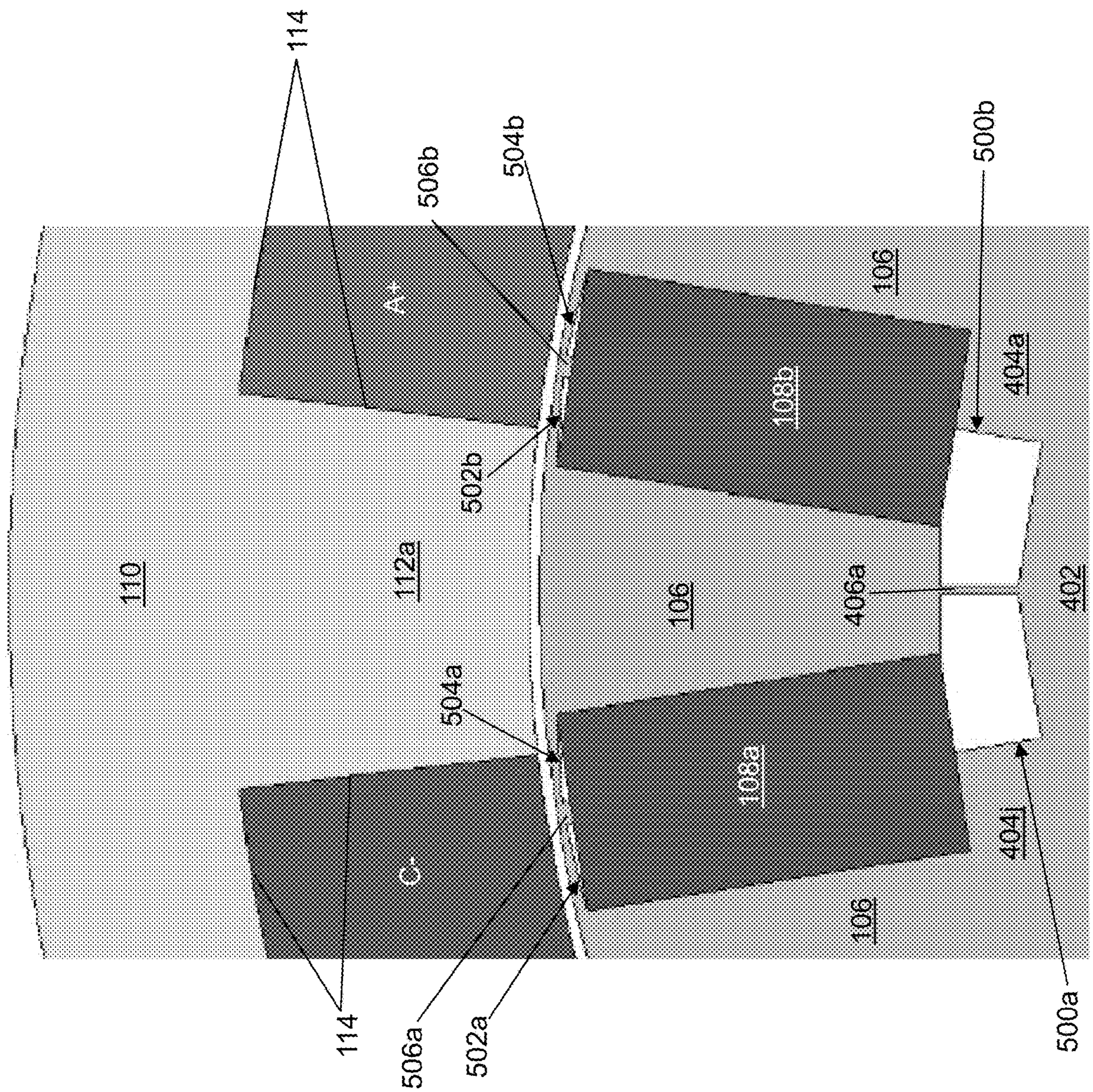
FIG. 3



114
114
114
114
110
112
C-
A+
105
112
112
400
106
106
106
B+
108
108
108
B-
108
108
106
106
108
108
114
112
106
106
112
114
404
404
108
108
A-
404
404
C+
106
106
108
108
406
112
404
408
112
106
102
106
104
116
404
108
406
108
C+
404
106
106
A-
114
404
108
108
114
114
106
404
404
106
112
402
112
108
108
106
108
108
106
B-
108
108
B+
106
106
106
114
112
112
A+
C-
112
114
114
114

FIG. 4

FIG. 5


114
506b
504b
500b
106
A+
108b
404a
502b
110
112a
106
406a
402
504a
108a
C-
404
106
114
506a
502a
500a

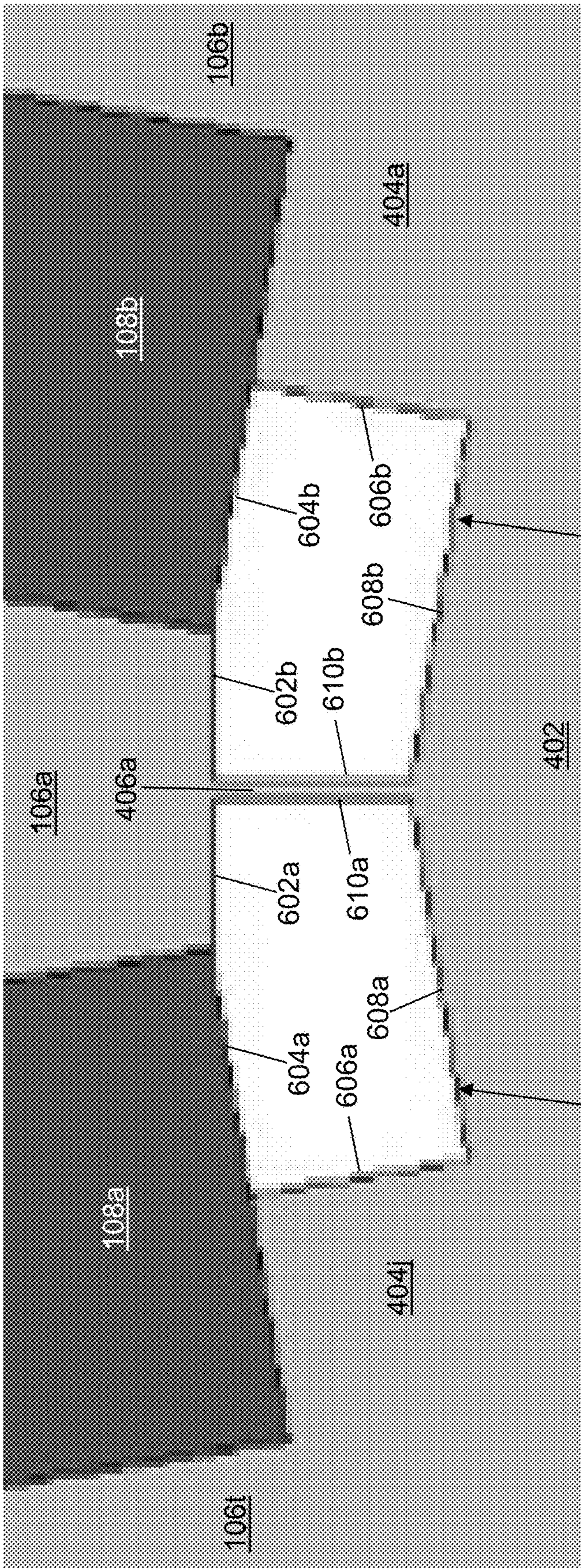

106b
108b
404a
604b
606b
500b
608b
602b
610b
402
106a
406a
602a
610a
608a
604a
606a
500a
108a
404
106

FIG. 6

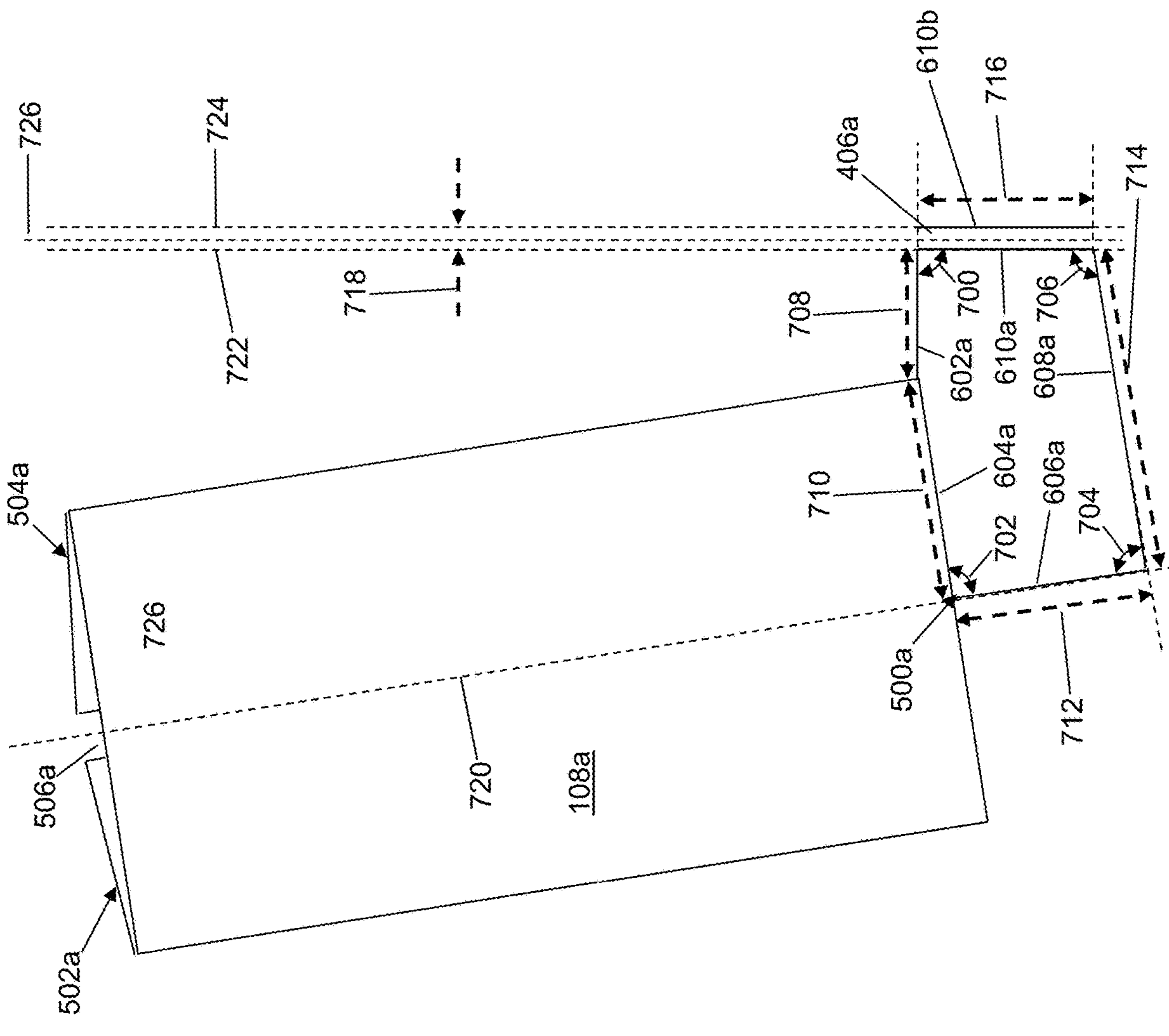

726
724
722
718
406a
610b
716
714
700
708
706
602a
610a
608a
604a
606a
710
702
704
500a
712
504a
726
720
108a
506a
502a

FIG. 7

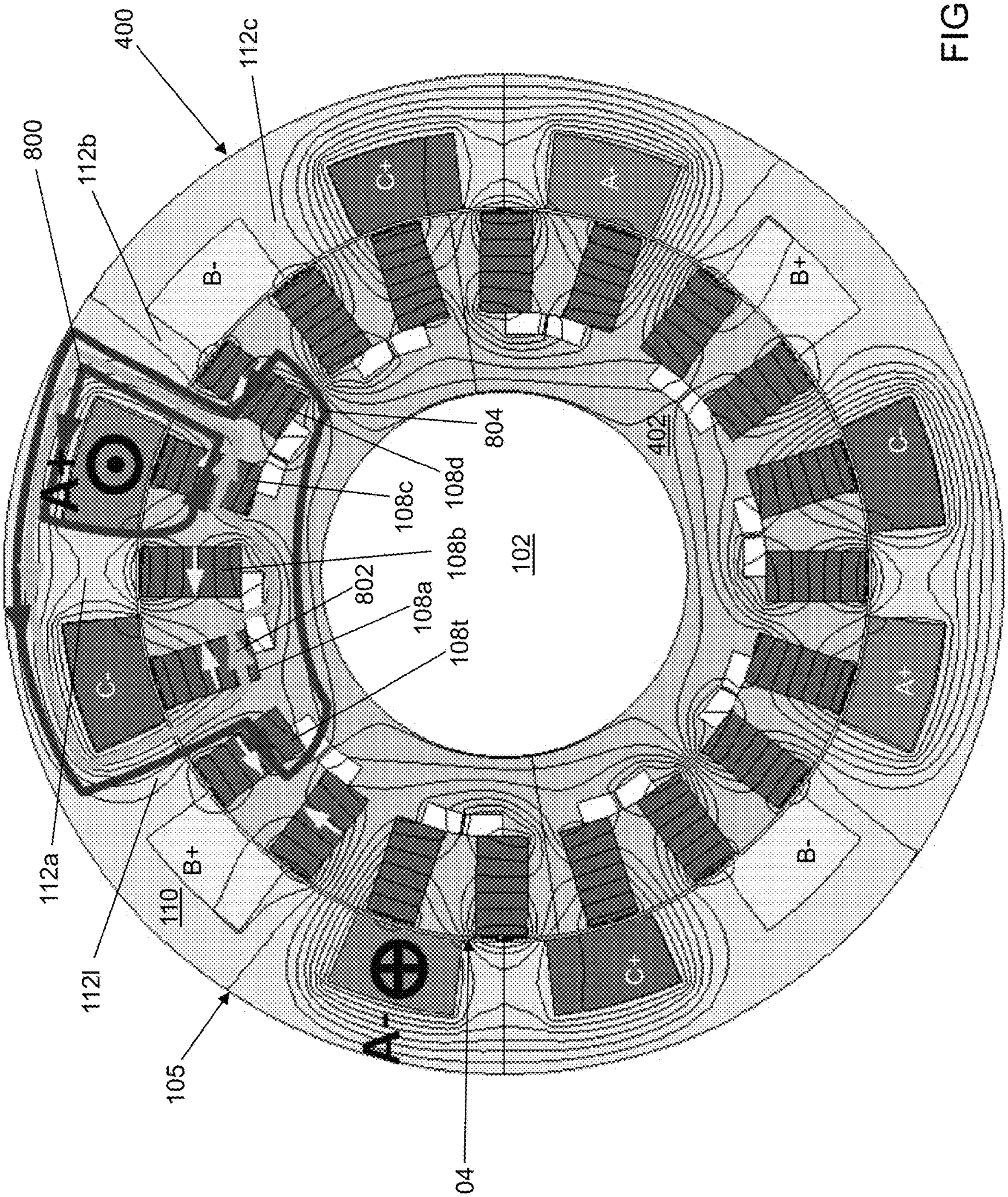

400
112c
800
112b
B-
C+
A-
B+
804
108d
108c
402
A+
C-
108b
102
802
108a
108t
112a
110
B+
112l
105
104
A-
C+
B-
A+

