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(54) **INTEGRATED ROTOR FOR AN
ELECTRICAL MACHINE AND
COMPRESSOR**

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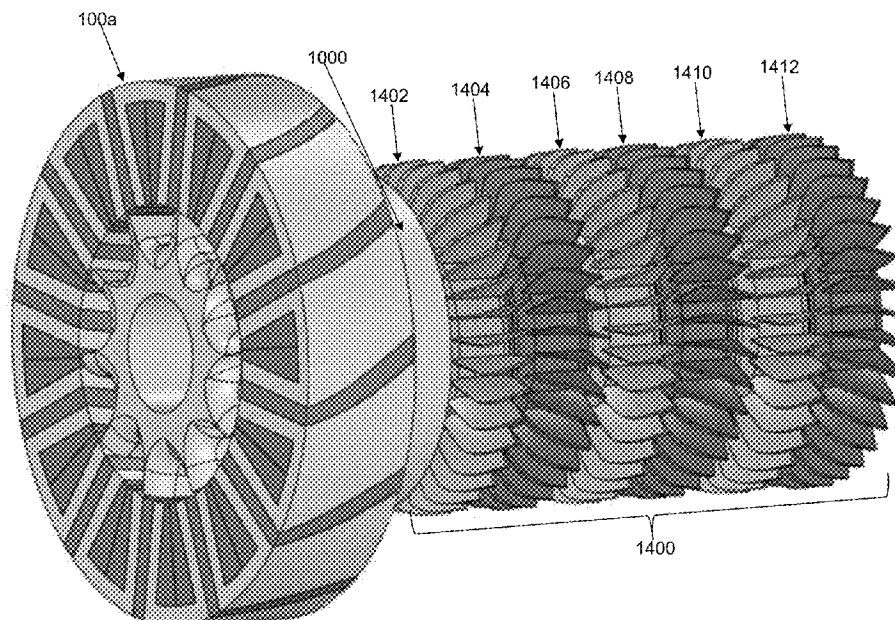
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(57) **ABSTRACT**

An electric machine includes a rotor, a stator, and a winding.
The rotor includes a rotor core and blades extending from
the rotor core. Each blade is curved in an axial direction
along the rotor core and is simultaneously configured as a
pole that carries a magnetic flux of the electrical machine
and as an airfoil that compresses a gas when the rotor is
rotated. The gas flows axially between successive blades of
the blades. The stator includes a stator core and teeth
extending from the stator core toward the blades. Slots are
defined between successive teeth. The winding is wound
through at least two slots. The stator is mounted radially

(Continued)



relative to the rotor so that a gap separates the blades from an exterior face of the teeth that is axially aligned along the stator core to follow an axial edge of a blade of the blades.