FIG. 8A

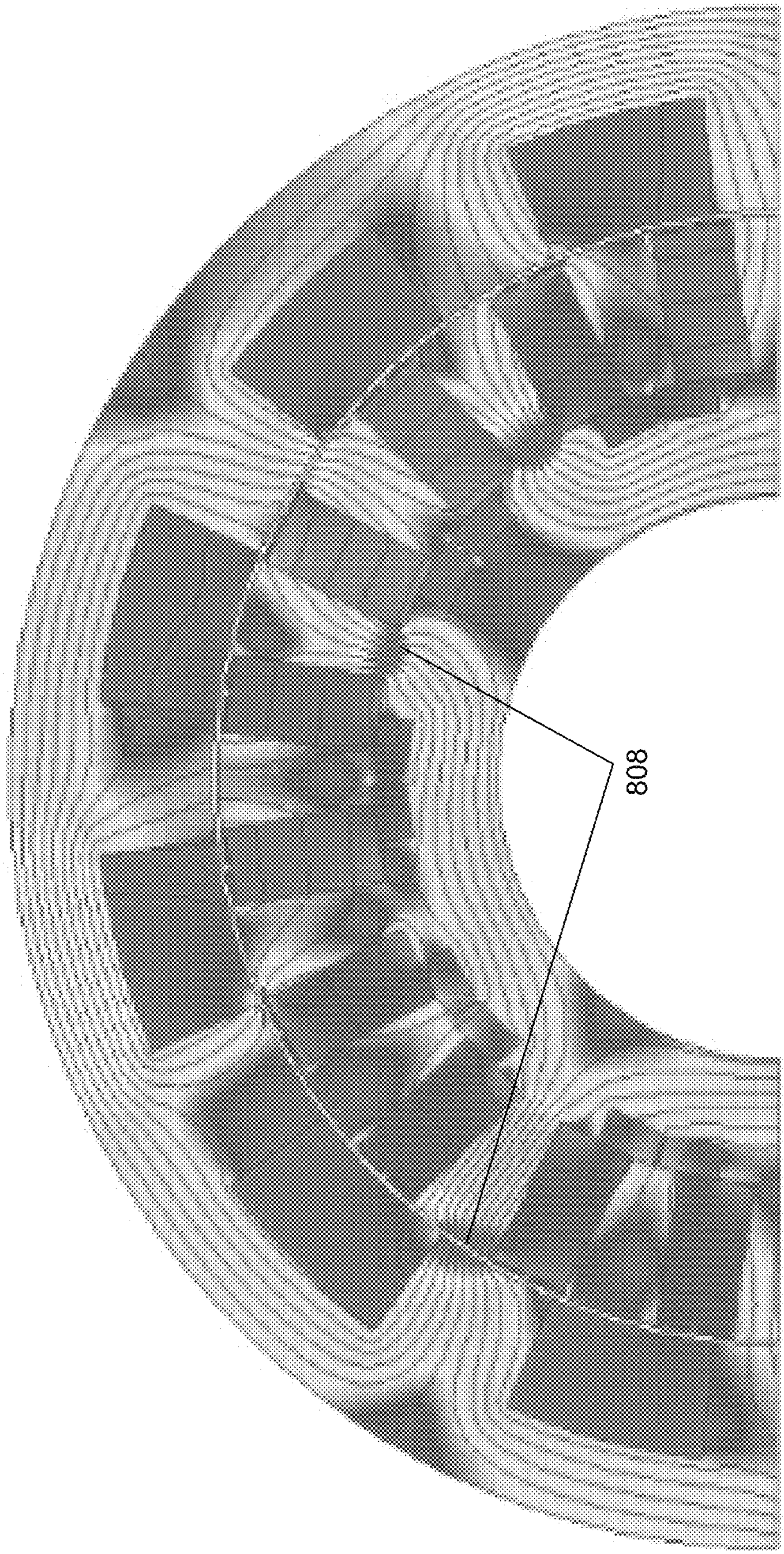
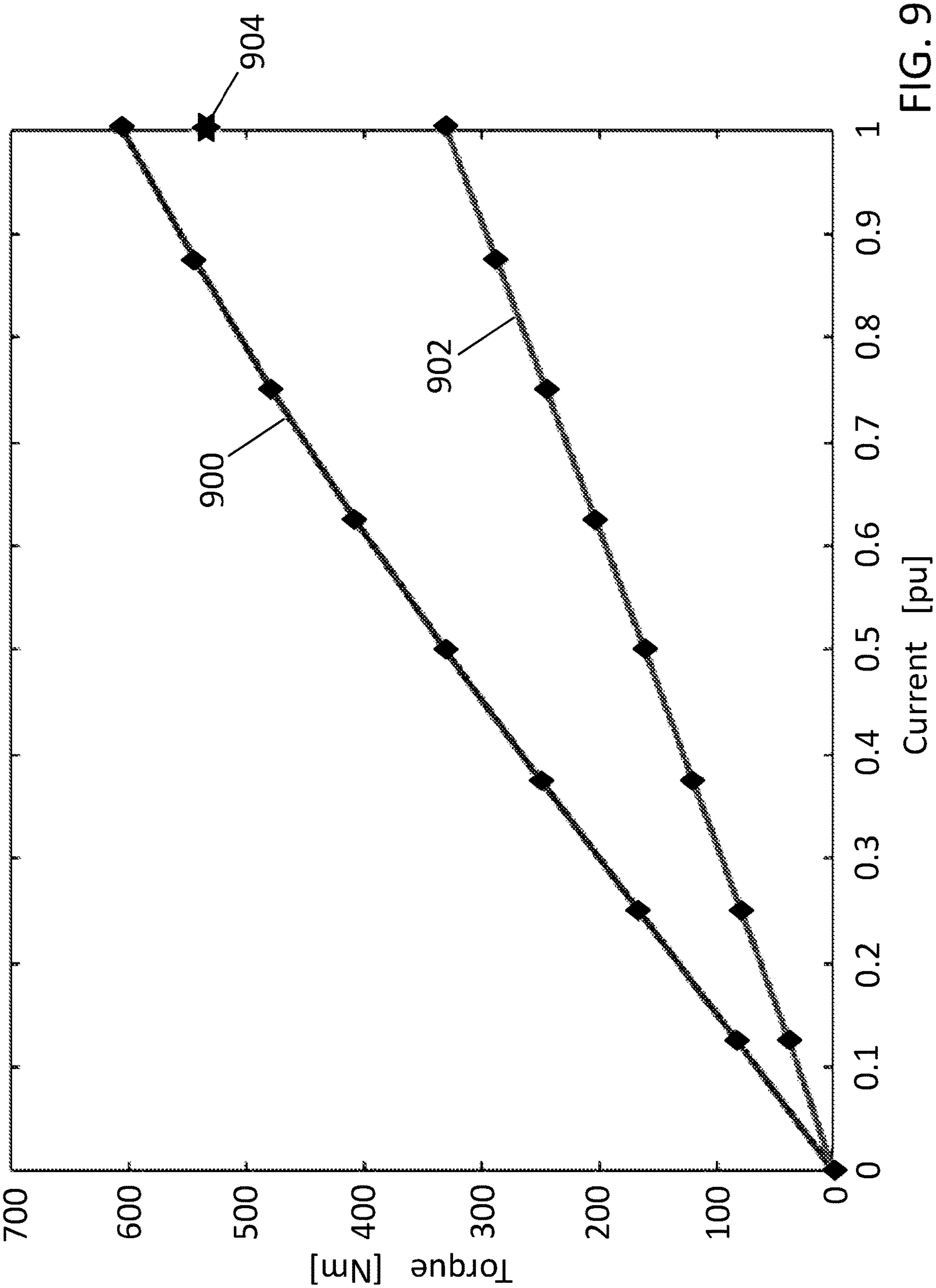


FIG. 8B



Torque [Nm]
700
600
500
400
300
200
100
0
Current [pu]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
900
902
904

FIG. 9

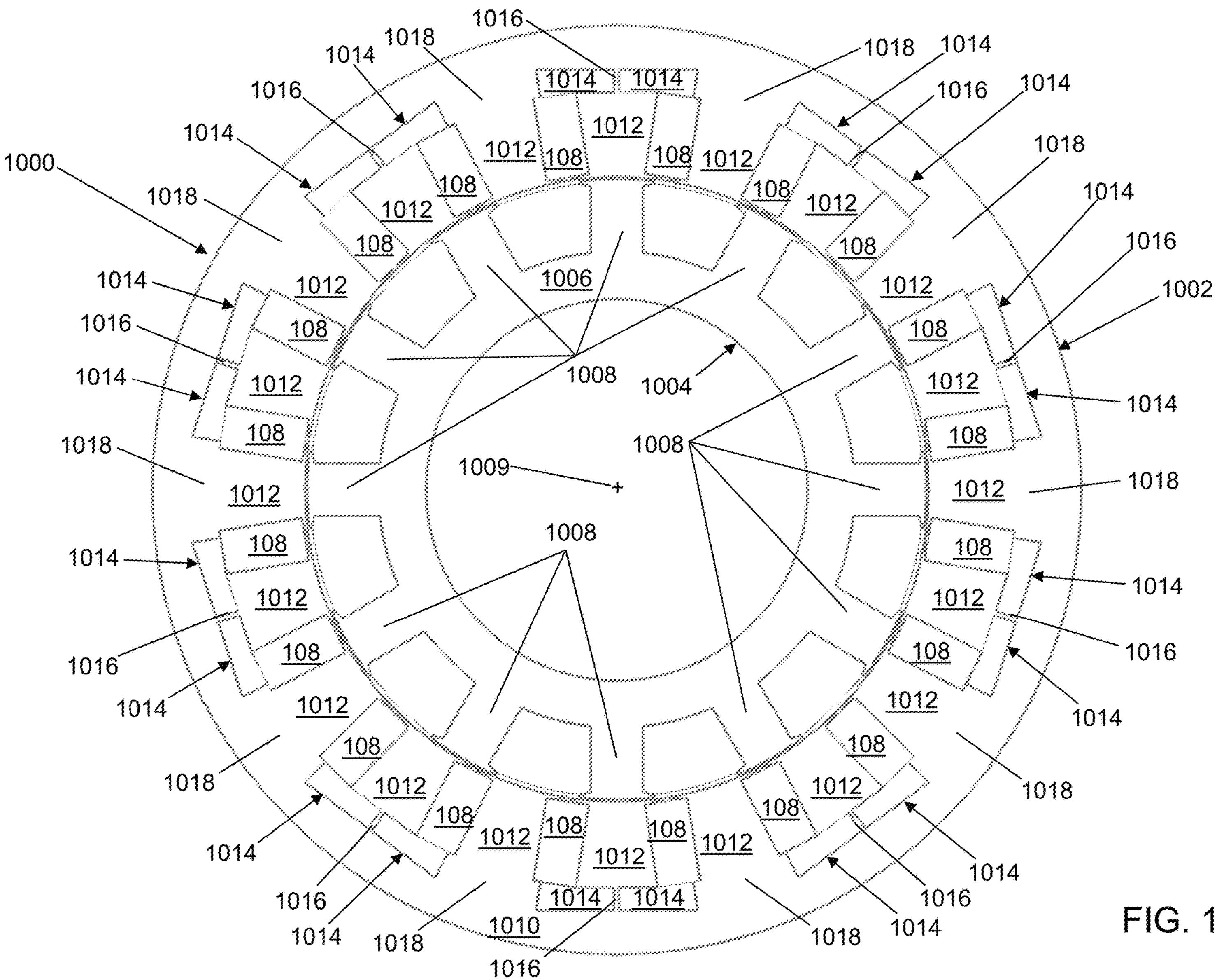


FIG. 10

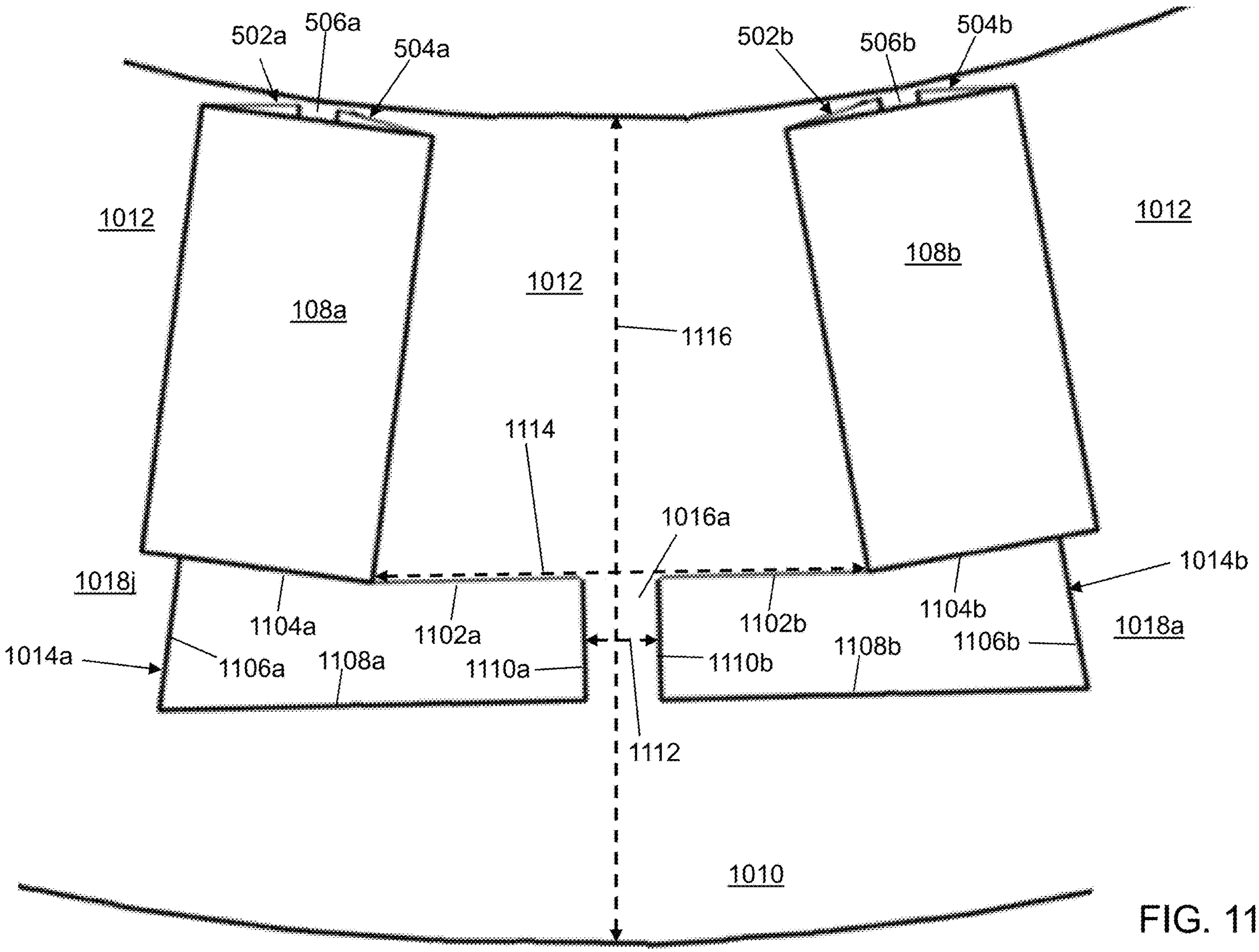

502a
506a
504a
502b
506b
504b
1012
108a
1012
1116
108b
1012
1114
1016a
1014b
1018j
1104a
1102a
1102b
1104b
1018a
1014a
1106a
1108a
1110a
1110b
1108b
1106b
1112
1010

FIG. 11

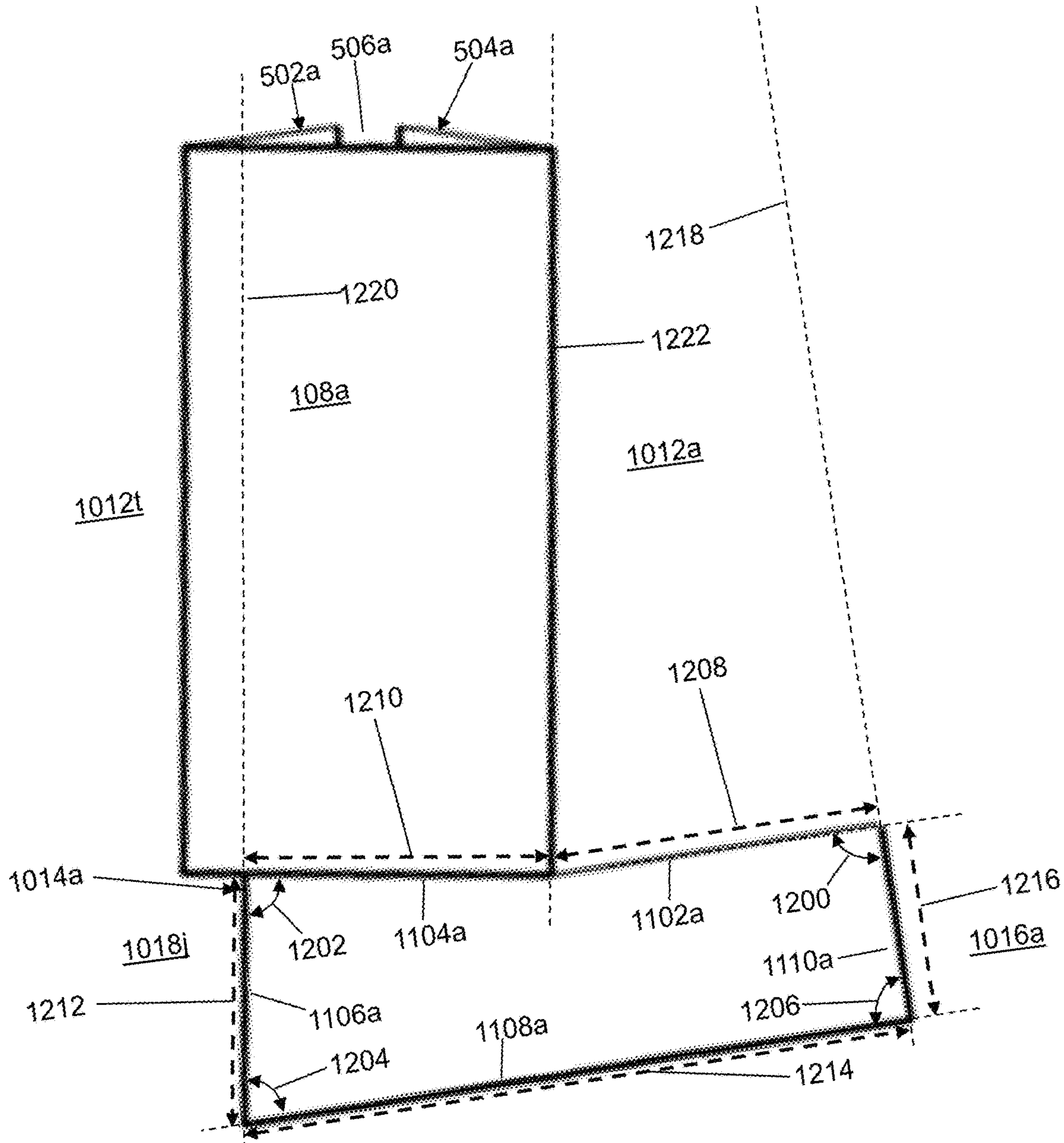

502a
506a
504a
1218
1220
1222
108a
1012a
1012t
1210
1208
1014a
1202
1104a
1102a
1200
1216
1018j
1016a
1110a
1212
1106a
1206
1108a
1204
1214

FIG. 12

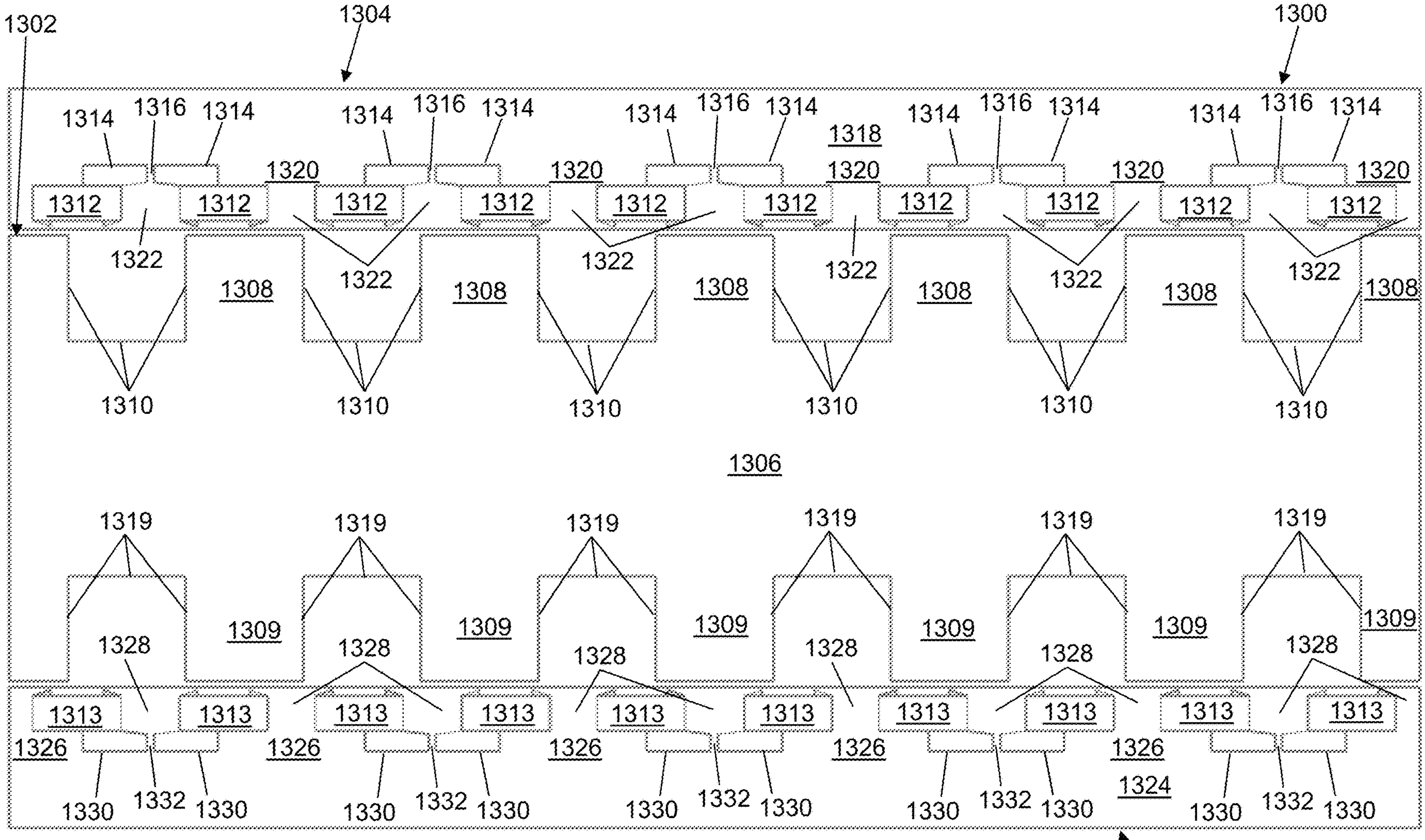

1302
1304
1300
1314
1316
1318
1320
1312
1322
1308
1310
1306
1319
1309
1328
1313
1326
1330
1332
1324
1305

FIG. 13

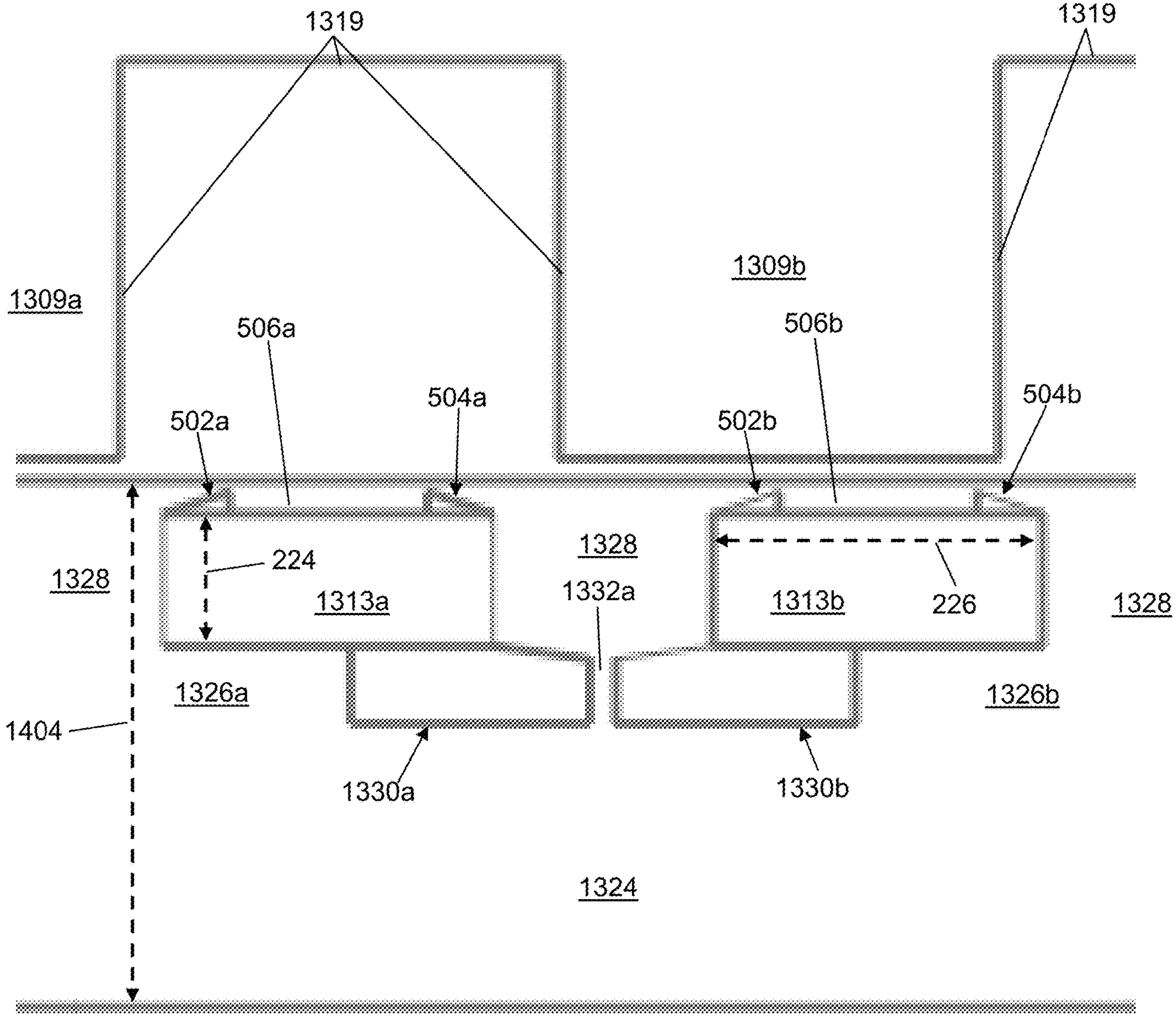

1319
1319
1309a
1309b
506a
506b
502a
504a
502b
504b
1328
224
1313a
1332a
1313b
226
1328
1328
1326a
1326b
1404
1330a
1330b
1324