20 Claims, 18 Drawing Sheets

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H02K 7/18 (2006.01)
H02K 1/24 (2006.01)
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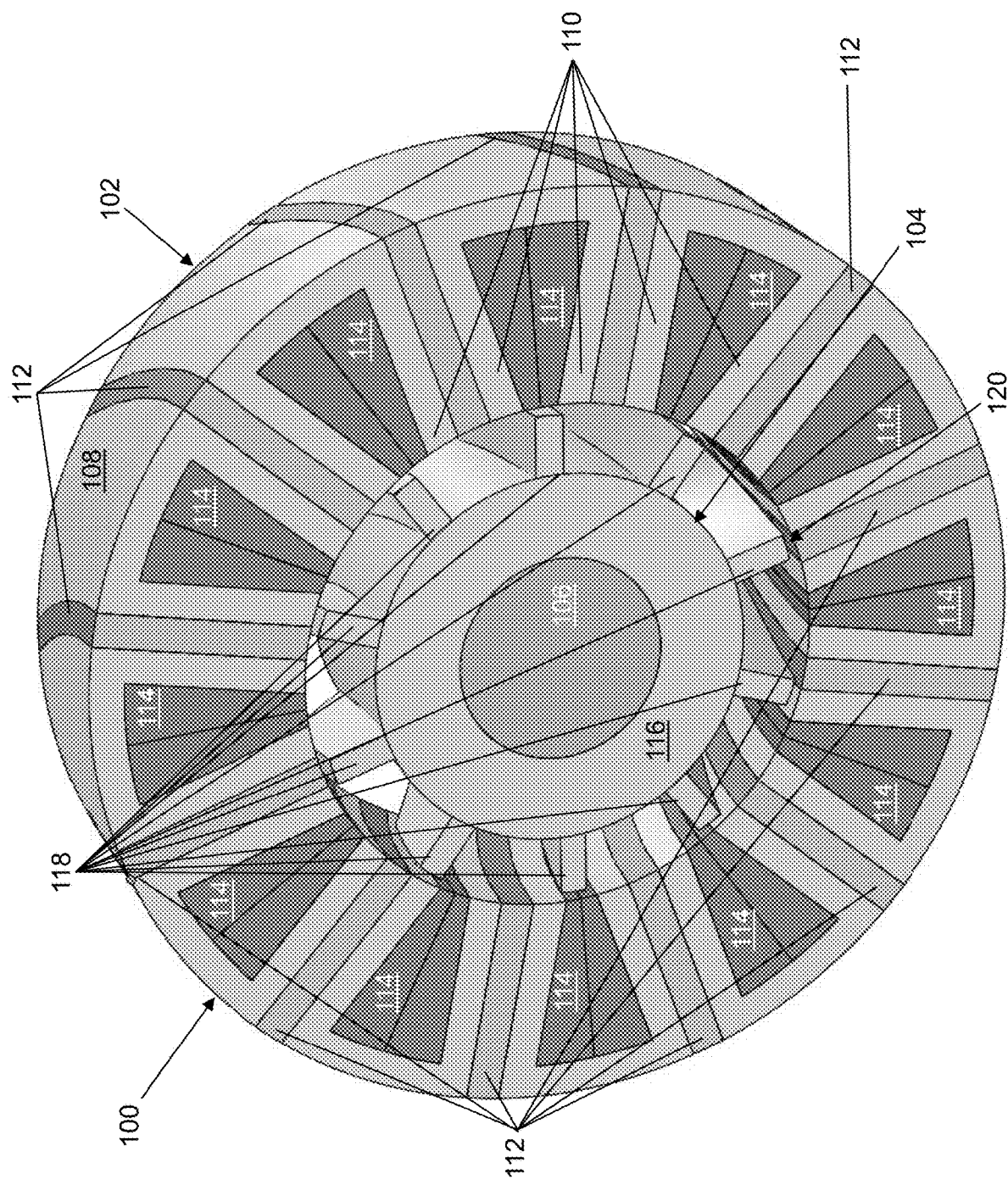
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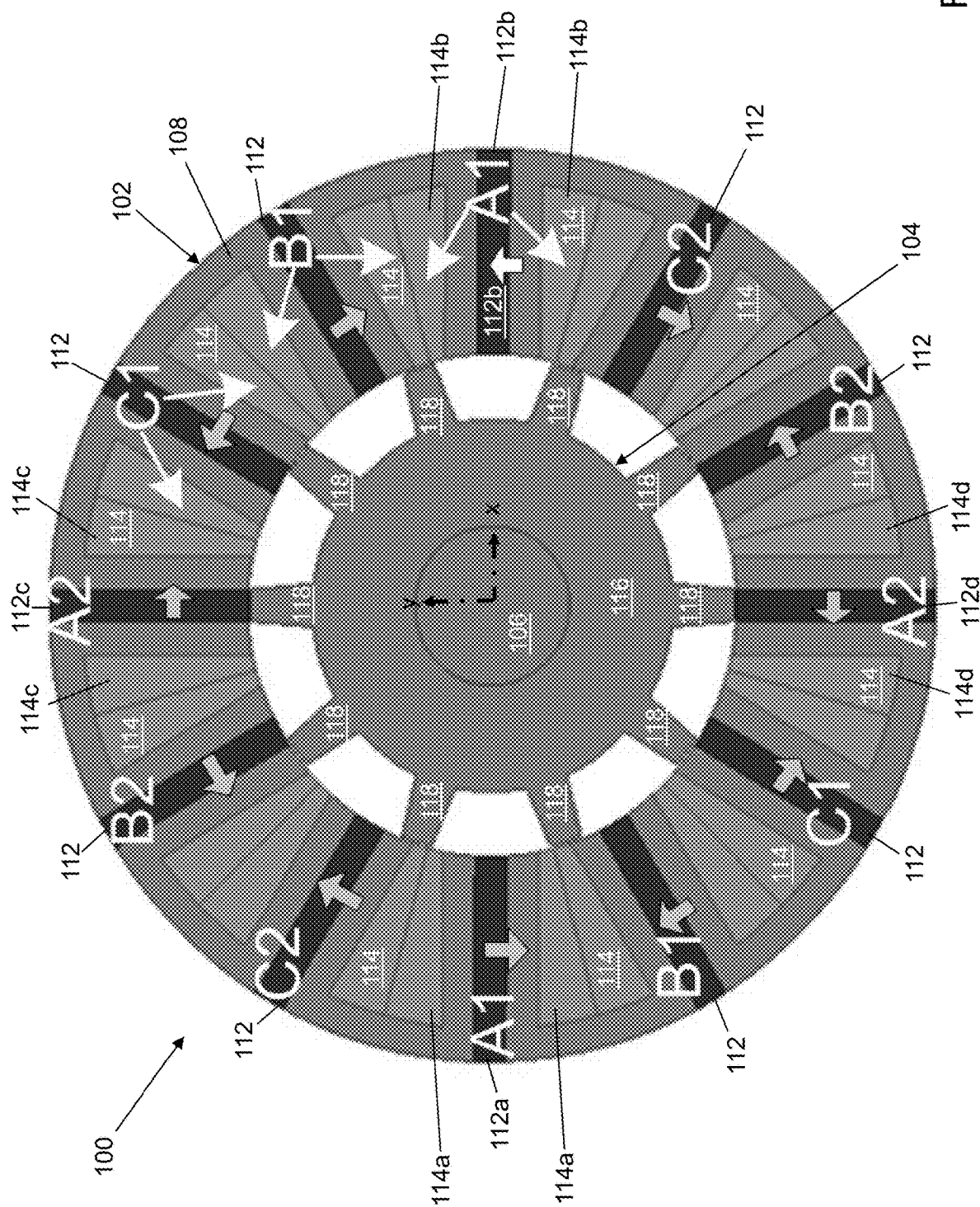