FIG. 14

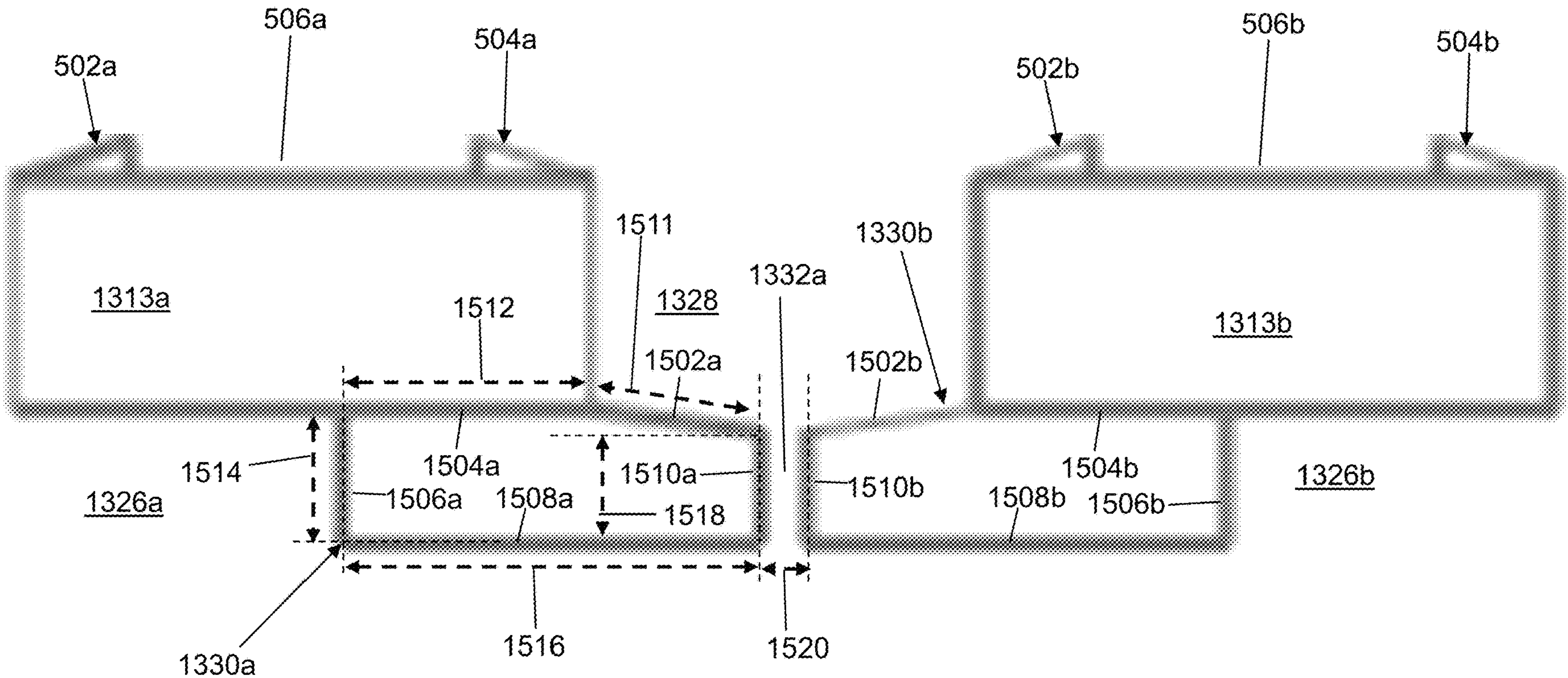

506a
504a
502a
506b
504b
502b
1511
1330b
1328
1332a
1313a
1313b
1512
1502a
1502b
1514
1504a
1510a
1510b
1504b
1326a
1506a
1508a
1518
1508b
1506b
1326b
1516
1520
1330a

FIG. 15

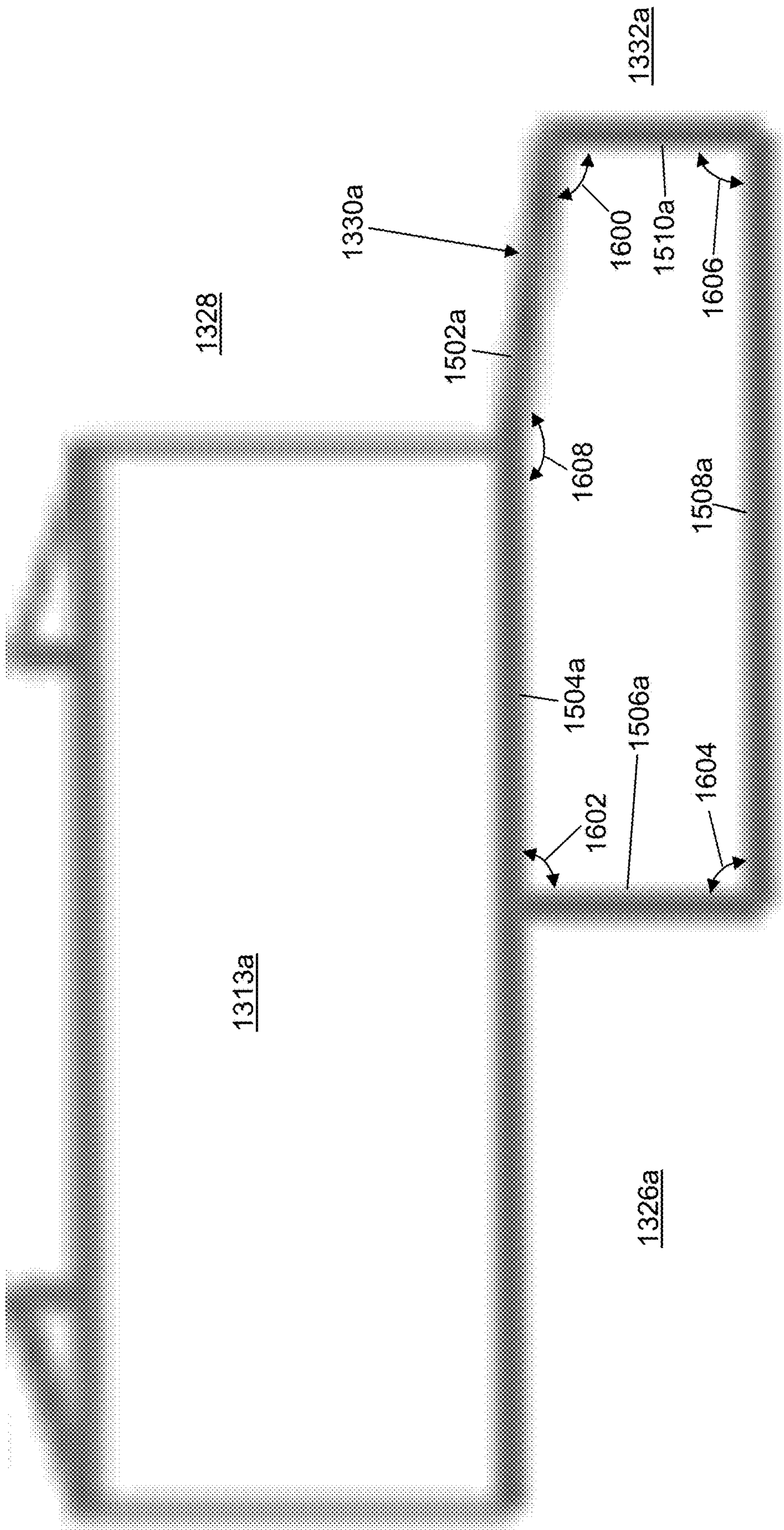

1332a
1330a
1600
1510a
1606
1328
1502a
1608
1508a
1504a
1506a
1604
1602
1313a
1326a

FIG. 16

ALTERNATING FLUX BARRIER AIR GAP IN A SPOKE TYPE MACHINE

BACKGROUND

The Vernier machine (VM) was first introduced as a synchronous reluctance motor variant less than 60 years ago and a permanent magnet version of this type of machine appeared only a little more than 20 years ago. In this type of machine, the rotor rotates relatively slowly, and only at a definite fraction of the angular velocity of the stator rotating field. Meanwhile, the motor torque steps up as the rotor speed steps down with this type of operation. This so-called electric gearing effect makes the VM an attractive alternative for direct-drive applications and is especially suitable for low speed motoring/braking operation. However, current designs of the Vernier permanent magnet machine (VPPM) have low power factor because the permanent magnets added to the rotor create additional harmonic flux leakage in the air gap.

To further increase torque density and cope with the low power factor feature of VPPMs, researchers have proposed two major designs of double air gap VPPMs in terms of machine structure: 1) a double rotor Vernier permanent magnet machine (DRVPPM), and 2) a dual stator Vernier permanent magnet machine (DSVPPM). It has been shown that torque improvement and copper loss reduction are achieved by the adaption of the double rotor structure, while the DSVPPM further improves both torque density and power factor with a dual stator spoke array VPPM topology. Unlike conventional single stator and rotor topology, however, introduction of an additional layer of rotor in DRVPPM or an additional layer of stator in DSVPPM significantly increases the machine manufacturing complexity, and poses a challenge to the mechanical structural integrity as well. A thermal issue becomes another concern because the inner stator is enclosed by rotating parts which limit the cooling options for windings positioned in that area.

SUMMARY

In an example embodiment, a rotor is provided. The rotor includes, but is not limited to, a first rotor core, a plurality of ribs, a plurality of rotor core teeth, a second rotor core, and a plurality of permanent magnets. The plurality of ribs each extend from the first rotor core. The plurality of rotor core teeth each extend from the first rotor core. A plurality of rotor air gaps are formed in the first rotor core between a rib of the plurality of ribs and a tooth of the plurality of rotor core teeth. The second rotor core extends from the plurality of ribs, from the plurality of rotor core teeth, and from a first wall of each rotor air gap of the plurality of rotor air gaps. The plurality of permanent magnets are mounted as spokes in pole pairs within the second rotor core. The second wall of each rotor air gap of the plurality of rotor air gaps is formed by a portion of an edge of a permanent magnet of the plurality of permanent magnets. A length of the portion of the edge is less than 80% of a length of the edge. A third wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a tooth of the plurality of rotor core teeth. A fourth wall of each rotor air gap of the plurality of rotor air gaps is formed by the first rotor core. A fifth wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a rib of the plurality of ribs. The first wall is connected between the second wall and the fifth wall. The third wall is connected between the second wall and the fourth wall. The fourth wall is connected between the third wall and the fifth wall. Each pair of permanent magnets of the plurality of permanent magnets has an associated pair of rotor air gaps of the plurality of rotor air gaps. A first rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps is a mirror image of a second rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps. Each pair of rotor air gaps of the plurality of rotor air gaps is separated by an associated rib of the plurality of ribs.

In another example embodiment, a rotor is provided. The rotor includes, but is not limited to, a first rotor core, a plurality of ribs, a plurality of rotor core teeth, a second rotor core, and a plurality of permanent magnets. The plurality of ribs each extend from the first rotor core. The plurality of rotor core teeth each extend from the first rotor core. A plurality of rotor air gaps are formed in the first rotor core between a rib of the plurality of ribs and a tooth of the plurality of rotor core teeth. The second rotor core extends from the plurality of ribs, from the plurality of rotor core teeth, and from a first wall of each rotor air gap of the plurality of rotor air gaps. The plurality of permanent magnets are mounted as spokes in pole pairs within the second rotor core. The second wall of each rotor air gap of the plurality of rotor air gaps is parallel to an edge of a permanent magnet of the plurality of permanent magnets. A length of the second wall is less than 80% of a length of the edge. A third wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a tooth of the plurality of rotor core teeth. A fourth wall of each rotor air gap of the plurality of rotor air gaps is formed by the first rotor core. A fifth wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a rib of the plurality of ribs. The first wall is connected between the second wall and the fifth wall. The third wall is connected between the second wall and the fourth wall. The fourth wall is connected between the third wall and the fifth wall. Each pair of permanent magnets of the plurality of permanent magnets has an associated pair of rotor air gaps of the plurality of rotor air gaps. A first rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps is a mirror image of a second rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps. Each pair of rotor air gaps of the plurality of rotor air gaps is separated by an associated rib of the plurality of ribs.

In yet another example embodiment, an electric machine is provided. The electric machine includes, but is not limited to, the rotor, the plurality of permanent magnets, a stator, and a stator winding. The stator includes, but is not limited to, a plurality of slots and a plurality of teeth. A slot of the plurality of slots is positioned between a pair of the plurality of teeth. The stator is mounted on a first side of the rotor separated by an air gap between a surface of the second rotor core and a tooth of the plurality of teeth. The stator winding is wound about the stator to form a number of poles between a set of terminals.

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 radial, spoke type, Vernier permanent magnet machine (VPPM) with a stator and a rotor positioned radially adjacent to each other in accordance with an illustrative embodiment.

FIG. **2** depicts a zoomed portion of the radial, spoke type, VPPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **3** shows flux lines that result from use of the radial, spoke type, VPPM of FIG. **1** in accordance with an illustrative embodiment.

FIG. **4** depicts a radial, spoke type, VPPM with alternating air gaps between permanent magnets and with the stator and a rotor positioned radially adjacent to each other in accordance with an illustrative embodiment.

FIG. **5** depicts a zoomed portion of the radial, spoke type, VPPM of FIG. **4** in accordance with an illustrative embodiment.

FIG. **6** depicts a zoomed portion of the alternating air gaps of the rotor of the radial, spoke type, VPPM of FIG. **4** in accordance with an illustrative embodiment.

FIG. **7** depicts an air gap and permanent magnet of the rotor of the radial, spoke type, VPPM of FIG. **4** in accordance with an illustrative embodiment.

FIG. **8**A shows flux lines at no load that result from use of the radial, spoke type, VPPM of FIG. **4** in accordance with an illustrative embodiment.

FIG. **8**B shows a flux distribution at rated load that result from use of the radial, spoke type, VPPM of FIG. **4** in accordance with an illustrative embodiment.

FIG. **9** shows a comparison of a torque generated as a function of current between the radial, spoke type, VPPMs of FIGS. **1** and **4** in accordance with illustrative embodiments.

FIG. **10** depicts a radial, spoke type, VPPM with alternating air gaps between permanent magnets and with the stator and the rotor positioned radially adjacent to each other in accordance with a second illustrative embodiment.

FIG. **11** depicts a zoomed portion of the alternating air gaps of the rotor of the radial, spoke type, VPPM of FIG. **10** in accordance with an illustrative embodiment.

FIG. **12** depicts an air gap and permanent magnet of the rotor of the radial, spoke type, VPPM of FIG. **10** in accordance with an illustrative embodiment.

FIG. **13** depicts a double air gap, axial VPPM with a first rotor and a second rotor positioned axially on either side of a stator in accordance with an illustrative embodiment.

FIG. **14** depicts a zoomed portion the double air gap, axial VPPM of FIG. **13** in accordance with an illustrative embodiment.

FIG. **15** depicts a zoomed portion of the alternating air gaps of the rotor of the double air gap, axial VPPM of FIG. **13** in accordance with an illustrative embodiment.

FIG. **16** depicts an air gap and permanent magnet of the rotor of the axial VPPM of FIG. **13** in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

A Vernier permanent magnet (PM) machine (VPPM) 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 pole pairs as in a conventional PM machine. Though the number of stator and rotor poles is unequal, the machine achieves smooth torque by synchronizing the space harmonics of the stator magneto-motive 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 VPPM rather than one component as in a conventional PM machine. The first component is the normal synchronous reaction torque produced by the magnets 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 combinations). An additional component is produced by the reluctance torque produced by the magnets 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, and these two rotates at the same speed of rotor rotating speed). As understood by a person of skill in the art, the PMVM may be used as a generator or as a motor.

The VPPM 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. To illustrate the magnetic field spatial modulation, a radial, spoke type VPPM **100** is shown in FIG. **1** where a counter-clockwise direction represents a positive angle notation. A rotating MMF is setup at an excitation frequency where a corresponding analytical form of the MMF is described in equation (1) below where k_h is an hth harmonic winding factor, N_t is a total number of turns, I_{pk} is a stator peak current, C_p is a number of parallel circuits, P_s is a number of stator poles, θ_s is a stator MMF spatial angle **208** (shown referring to FIG. **2**), and γ is a current phase shift angle. An air gap permeance p_g due to a stator pulsating tooth is described by equation (2), where p_0 and p_h are a DC and an hth harmonic component of permeance and S_s is a number of stator slots. A rotor PM MMF F_{pmg} can be defined using equation (3), where F_{pmgh} is an hth harmonic component of the PM MMF, P_r is a number of rotor poles, and θ_r is a rotor PM MMF spatial angle **210** (shown referring to FIG. **2**). Consequently, a rotor flux density modulation effect from a product of the rotor PM MMF F_{pmg} and air gap permeance p_g can be computed. A fundamental component is defined in equation (4), where

$$c_1 = F_{pmg1}\frac{p_1}{2} \text{ and } c_0 = F_{pmg1}\frac{p_0}{2}.$$

$$F_{sg} = \sum_{h=1,5,7,11\ldots}\left(\frac{3}{2}\cdot\frac{4}{\pi}\right)\frac{k_h N_t I_{pk}}{hC_p P_s}\cos\left(h\frac{P_s}{2}\theta_s \mp (\omega_e t - \gamma)\right) \tag{1}$$

$$p_g = p_0 + p_h\sum_{h=1,5,7,11\ldots}\cos(hS_s\theta_s) \tag{2}$$

$$F_{pmg} = F_{pmgh}\sum_{h=1,5,7,11\ldots}\cos\left(h\frac{P_r}{2}\theta_r\right) \tag{3}$$

$$B_{rg} = c_1\cos\left(\frac{P_r}{2}\theta_r - S_s\theta_s\right) + c_0\cos\left(\frac{P_r}{2}\theta_r\right) + c_1\cos\left(\frac{P_r}{2}\theta_r + S_s\theta_s\right) \tag{4}$$

The rotor torque can then be expressed as the rate of change of the field energy stored in the air gap as:

$$T = \frac{\partial}{\partial\theta_{rm}}\left[\int_{V_{gap}} B_{gap}H_{gap}dV_{gap}\right] \approx \frac{d_{iS}l_i}{2}\int_0^{2\pi}\left(\frac{\partial}{\partial\theta_{rm}}B_{rg}\right)F_{Sg}d\theta_s \tag{5}$$

where B_{gap} is an air gap flux density, H_{gap} is a magnetic field intensity, H_{gap} is a volume, d_{iS} is an inner stator radius, and l_i is a stack length. After substituting $\theta_r=\theta_s-\theta_{rm}$ to B_{rg} in equation (5), the integration becomes that shown in equation (6)

$$T = \frac{3d_{iS}l_i}{2\pi}\frac{N_tI_{pk}P_r}{C_pP_s}\int_0^{2\pi}\left\{\sum_{h=1,5,7,11,\ldots}\frac{k_h}{h}\cos\left(h\frac{P_s}{2}\theta_s \mp (\omega_et-\gamma)\right)\left[c_1\sin\left(\left(\frac{P_r}{2}-S_s\right)\theta_s-\frac{P_r}{2}\theta_{rm}\right)+ c_0\sin\left(\frac{P_r}{2}(\theta_s-\theta_{rm})\right)+c_1\sin\left(\left(\frac{P_r}{2}+S_s\right)\theta_s-\frac{P_r}{2}\theta_{rm}\right)\right]\right\}d\theta_s \tag{6}$$

where θ_{rm} is a relative spatial angle **212** (shown referring to FIG. **2**).

To fully utilize all three rotor fields for torque generation, it is desired to couple them with as many low order stator MMFs as possible. The trigonometric terms within the integration of equation (6) need to satisfy the condition that the fundamental spatial frequency of stator MMF equals that of the first term of B_{rg} as shown in equation (7)

$$\frac{P_r}{2} = \pm\frac{P_s}{2}+S_s \tag{7}$$

where '+' and '–" can both result in the same stator spatial MMF. The other two terms in B_{rg} can be uniquely determined to couple with the specific stator MMF harmonics for a given number of stator poles P_s as shown in equations (8a)-(8f):

$$-h\frac{P_s}{2} = \frac{P_r}{2}-S_s,\ h=1 \tag{8a}$$

$$h\frac{P_s}{2} = \frac{P_r}{2}-S_s,\ h=5 \tag{8b}$$

$$h\frac{P_s}{2} = \frac{P_r}{2}+S_s,\ h=11 \tag{8c}$$

$$h\frac{P_s}{2} = \frac{P_r}{2}-S_s,\ h=1 \tag{8d}$$

$$h\frac{P_s}{2} = \frac{P_r}{2}-S_s,\ h=7 \tag{8e}$$

$$h\frac{P_s}{2} = \frac{P_r}{2}+S_s,\ h=13 \tag{8f}$$

If equations (8a)-(8f) and

$$c_1 = F_{pmg1}\frac{p_1}{2} \text{ and } c_0 = F_{pmg1}\frac{p_0}{2}$$

are substituted into equation (6) $T_\mp$ a corresponding torque can be defined as:

$$T_- = \frac{3d_{iS}l_i}{4\pi}\frac{N_tI_{pk}P_r}{C_pP_s}F_{pmg1}\left(p_1\frac{k_1}{1}+p_0\frac{k_5}{5}+p_1\frac{k_{11}}{11}\right)\sin\left(\gamma-\left(\frac{P_r}{2}\theta_{rm}+\omega_et\right)\right),\quad \text{if } P_r=2S_s-P_s \tag{9}$$

and

$$T_+ = \frac{3d_{iS}l_i}{4\pi}\frac{N_tI_{pk}P_r}{C_pP_s}F_{pmg1}\left(p_1\frac{k_1}{1}+p_0\frac{k_7}{7}+p_1\frac{k_{13}}{13}\right)\sin\left(\left(\omega_et-\frac{P_r}{2}\theta_{rm}\right)-\gamma\right),\quad \text{if } P_r=2S_s+P_s$$

The oscillating sine term in equation (9) can be set to constant if $\theta_{rm}=\mp2\omega_et/P_r$, a mechanical rotor speed can be derived as

$$\omega_{rm} = \frac{\partial\theta_{rm}}{\partial t} = \mp2\omega_e/P_r,$$

suggesting that the rotor speed is inversely proportional to the number of rotor pole pairs P_r. A primitive quantitative comparison can be carried out based on equation (9) to obtain a general sense about which sign should be chosen in equation (7). Assuming the current phase shift angle γ is tuned to unity, the trigonometric term operates at a maximum per ampere (MTPA) point for both cases for a given size and stator excitation VPM. If one further assumes am ideal full pitched concentrated winding without skew and slots effects, the winding factor diminishes to unity with a three phase machine, $S_s=3P_s$. If $P_r=2S_s\pm P_s$ is substituted into $T_\mp$, the torque ratio of the two is defined as shown in equation (10):

$$\frac{T_+}{T_-} = \frac{7F_{pmg1}\left(p_1\frac{14}{13}+p_0\frac{1}{7}\right)}{5F_{pmg1}\left(p_1\frac{12}{11}+p_0\frac{1}{5}\right)} \tag{10}$$

Usually F_{pmg1} in a design in which $P_r=2S_s+P_s$ is greater or equal to that in $P_r=2S_s-P_s$. Assuming

$$p_0 = p_1,\ \frac{T_+}{T_-} \geq 1.32$$

is obtained, which indicates that ideally a $P_r=2S_s+P_s$ design produces 32% more torque compared to a $P_r=2S_s-P_s$ design with only a rotor pole number difference. Regardless of choice of the rotor pole number P_r between the two cases, the term P_r/P_s reveals a gear effect from the VPPM **100**.

Referring to FIG. **1**, radial, spoke type VPPM **100** is shown in accordance with an illustrative embodiment. Radial, spoke type VPPM **100** may include a shaft **102**, a rotor **104**, and a stator **105** positioned radially adjacent to each other. In the illustrative embodiment of FIG. **1**, rotor **104** is mounted to shaft **102** interior of stator **105**. Shaft **102**, rotor **104**, and stator **105** have generally circular cross sections as shown with reference to FIG. **1**. Rotor **104** is mounted to shaft **102** for rotation with shaft **102**.

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.

Stator **105** may be formed of a ferromagnetic material such as iron, cobalt, nickel, etc. Stator **105** may include a stator core **110** and a plurality of teeth **112**. The plurality of teeth **112** extend from stator core **110** towards a center **116** of an interior of shaft **102**, rotor **104**, and stator **105**. A plurality of slot walls **114** define edges 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 **105** includes 12 teeth that define 12 stator slots $S_s=12$. As understood by a person of skill in the art, stator **105** may be formed of laminations mounted closely together in an axial direction.

In the illustrative embodiment, radial, spoke type VPPM **100** is a three-phase machine, $N_{ph}=3$, with windings that are connected to provide three-phases, A, B, and C. The windings (not shown) are wound within the plurality of slot walls **114** as understood by a person of skill in the art. The windings are wound about stator **105** to form a number of poles P_s between a set of terminals (not shown). In an illustrative embodiment, the windings are concentrated windings since the power factor has been determined to be inversely proportional to the slots per pole per phase q of stator **105**. As understood by a person of skill in the art, using concentrated windings, q is fractional and strictly less than 1. S_s then becomes a dependent variable to the number of stator poles i.e. $S_s=3P_s$. A stator tooth pitch and a back iron height are chosen to sustain a certain amount of flux under a rated current operation by not compromising a slot area to achieve a reasonable current density. For further details, see B. Kim and T. A. Lipo, "Operation and Design Principles of a PM Vernier Motor," *IEEE Trans. Ind. Appl.*, vol. 50, no. 6, pp. 3656-3663, November 2014. In the illustrative embodiment of FIG. **1**, radial, spoke type VPPM **100** has four stator poles $P_s=S_s/N_{ph}$.

Rotor **104** may be formed of a ferromagnetic material such as iron, cobalt, nickel, etc. Rotor **104** may include a rotor core **106** and a plurality of permanent magnets **108** mounted radially as spokes within rotor core **106**. As understood by a person of skill in the art, rotor core **106** may be formed of laminations mounted closely together in the axial direction. The plurality of permanent magnets **108** are electrically isolated from each other. Openings are formed in rotor core **106** that are sized and shaped to hold the plurality of permanent magnets **108**. Each permanent magnet of the plurality of permanent magnets **108** is magnetized to form a south pole on a first side and a north pole on a second side opposite the first side. The plurality of permanent magnets **108** are mounted with N poles adjacent N poles and S poles adjacent S poles to form pole pairs. For illustration referring to FIG. **2**, a first permanent magnet **108***a* and a second permanent magnet **108***b* form a first pole pair with the arrows pointing from the S pole to the N pole. The pole pairs are formed at a regular pitch circumferentially around rotor **104**.