Fig. 2

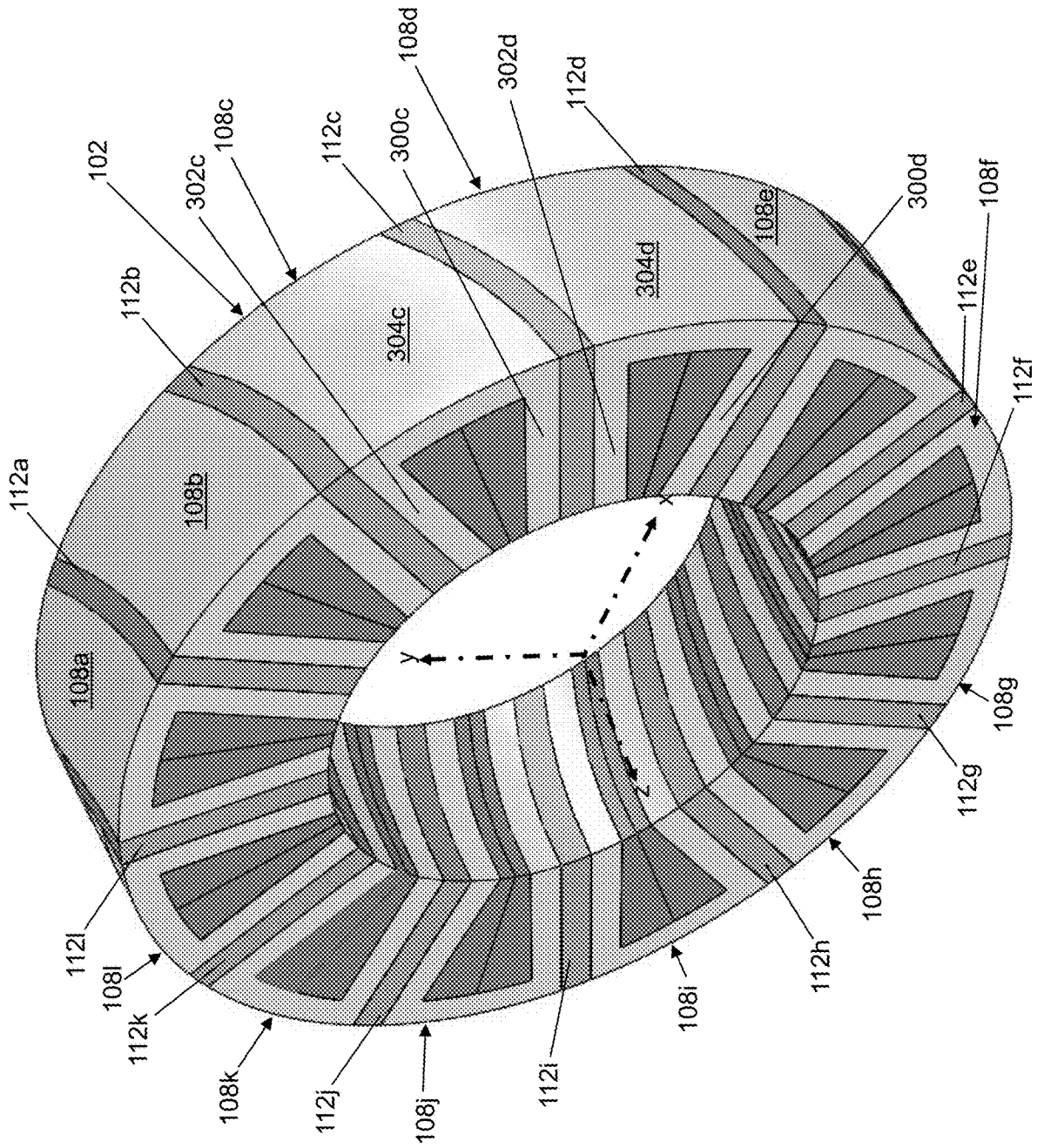


Fig. 3