Each permanent magnet of the plurality of permanent magnets **108** may be identical (though mounted with an opposing magnetization direction for adjacent magnets) and may be formed of rare earth magnets, such as neodymium and dysprosium, of ferrite based magnets, etc. Referring to FIG. **2**, each permanent magnet of the plurality of permanent magnets **108** has a height **224** that extends radially across rotor **104** and a width **226** that extends perpendicular to height **224**. Each permanent magnet of the plurality of permanent magnets **108** has a depth (not shown) that extends in an axial direction perpendicular to height **224** and to width **226**.

Referring to FIG. **2**, a quarter portion of radial, spoke type VPPM **100** is shown in accordance with an illustrative embodiment. First slot walls **114***a* define a first slot between a first tooth **112***a* and a second tooth **112***b* of the plurality of teeth **112**. Second slot walls **114***b* define a second slot between a second tooth **112***b* and a third tooth **112***c* of the plurality of teeth **112**. Third slot walls **114***c* define a third slot between third tooth **112***c* and a fourth tooth **112***d* of the plurality of teeth **112**. The plurality of teeth **112** may be straight-sided or may be angled, for example, radially toward center **116** of radial, spoke type VPPM **100**. The plurality of permanent magnets **108** include a first PM **108***a*, a second PM **108***b*, a third PM **108***c*, a fourth PM **108***d*, and a fifth PM **108***d*.

A first radial line **202** extends from center **116** parallel to a first slot wall of first slot walls **114***a* on a left edge of second tooth **112***b*. A second radial line **204** extends from center **116** through a center of a second slot wall of second slot walls **114***b* between a right edge of second tooth **112***b* and a left edge of third tooth **112***c*. A third radial line **206** extends from center **116** through a center of third tooth **112***c*. Stator spatial angle **208**, θ_s, is defined between first radial line **202** and third radial line **206**. Rotor spatial angle **210**, θ_r, is defined between first radial line **202** and second radial line **204**. Relative spatial angle **212**, θ_{rm}, is defined between second radial line **204** and third radial line **206**.

A first radial distance **214** defines a radius of shaft **102**. Rotor **104** has a radial width **216**. A second radial distance **216** defines a radius of shaft **102**. A third radial distance **218** defines a first air gap width between an outer radial surface of rotor **104** and a slot of the plurality of slots of stator **105**. A fourth radial distance **220** defines a second air gap width between the outer radial surface of rotor **104** and a tooth of the plurality of teeth **112** of stator **105**. A fifth radial distance **220** defines a width of stator **105** at each tooth of the plurality of teeth **112** of stator **105**. A slot width **228** defines a width across each slot of stator **105**. Rotor **104** and stator **105** are separated by an air gap that has a varying width between rotor **104** and stator **105** due to the changing height between the plurality of slots and the plurality of teeth **111**.

Referring to FIG. **3**, flux lines that result from use of radial, spoke type VPPM **100** under no load is shown in accordance with an illustrative embodiment. For reference, a twelfth tooth **1121** of the plurality of teeth **112** is labeled. A fifth PM **108***e* and a twentieth PM **118***t* are labeled with white arrows denoting the PM magnetizing directions. One set of coils of phase A are marked out with the 'dot' representing a positive direction of current associated with coil A, and a 'cross' representing a negative direction of current associated with coil A. The flux lines from the PMs that links to coil set A can be seen surrounding each associated slot where a one-fourth model of the flux line distribution is shown due to symmetry. A first magnet flux path **300** and a second magnet flux path **302** are two major rotor magnet flux paths that link to coil A with the arrows indicating the corresponding flux direction.

Referring to FIG. **4**, a second radial, spoke type VPPM **400** is shown in accordance with an illustrative embodiment. Second radial, spoke type VPPM **400** may include shaft **102**, rotor **104**, stator **105**, a rotor inner core **402**, and a plurality of rotor inner core teeth **404** positioned radially adjacent to each other. The plurality of rotor inner core teeth **404** extend outward from rotor inner core **402** relative to center **116**. In the illustrative embodiment of FIG. **4**, rotor **104** is mounted to the plurality of rotor inner core teeth **404**, and rotor inner core **402** is mounted to shaft **102** interior of rotor core **106**. Shaft **102**, rotor inner core **402**, rotor **104**, and stator **105** have generally circular cross sections as shown with reference to FIG. **4**. A inner rotor radius **408** defines a radius of an inner surface of rotor inner core **402** relative to center **116**.

Rotor inner core **402** is mounted to shaft **102** for rotation with shaft **102**. A plurality of ribs **406** further extend radially from center **116** between rotor air gaps formed between the plurality of rotor inner core teeth **404**. As understood by a person of skill in the art, rotor core **106**, rotor inner core **402**, the plurality of ribs **406**, and the plurality of rotor inner core teeth **404** may be formed of laminations mounted closely together in the axial direction. Rotor inner core **402**, the plurality of ribs **406**, and the plurality of rotor inner core teeth **404** may be formed of a material similar to or the same as rotor core **106**.

Referring to FIG. **5**, a zoomed portion of second radial, spoke type, VPPM **400** is shown in accordance with an illustrative embodiment. A first rotor air gap **500***a* is formed in rotor inner core **402** between a twelfth rotor inner core tooth **404***j* of the plurality of rotor inner core teeth **404** and a first rib **406***a* of the plurality of ribs **406** below first PM **108***a*. Each tooth of the plurality of rotor inner core teeth **404** may be identical. Each rib of the plurality of ribs **406** may be identical. A second rotor air gap **500***b* is formed in rotor inner core **402** between first rib **406***a* of the plurality of ribs **406** and a first rotor inner core tooth **404***a* of the plurality of rotor inner core teeth **404** below second PM **108***b*. First rib **406***a* may extend radially from center **116** centered between first rotor air gap **500***a* and second rotor air gap **500***b*.

A first upper, left PM air gap **502***a* and a first upper, right PM air gap **504***a* may be formed above first PM **108***a* with a first upper rib **506***a* positioned between first upper, left PM air gap **502***a* and first upper, right PM air gap **504***a*. A second upper, left PM air gap **502***b* and a second upper, right PM air gap **504***b* may be formed above second PM **108***b* with a second upper rib **506***b* positioned between second upper, left PM air gap **502***b* and second upper, right PM air gap **504***b*. Though not shown, similar upper air gaps **502**, **504** may be formed in rotor **104** of radial, spoke type, VPPM **100**. Identical upper air gaps may be formed around each PM of the plurality of PMs **108**.

Referring to FIG. **6**, a zoomed portion of first rotor air gap **500***a* and second rotor air gap **500***b* of rotor inner core **402** of second radial, spoke type, VPPM **400** is shown in accordance with an illustrative embodiment. First rotor air gap **500***a* may be defined by a first wall **602***a*, a second wall **604***a*, a third wall **606***a*, a fourth wall **608***a*, and a fifth wall **610***a*. Second rotor air gap **500***b* may be similarly defined by a first wall **602***b*, a second wall **604***b*, a third wall **606***b*, a fourth wall **608***b*, and a fifth wall **610***b* such that second rotor air gap **500***b* is a mirror image of first rotor air gap **500***a* relative to first rib **406***a*. Pairs of rotor air gaps may be defined between successive pairs of PMs of the plurality of PMs **108**. Fifth wall **610***a* extends along an edge of first rib **406***a* facing into first rotor air gap **500***a*. Second wall **604***a* extends along an edge of first PM **108***a* facing into first rotor air gap **500***a*. First wall **602***a* extends from an edge of first PM **108***a* to a top edge of first rib **406***a* between an edge of second wall **604***a* and an edge of fifth wall **610***a*. Fourth wall **608***b* extends from a bottom edge of first rib **406***a* between an edge of third wall **606***a* and a second edge of fifth wall **610***a*.

The rotor air gaps **500** act as flux barriers and may be filled with air or other material with a permeability approximately equal to air. Second wall **604***a* and second wall **604***b* of each rotor air gap may include an intermediate layer of material to separate first PM **108***a* from first rotor air gap **500***a* and to separate second PM **108***b* from second rotor air gap **500***b*, respectively. The intermediate layer may be formed of a material having a low permeability (e.g., approximately equal to air). Alternatively, second wall **604***a* and second wall **604***b* may be formed by first PM **108***a* and separate second PM **108***b*, respectively.

Referring to FIG. **7**, first rotor air gap **500***a* and first PM **108***a* of second radial, spoke type, VPPM **400** are shown in accordance with an illustrative embodiment. A first angle **700** is defined between first wall **602***a* and fifth wall **610***a*. A second angle **702** is defined between second wall **604***a* and third wall **606***a*. A third angle **704** is defined between third wall **606***a* and fourth wall **608***a*. A fourth angle **706** is defined between fourth wall **608***a* and fifth wall **610***a*. A sixth angle (not labeled) between first wall **602***a* and second wall **604***a* is equal to 180 degrees minus first angle **700** in degrees. A sixth angle (not labeled) between first wall **602***a* and second wall **604***a* is equal to 180 degrees minus fourth angle **706**. In the illustrative embodiment, first angle **700**, second angle **702**, and third angle **704** are equal to ninety degrees. As a result, in the illustrative embodiment, second wall **604***a* and fourth wall **608***a* are parallel to each other, and third wall **606***a* is perpendicular to second wall **604***a* and fourth wall **608***a*. Third wall **606***a* is parallel to a center line **720** that extends through a center of first PM **108***a*. In the illustrative embodiment, center line **720** is parallel to the side walls of each of the plurality of PMs **108**. In alternative embodiments, the side walls of each of the plurality of PMs **108** may not be parallel to center line **720**.

A first wall length **708** defines a length of first wall **602***a*. A second wall length **710** defines a length of second wall **604***a*. A third wall length **712** defines a length of third wall **606***a*. A fourth wall length **714** defines a length of fourth wall **602***a*. A fifth wall length **716** defines a length of fifth wall **610***a*. Fifth wall length **716** further defines a height of first rib **406***a*, and a rib width **718** defines a width of first rib **406***a*. Rib width **718** is defined between a first line **722** that is parallel to and includes fifth wall **610***a* and a second line **724** that is parallel to and includes fifth wall **610***b*. A radial line **726** centered between first line **722** and second line **724** extends through center **116**. First line **722** and second line **724** are parallel to radial line **726**.

Second wall length **710** may be selected as a percentage of width **226** of first PM **108***a*. For example, illustrative percentages for second wall length **710** may be 40% to 80% of width **226** of first PM **108***a*. Third wall length **712** also may be selected as a percentage of width **226** of first PM **108***a*. For example, illustrative percentages for third wall length **712** may be 20% to 40% of width **226** of first PM **108***a*. Rib width **718** may be selected as a percentage of an inner rotor radius **408**. For example, illustrative percentages for rib width **718** may be 0.3% to 2.5% of inner rotor radius **408**. For example, first angle **700** can be selected between 30 and 150 degrees.

Though each air rotor air gap of the rotor air gaps **500** is shown with five walls, each air rotor air gap of the rotor air gaps **500** may include a fewer or a greater number of walls dependent on a selection of the angle of first angle **700**. Though each corner defined by first angle **700**, second angle **702**, third angle **704**, and fourth angle **706** is squared in the illustrative embodiment, the corners may be rounded.

Referring to FIG. **8**A, flux lines that result from use of second radial, spoke type VPPM **400** under no load is shown in accordance with an illustrative embodiment. There are three major rotor magnet flux paths, linking four magnets to coil A. A first flux path **800** surrounds a first slot bordered by first tooth **112***a* and second tooth **112***b* and extends through third PM **108***c*. A second flux path **802** surrounds the first slot bordered by first tooth **112***a* and second tooth **112***b* and a twelfth slot bordered by twelfth tooth **1121** and first tooth **112***a* and extends through first PM **108***a* and third PM **108***c*. Second flux path **802** also extends across first rib **406***a* between first rotor air gap **500***a* of first PM **108***a* and second rotor air gap **500***b* of second PM **108***b*. A third flux path **804** surrounds the first slot bordered by first tooth **112***a* and second tooth **112***b* and the twelfth slot bordered by twelfth tooth **1121** and first tooth **112***a* and extends through twentieth PM **108***t* and fourth PM **108***d* to link two more PMS to coil A relative to a number of PMs linking to the same coil of radial, spoke type VPPM **100** shown in FIG. **3**. In other words, the alternating use of first rotor air gap **500***a* and second rotor air gap **500***b* as rotor flux barriers supports the use of an enlarged rotor back iron without providing a magnetic short circuit to the plurality of PMs **108**. Flux leakage in the air gap and the leakage iron path is also greatly reduced compared to that of radial, spoke type VPPM **100**.

Furthermore, second radial, spoke type VPPM **400** provides a flux path not only for the magnet flux, but also for the stator MMF at rated load as shown referring to FIG. **8**B fourth flux path **808**. The stator MMF does not need to traverse across the spoke type magnets, which are effectively large air gaps. Thus, the flux density that limits the torque production capability is significantly increased. $P_r=2S_s-P_s$ was chosen in the illustrative embodiment due to the challenge of fitting thick ferrite magnets into a limited rotor space. This would not be a problem for second radial, spoke type VPPM **400** having a larger diameter and the results could be further improved.

A comparison between the radial, spoke type, VPPMs of FIGS. **1** and **4** in accordance with illustrative embodiments and an existing interior PM machine (IPPM) was performed. A performance comparison is tabulated in Table 1 below. To make a fair comparison between the IPPM, radial, spoke type VPPM **100**, and second radial, spoke type VPPM **400**, a machine outer stator diameter of 355.6 millimeters (mm), a stack length of 311.15 mm, and a current density of 4.6 ARMS/mm^2 for the stator excitation were all kept the same. Ferrite PMs were used for radial, spoke type VPPM **100** and for second radial, spoke type VPPM **400**; whereas, a neodymium, iron and boron alloy rare earth PM was used for the IPPM.

TABLE 1

	Torque	Power Factor [lagging]
IPPM	534	0.85
VPPM 100	329	0.61
VPPM 400	606	0.82

FIG. **9** shows a comparison of a torque generated as a function of excitation current between the radial, spoke type, VPPMs of FIGS. **1** and **4** and the IPPM in accordance with illustrative embodiments. A first curve **900** shows the torque generated as a function of excitation current for second radial, spoke type VPPM **400**. A second curve **902** shows the torque generated as a function of excitation current for radial, spoke type VPPM **100**. An operating point **904** shows the torque generated for the IPPM. The results of FIG. **9** indicate that second radial, spoke type VPPM **400** greatly improves the torque production relative to radial, spoke type VPPM **100**. The improvement was by 84%. The torque capability of second radial, spoke type VPPM **400** even surpasses that of the IPPM with a satisfactory power factor 0.82 achieved at the same time as shown in Table 1.

Ferrite magnets were used as a replacement for rare earth magnets to reduce an active material cost of second radial, spoke type VPPM **400**. Overall, the single air gap topology of second radial, spoke type VPPM **400** reduces a manufacturing complexity, mechanical structural challenges, and thermal issues, which are predominant problems for existing high torque density spoke type Vernier machine solutions that have a dual stator topology. Second radial, spoke type VPPM **400** shows considerable utility in low and medium speed applications both as a motor and a generator.

Referring to FIG. **10**, a third radial, spoke type VPPM **1000** is shown in accordance with an illustrative embodiment. Third radial, spoke type VPPM **1000** may include a rotor **1002** and a stator **1004** positioned radially adjacent to each other with stator **1004** interior of rotor **1002**. Though not shown, rotor **1002** is mounted to a shaft for rotation around stator **1004**. Third radial, spoke type VPPM **1000** is otherwise similar to second radial, spoke type VPPM **400**. Rotor **1002** and stator **1004** have generally circular cross sections as shown with reference to FIG. **10**.

Stator **1004** may be formed of a ferromagnetic material such as iron, cobalt, nickel, etc. Stator **1004** may include a stator core **1006** and a plurality of teeth **1008**. The plurality of teeth **1008** extend outward from stator core **1006** away from a center **1009** of an interior of third radial, spoke type VPPM **1000**. Similar to stator **105**, a plurality of slot walls define edges of stator slots where a slot is positioned between a pair of the plurality of teeth **1008**. In the illustrative embodiment, the plurality of teeth **1008** of stator **1004** includes 12 teeth that define 12 stator slots S_s=12. In the illustrative embodiment of FIG. **10**, the plurality of teeth **1008** are T-shaped though other shapes are possible. As understood by a person of skill in the art, stator **1004** may be formed of laminations mounted closely together in the axial direction.

Rotor **1002** may formed of a ferromagnetic material such as iron, cobalt, nickel, etc. Rotor **1002** may include a rotor outer core **1010**, a rotor core **1012**, the plurality of permanent magnets **108**, a plurality of rotor outer core teeth **1018**, and a plurality of ribs **1016**. The plurality of permanent magnets **108** is mounted radially as spokes within rotor core **1012**. As understood by a person of skill in the art, rotor outer core **1010**, rotor core **1012**, the plurality of rotor inner core teeth **1018**, and the plurality of ribs **1016** may be formed of the same or similar materials and as laminations mounted closely together in the axial direction.

In the illustrative embodiment of FIG. **10**, the plurality of rotor outer core teeth **1018** and the plurality of ribs **1016** are mounted to rotor outer core **1010** to extend inward from rotor outer core **1010** toward center **1009**. Rotor core **1012** is mounted to extend inward from the plurality of rotor outer core teeth **1018** and the plurality of ribs **1016**. The plurality of ribs **1016** extend between a plurality of rotor air gaps **1014** formed between the plurality of rotor outer core teeth **1018** and the plurality of ribs **1016** in a manner similar to the rotor air gaps of second radial, spoke type, VPPM **400**.

Referring to FIG. **11**, a zoomed portion of third radial, spoke type, VPPM **1000** is shown in accordance with an illustrative embodiment. A first rotor air gap **1014***a* is formed in rotor outer core **1010** between a twelfth rotor outer core tooth **1018***j* of the plurality of rotor outer core teeth **1018** and a first rib **1016***a* of the plurality of ribs **1016** below first PM **108***a*. Each tooth of the plurality of rotor outer core teeth **1018** may be identical. Each rib of the plurality of ribs **1016** may be identical. A second rotor air gap **1014***b* is formed in rotor outer core **1010** between first rib **1016***a* of the plurality of ribs **1016** and a first rotor outer core tooth **1018***a* of the plurality of rotor outer core teeth **1018** below second PM **108***b*. First rib **1016***a* may extend radially from center **1009** centered between first rotor air gap **1014***a* and second rotor air gap **1014***b*.

First upper, left PM air gap **502***a* and first upper, right PM air gap **504***a* may be formed above first PM **108***a* with first upper rib **506***a* positioned between first upper, left PM air gap **502***a* and first upper, right PM air gap **504***a*. Second upper, left PM air gap **502***b* and second upper, right PM air gap **504***b* may be formed above second PM **108***b* with second upper rib **506***b* positioned between second upper, left PM air gap **502***b* and second upper, right PM air gap **504***b*. Identical upper air gaps may be formed around each PM of the plurality of PMs **108**.

Similar to first rotor air gap **500***a*, first rotor air gap **1014***a* may be defined by a first wall **1102***a*, a second wall **1104***a*, a third wall **1106***a*, a fourth wall **1108***a*, and a fifth wall **1110***a*. Similar to second rotor air gap **500***b*, second rotor air gap **1014***b* may be similarly defined by a first wall **1102***b*, a second wall **1104***b*, a third wall **1106***b*, a fourth wall **1108***b*, and a fifth wall **1110***b* such that second rotor air gap **1014***b* is a mirror image of first rotor air gap **1014***a* relative to first rib **1016***a*. Pairs of rotor air gaps may be defined between successive pairs of PMs of the plurality of PMs **108**. Fifth wall **1110***a* extends along an edge of first rib **1016***a* facing into first rotor air gap **1014***a*. Second wall **1104***a* extends along an edge of first PM **108***a* facing into first rotor air gap **1014***a*. First wall **1102***a* extends from an edge of first PM **108***a* to a top edge of first rib **1016***a* between an edge of second wall **1104***a* and an edge of fifth wall **1110***a*. Fourth wall **1108***b* extends from a bottom edge of first rib **1016***a* between an edge of third wall **1106***a* and a second edge of fifth wall **1110***a*. A rib width **1112** defines a width of first rib **1016***a*. a PM distance **1114** defines a distance between a corner of first PM **108***a* at an end of first wall **1102***a* and a corner of second PM **108***b* at an end of first wall **1102***b*.

Referring to FIG. **12**, first rotor air gap **1014***a* and first PM **108***a* of third radial, spoke type, VPPM **1000** are shown in accordance with an illustrative embodiment. A first angle **1200** is defined between first wall **1102***a* and fifth wall **1110***a*. A second angle **1202** is defined between second wall **1104***a* and third wall **1106***a*. A third angle **1204** is defined between third wall **1106***a* and fourth wall **1108***a*. A fourth angle **1206** is defined between fourth wall **1108***a* and fifth wall **1110***a*. A sixth angle (not labeled) between first wall **1102***a* and second wall **1104***a* is equal to 90 degrees plus second angle **700** in degrees. In the illustrative embodiment, first angle **1200** and fourth angle **1206** are equal to ninety degrees. As a result, in the illustrative embodiment, first wall **1102***a* and fourth wall **1108***a* are parallel to each other, and fifth wall **1110***a* is perpendicular to first wall **1102***a* and fourth wall **1108***a*. Fifth wall **1110***a* is parallel to a radial line **1218** that extends towards center **1009**. Third wall **1106***a* is parallel to a line **1220** that is also parallel to a surface **1222** of first PM **108***a* that forms the intersection of first wall **1102***a* and second wall **1104***a*.

A first wall length **1208** defines a length of first wall **1102***a*. A second wall length **1210** defines a length of second wall **1104***a*. A third wall length **1212** defines a length of third wall **1106***a*. A fourth wall length **1214** defines a length of fourth wall **1102***a*. A fifth wall length **1216** defines a length of fifth wall **1110***a*. Fifth wall length **1216** further defines a height of first rib **1016***a*.

Second wall length **1210** may be selected as a percentage of width **226** of first PM **108***a*. For example, illustrative percentages for second wall length **1210** may be 40% to 80% of width **226** of first PM **108***a*. Third wall length **1212** also may be selected as a percentage of width **226** of first PM **108***a*. For example, illustrative percentages for third wall length **1212** may be 40% to 80% of width **226** of first PM **108***a*. Rib width **1112** may be selected as a percentage of total rotor width **1116**. For example, illustrative percentages for rib width **1112** may be 0.3% to 2.5% of total rotor width **1116**.

Referring to FIG. **13**, a double air gap, axial VPPM **1300** is shown in accordance with an illustrative embodiment. Axial VPPM **1300** may include a stator **1302**, a first rotor **1304**, and a second rotor **1306** positioned axially adjacent each other with stator **1302** mounted between first rotor **1304** and second rotor **1306**. Though not shown, first rotor **1304** and second rotor **1306** are mounted to a shaft for rotation relative to stator **1302**. Though not visible because axial VPPM **1300** is shown straightened out for simplicity, stator **1302**, first rotor **1304**, and second rotor **1306** have generally circular cross sections.

Stator **1302** may be formed of a ferromagnetic material such as iron, cobalt, nickel, etc. As understood by a person of skill in the art, stator **1302** may be formed of laminations mounted closely together in the radial direction.

Stator **1302** may include a stator core **1306**, a first plurality of teeth **1308**, and a second plurality of teeth **1309**. The first plurality of teeth **1308** and the second plurality of teeth **1309** may be mirror images of each other relative to a center of stator core **1306** that extends lengthwise between the first plurality of teeth **1308** and the second plurality of teeth **1309**. The first plurality of teeth **1308** extend outward from stator core **1306** toward first rotor **1304** forming a first air gap between an outer surface of the first plurality of teeth **1308** and first rotor **1304**. Similar to stator **105**, a plurality of first slot walls **1310** define edges of stator slots where a slot is positioned between a pair of the first plurality of teeth **1308**.

The second plurality of teeth **1309** extend outward from stator core **1306** toward second rotor **1306** forming a second air gap between an outer surface of the second plurality of teeth **1309** and second rotor **1306**. Similar to stator **105**, a plurality of second slot walls **1319** define edges of stator slots where a slot is positioned between a pair of the second plurality of teeth **1309**. In the illustration of FIG. **13**, the first plurality of teeth **1308** of stator **1302** includes six teeth that define six stator slots though an actual number of stator slots is again S_{s1}=12 for the first plurality of teeth **1308** and the second plurality of teeth **1309**.

First rotor **1304** and second rotor **1306** may be mirror images of each other relative to the center of stator core **1306** that extends lengthwise between the first plurality of teeth **1308** and the second plurality of teeth **1309**. First rotor **1304** and second rotor **1306** may be formed of a ferromagnetic material such as iron, cobalt, nickel, etc. First rotor **1304** may include a first rotor outer core **1318**, a first rotor core **1322**, a first plurality of permanent magnets **1312**, a first plurality of rotor outer core teeth **1320**, and a first plurality of ribs **1316**. The first plurality of permanent magnets **1312** may be similar to the plurality of permanent magnets **108** and mounted radially as spokes within first rotor core **1322**. As understood by a person of skill in the art, first rotor outer core **1318**, first rotor core **1322**, the first plurality of rotor outer core teeth **1320**, and the first plurality of ribs **1316** may be formed of the same or similar materials and as laminations mounted closely together in the radial directions.

In the illustrative embodiment of FIG. **13**, the first plurality of rotor outer core teeth **1320** and the first plurality of ribs **1316** are mounted to first rotor outer core **1318** to extend inward from first rotor outer core **1318** toward stator **1302**. First rotor core **1322** is mounted to extend inward from the first plurality of rotor outer core teeth **1320** and the first plurality of ribs **1316**. The first plurality of ribs **1316** extend between a first plurality of rotor air gaps **1314** formed between the first plurality of rotor outer core teeth **1320** and the first plurality of ribs **1316** in a manner similar to the rotor air gaps of second radial, spoke type, VPPM **400** relative to the plurality of PMs **108**.

Second rotor **1305** may include a second rotor outer core **1324**, a second rotor core **1328**, a second plurality of permanent magnets **1313**, a second plurality of rotor outer core teeth **1326**, and a second plurality of ribs **1332**. The second plurality of permanent magnets **1313** may be similar to the first plurality of permanent magnets **1312** and mounted radially as spokes within second rotor core **1328**. As understood by a person of skill in the art, second rotor outer core **1324**, second rotor core **1328**, the second plurality of rotor outer core teeth **1326**, and the second plurality of ribs **1332** may be formed of the same or similar materials and as laminations mounted closely together in the axial or radial directions.

In the illustrative embodiment of FIG. **13**, the second plurality of rotor outer core teeth **1326** and the second plurality of ribs **1332** are mounted to second rotor outer core **1324** to extend inward from second rotor outer core **1324** toward stator **1302**. Second rotor core **1328** is mounted to extend inward from the second plurality of rotor outer core teeth **1326** and the second plurality of ribs **1332**. The second plurality of ribs **1332** extend between a second plurality of rotor air gaps **1330** formed between the second plurality of rotor outer core teeth **1326** and the second plurality of ribs **1332** in a manner similar to the rotor air gaps of second radial, spoke type, VPPM **400** relative to the plurality of PMs **108**.