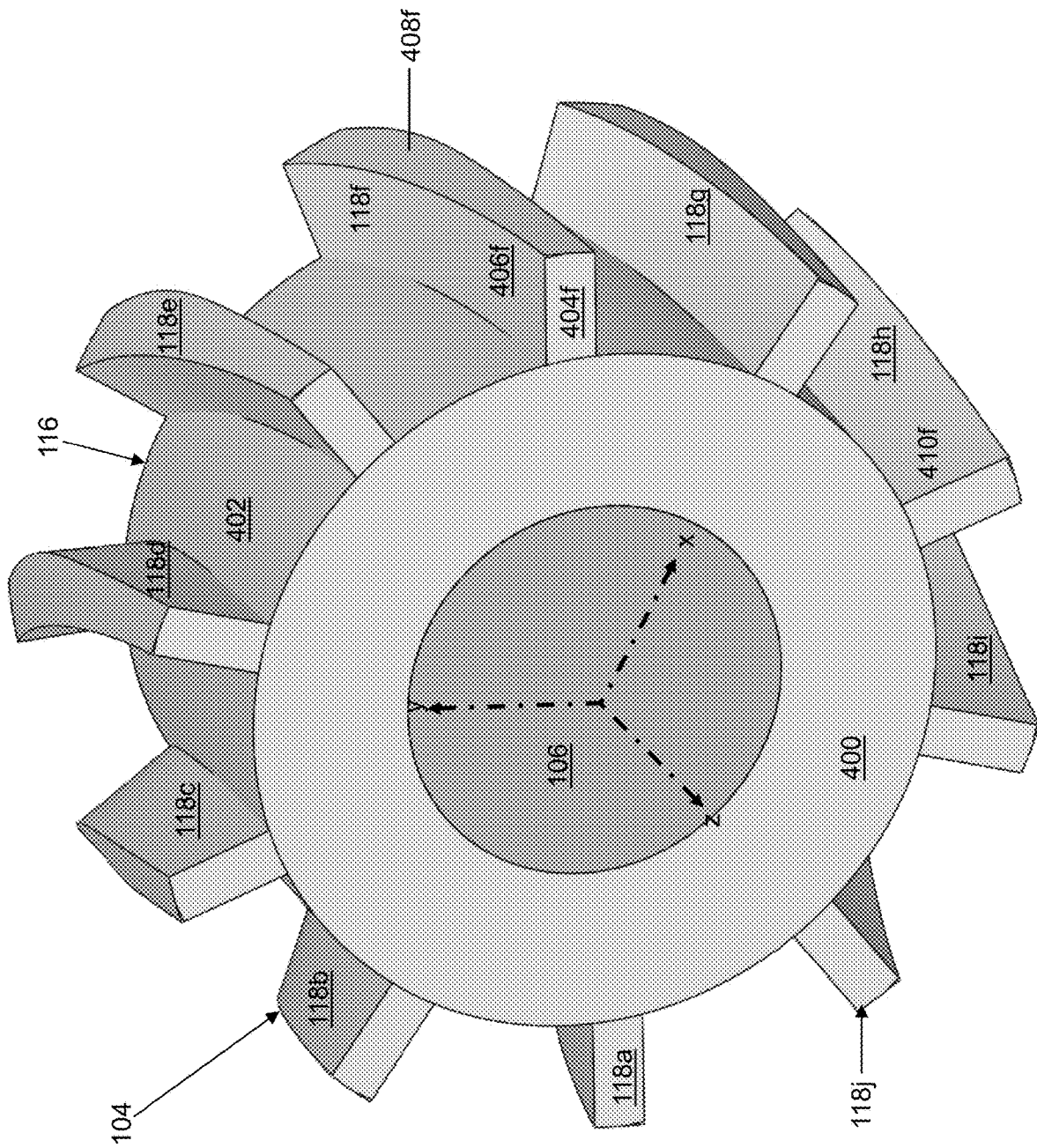


Fig. 4

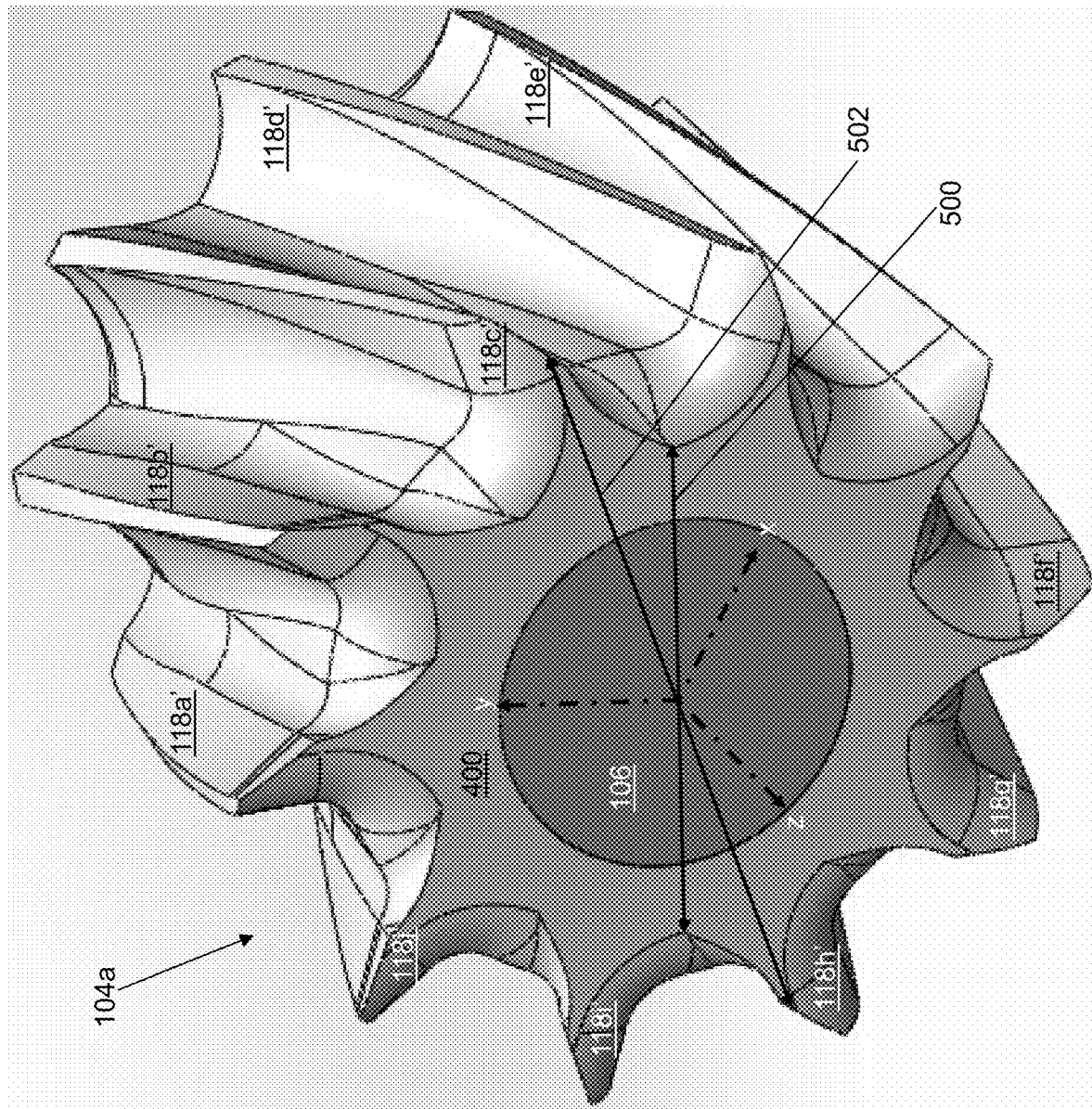