Referring to FIG. **14**, a zoomed portion of axial VPPM **1300** is shown in accordance with an illustrative embodiment. A first rotor air gap **1330***a* is formed in second rotor outer core **1324** between a first rotor outer core tooth **1326***a* of the second plurality of rotor outer core teeth **1326** and a first rib **1332***a* of the second plurality of ribs **1332** adjacent first PM **1313***a* of the second plurality of permanent magnets **1313**. Each tooth of the first plurality of rotor outer core teeth **1320** and the second plurality of rotor outer core teeth **1326** may be identical. Each rib of first plurality of ribs **1316** and the second plurality of ribs **1332** may be identical. A second rotor air gap **1330***b* is formed in second rotor outer core **1324** between first rib **1332***a* of the second plurality of ribs **1332** and a second rotor outer core tooth **1326***b* of the plurality of second plurality of rotor outer core teeth **1326** adjacent second PM **1313***b*. First rib **1332***a* may extend toward the center of stator core **1306** that extends lengthwise between the first plurality of teeth **1308** and the second plurality of teeth **1309**. First rib **1332***a* is centered between first rotor air gap **1330***a* and second rotor air gap **1330***b*. Each pair of rotor air gaps of the first plurality of rotor air gaps **1314** and of the second plurality of rotor air gaps **1330** may be identical.

First upper, left PM air gap **502***a* and first upper, right PM air gap **504***a* may be formed between first PM **108***a* and the second plurality of teeth **1309** with first upper rib **506***a* positioned between first upper, left PM air gap **502***a* and first upper, right PM air gap **504***a*. Second upper, left PM air gap **502***b* and second upper, right PM air gap **504***b* may be formed between second PM **108***b* and the second plurality of teeth **1309** with second upper rib **506***b* positioned between second upper, left PM air gap **502***b* and second upper, right PM air gap **504***b*. Identical upper air gaps may be formed around each PM of the first plurality of permanent magnets **1312** and of the second plurality of permanent magnets **1313**. Rotor width **1400** defines a width of first rotor **1304** and of second rotor **1305**.

Referring to FIG. **15**, a zoomed portion of a pair of rotor air gaps of axial VPPM **1300** are shown in accordance with an illustrative embodiment. Similar to first rotor air gap **500***a*, a first rotor air gap **1330***a* may be defined by a first wall **1502***a*, a second wall **1504***a*, a third wall **1506***a*, a fourth wall **1508***a*, and a fifth wall **1510***a*. Similar to second rotor air gap **500***b*, a second rotor air gap **1330***b* may be similarly defined by a first wall **1502***b*, a second wall **1504***b*, a third wall **1506***b*, a fourth wall **1508***b*, and a fifth wall **1510***b* such that second rotor air gap **1330***b* is a mirror image of first rotor air gap **1330***a* relative to first rib **1332***a*. Identical pairs of rotor air gaps may be defined between successive pairs of PMs of the first plurality of permanent magnets **1312** and of the second plurality of permanent magnets **1313**. Fifth wall **1510***a* extends along an edge of first rib **1332***a* facing into first rotor air gap **1330***a*. Second wall **1504***a* extends along an edge of first PM **1313***a* facing into first rotor air gap **1330***a*. First wall **1502***a* extends from an edge of first PM **1313***a* to a top edge of first rib **1332***a* between an edge of second wall **1504***a* and an edge of fifth wall **1510***a*. Fourth wall **1508***b* extends from a bottom edge of first rib **1332***a* between an edge of third wall **1506***a* and a second edge of fifth wall **1510***a*. A rib width **1520** defines a width of first rib **1332***a*.

A first wall length **1511** defines a length of first wall **1502***a*. A second wall length **1512** defines a length of second wall **1504***a*. A third wall length **1514** defines a length of third wall **1506***a*. A fourth wall length **1516** defines a length of fourth wall **1502***a*. A fifth wall length **1518** defines a length of fifth wall **1510***a*. Fifth wall length **1518** further defines a height of first rib **1332***a*.

Referring to FIG. **16**, first rotor air gap **1330***a* and first PM **1313***a* of axial VPPM **1300** are shown in accordance with an illustrative embodiment. A first angle **1600** is defined between first wall **1502***a* and fifth wall **1510***a*. A second angle **1602** is defined between second wall **1504***a* and third wall **1506***a*. A third angle **1604** is defined between third wall **1506***a* and fourth wall **1508***a*. A fourth angle **1606** is defined between fourth wall **1508***a* and fifth wall **1510***a*. A sixth angle **1608** is defined between first wall **1502***a* and second wall **1504***a*. In the illustrative embodiment, second angle

1602, third angle **1604**, and fourth angle **1606** are equal to ninety degrees. Sixth angle **1608** equals 270 degrees minus first angle **1600**. As a result, in the illustrative embodiment, second wall **1502***a* and fourth wall **1508***a* are parallel to each other, and third wall **1506***a* and fifth wall **1110***a* are parallel to each other. Fifth wall **1510***a* is perpendicular to fourth wall **1108***a*, and third wall **1506***a* is perpendicular to second wall **1502***a* and fourth wall **1508***a*. First wall **1502***a* connects second wall **1504***a* and fifth wall **1510***a*.

Second wall length **1512** may be selected as a percentage of width **226** of first PM **1332***a*. For example, illustrative percentages for second wall length **1512** may be 40% to 80% of width **226** of first PM **1332***a*. Third wall length **1514** also may be selected as a percentage of width **226** of first PM **1332***a*. For example, illustrative percentages for third wall length **1514** may be 40% to 80% of width **226** of first PM **1332***a*. Rib width **1520** may be selected as a percentage of a radius to an inner surface of first rotor **1304** and second rotor **1305**. For example, illustrative percentages for rib width **1520** may be 0.3% to 2.5% of the inner radius.

Though second radial, spoke type, VPPM **400**, third radial, spoke type, VPPM **1000**, and axial VPPM **1300** have been described as Vernier machines the plurality of rotor air gaps **500**, the plurality of rotor air gaps **1014**, the first plurality of rotor air gaps **1314**, and the second plurality of rotor air gaps **1330** could be implemented in a similar manner in electric machines that are not implemented as Vernier machines based on the number of stator pole pairs and the number of rotor pole pairs.

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 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. A rotor comprising:

a first rotor core;

a plurality of ribs that each extend from the first rotor core;

a plurality of rotor core teeth that each extend from the first rotor core, wherein a plurality of rotor air gaps are formed in the first rotor core between a rib of the plurality of ribs and a tooth of the plurality of rotor core teeth;

a second rotor core that extends from the plurality of ribs, from the plurality of rotor core teeth, and from a first wall of each rotor air gap of the plurality of rotor air gaps; and

a plurality of permanent magnets mounted as spokes in pole pairs within the second rotor core, wherein each permanent magnet of the plurality of permanent magnets is included in only one pole pair of the pole pairs, wherein each pole pair of the pole pairs includes two adjacent permanent magnets of the plurality of permanent magnets;

wherein a second wall of each rotor air gap of the plurality of rotor air gaps borders a portion of an edge of a permanent magnet of the plurality of permanent magnets, wherein a length of the portion of the edge is greater than 40% and less than 80% of a length of the edge, wherein only one rotor air gap borders each permanent magnet of the plurality of permanent magnets,

wherein a third wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a tooth of the plurality of rotor core teeth,

wherein a fourth wall of each rotor air gap of the plurality of rotor air gaps is formed by the first rotor core,

wherein a fifth wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a rib of the plurality of ribs,

wherein the first wall is connected between the second wall and the fifth wall, wherein the third wall is connected between the second wall and the fourth wall, wherein the fourth wall is connected between the third wall and the fifth wall,

wherein each pole pair of permanent magnets of the plurality of permanent magnets has an associated pair of rotor air gaps of the plurality of rotor air gaps, wherein a first rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps is a mirror image of a second rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps, wherein each pair of rotor air gaps of the plurality of rotor air gaps is separated by an associated rib of the plurality of ribs.

2. The rotor of claim **1**, wherein the second wall is formed of a first material, wherein the first material has a permeability approximately equal to air.

3. The rotor of claim **1**, wherein the first rotor core and the second rotor core have a circular cross section, and the first rotor core is radially interior of the second rotor core.

4. The rotor of claim **1**, wherein the first rotor core and the second rotor core have a circular cross section, and the second rotor core is radially interior of the first rotor core.

5. The rotor of claim **1**, wherein the first rotor core and the second rotor core have a circular cross section, wherein a first inner radius of the first rotor core is equal to a second inner radius of the second rotor core, wherein the first rotor core is mounted in an axial direction relative to the second rotor core.

6. A rotor comprising:

a first rotor core;

a plurality of ribs that each extend from the first rotor core;

a plurality of rotor core teeth that each extend from the first rotor core, wherein a plurality of rotor air gaps are formed in the first rotor core between a rib of the plurality of ribs and a tooth of the plurality of rotor core teeth;

a second rotor core that extends from the plurality of ribs, from the plurality of rotor core teeth, and from a first wall of each rotor air gap of the plurality of rotor air gaps; and

a plurality of permanent magnets mounted as spokes in pole pairs within the second rotor core, wherein each permanent magnet of the plurality of permanent magnets is included in only one pole pair of the pole pairs, wherein each pole pair of the pole pairs includes two adjacent permanent magnets of the plurality of permanent magnets;

wherein a second wall of each rotor air gap of the plurality of rotor air gaps borders an edge of a permanent magnet of the plurality of permanent magnets, wherein a length of the second wall is greater than 40% and less than 80% of a length of the edge, wherein only one rotor air gap borders each permanent magnet of the plurality of permanent magnets,

wherein a third wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a tooth of the plurality of rotor core teeth,

wherein a fourth wall of each rotor air gap of the plurality of rotor air gaps is formed by the first rotor core,

wherein a fifth wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a rib of the plurality of ribs,

wherein the first wall is connected between the second wall and the fifth wall, wherein the third wall is connected between the second wall and the fourth wall, wherein the fourth wall is connected between the third wall and the fifth wall,

wherein each pole pair of permanent magnets of the plurality of permanent magnets has an associated pair of rotor air gaps of the plurality of rotor air gaps, wherein a first rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps is a mirror image of a second rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps, wherein each pair of rotor air gaps of the plurality of rotor air gaps is separated by an associated rib of the plurality of ribs.

7. The rotor of claim **6**, wherein each rotor air gap of the plurality of rotor air gaps is filled with a first material that has a permeability approximately equal to air.

8. The rotor of claim **6**, wherein each rotor air gap of the plurality of rotor air gaps is filled with air.

9. The rotor of claim **6**, wherein the first rotor core, the plurality of ribs, the plurality of rotor core teeth, and the second rotor core are formed of a continuous piece of ferromagnetic material.

10. The rotor of claim **6**, wherein the permanent magnet of the plurality of permanent magnets has a rectangular shape, wherein the third wall is parallel to a side wall of the permanent magnet of the plurality of permanent magnets to which it is associated, wherein the side wall does not include the edge of the permanent magnet.

11. The rotor of claim **6**, wherein the first rotor core and the second rotor core have a circular cross section, wherein the fifth wall is parallel to a radial line to a center of the circular cross section.

12. The rotor of claim **6**, wherein the first rotor core and the second rotor core have a circular cross section, wherein a first inner radius of the first rotor core is equal to a second inner radius of the second rotor core, wherein the first rotor core is mounted in an axial direction relative to the second rotor core, wherein the third wall and the fifth wall are parallel to each other, wherein the second wall and the fourth wall are parallel to each other.

13. The rotor of claim **6**, wherein at least three angles formed between adjacent walls of the first wall, the second wall, the third wall, the fourth wall, and the fifth wall are approximately ninety degrees.

14. The rotor of claim **6**, wherein each associated rib is centered between the first wall of the first rotor air gap and the first wall of the second rotor air gap.

15. The rotor of claim **6**, wherein a length of the fifth wall is less than a length of the third wall.

16. The rotor of claim **6**, wherein a length of the third wall is between 20% and 40% of the length of the edge.

17. The rotor of claim **6**, wherein the first rotor core and the second rotor core have a circular cross section, wherein a width of each rib measured perpendicular to the fifth wall is between 0.3% and 2.5% of a radial length of an inner radius of the rotor.

18. An electric machine comprising:

a rotor comprising

a first rotor core;

a plurality of ribs that each extend from the first rotor core;

a plurality of rotor core teeth that each extend from the first rotor core, wherein a plurality of rotor air gaps are formed in the first rotor core between a rib of the plurality of ribs and a tooth of the plurality of rotor core teeth; and

a second rotor core that extends from the plurality of ribs, from the plurality of rotor core teeth, and from a first wall of each rotor air gap of the plurality of rotor air gaps;

a plurality of permanent magnets mounted as spokes in pole pairs within the rotor, wherein each permanent magnet of the plurality of permanent magnets is included in only one pole pair of the pole pairs, wherein each pole pair of the pole pairs includes two adjacent permanent magnets of the plurality of permanent magnets;

a stator comprising a plurality of slots and a plurality of teeth, wherein a slot of the plurality of slots is positioned between a pair of the plurality of teeth, and further wherein the stator is mounted on a first side of the rotor separated by an air gap between a surface of the second rotor core and a tooth of the plurality of teeth; and

a stator winding wound about the stator to form a number of poles between a set of terminals;

wherein a second wall of each rotor air gap of the plurality of rotor air gaps borders a portion of an edge of a permanent magnet of the plurality of permanent magnets, wherein a length of the portion of the edge is greater than 40% and less than 80% of a length of the edge, wherein only one rotor air gap borders each permanent magnet of the plurality of permanent magnets,

wherein a third wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a tooth of the plurality of rotor core teeth,

wherein a fourth wall of each rotor air gap of the plurality of rotor air gaps is formed by the first rotor core,

wherein a fifth wall of each rotor air gap of the plurality of rotor air gaps is formed by a first side of a rib of the plurality of ribs,

wherein the first wall is connected between the second wall and the fifth wall, wherein the third wall is connected between the second wall and the fourth wall, wherein the fourth wall is connected between the third wall and the fifth wall,

wherein each pole pair of permanent magnets of the plurality of permanent magnets has an associated pair of rotor air gaps of the plurality of rotor air gaps, wherein a first rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps is a mirror image of a second rotor air gap of each pair of rotor air gaps of the plurality of rotor air gaps, wherein each pair of rotor air gaps of the plurality of rotor air gaps is separated by an associated rib of the plurality of ribs.

19. The electric machine of claim **18**, wherein a number of the pole pairs of the rotor is greater than the number of poles of the stator winding.

20. The electric machine of claim **18**, wherein the stator winding is a concentrated winding.

* * * * *