Fig. 5

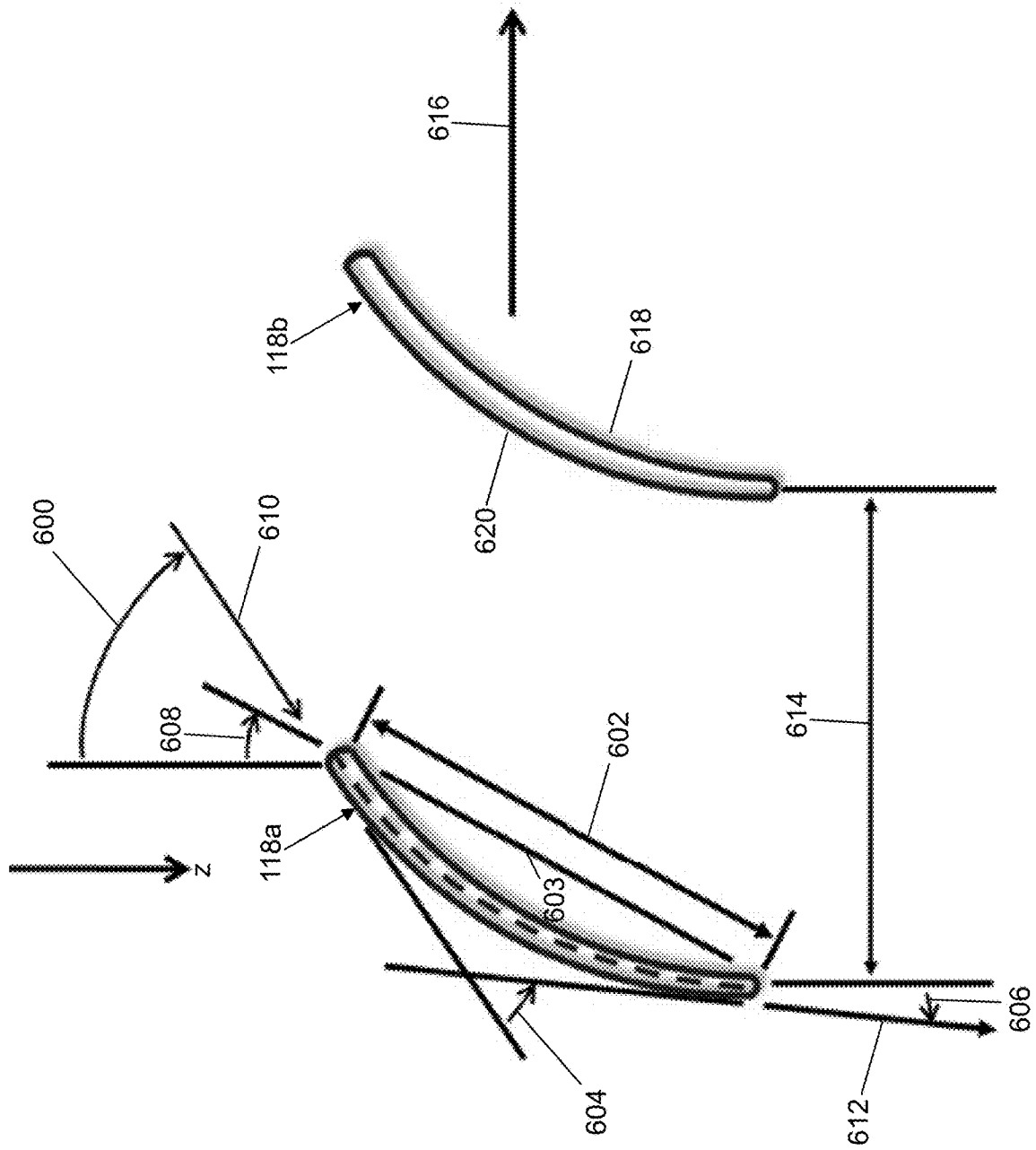


Fig. 6

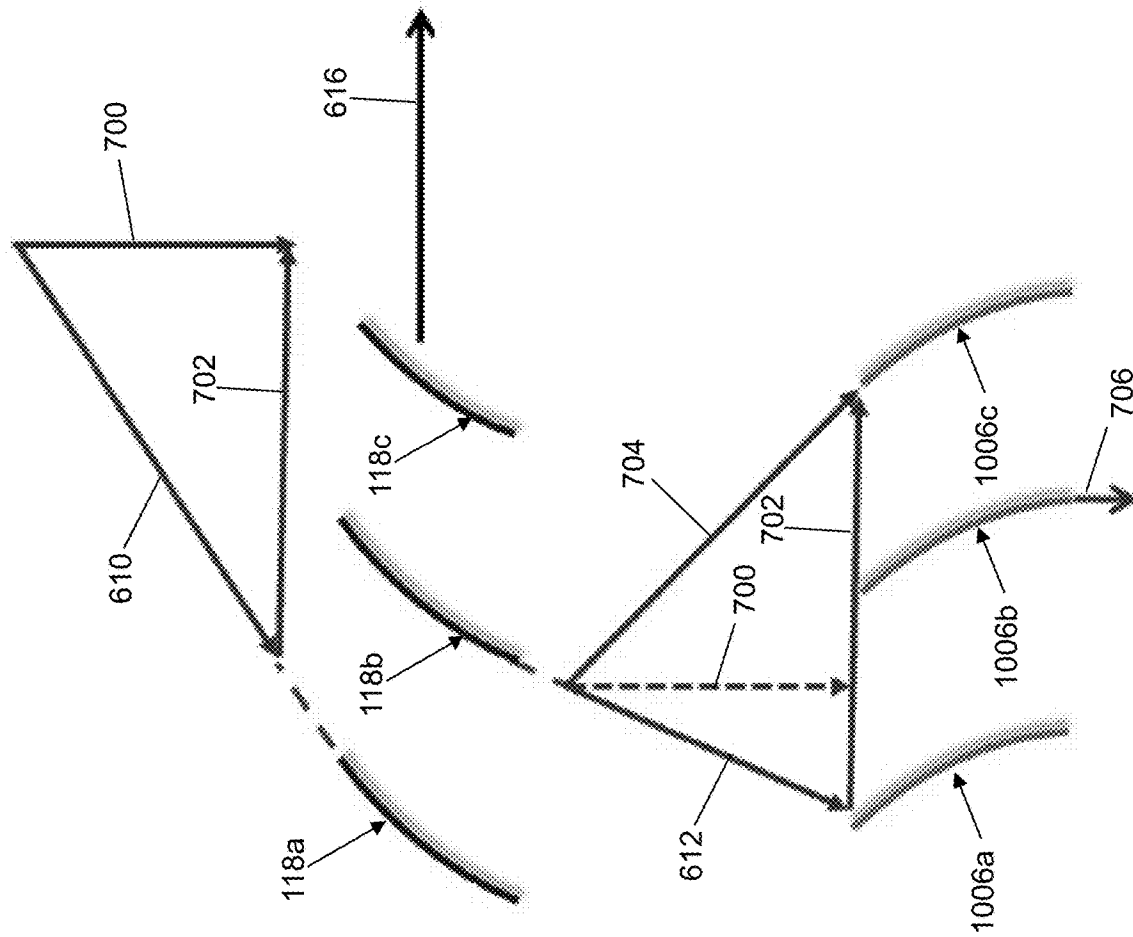


Fig. 7

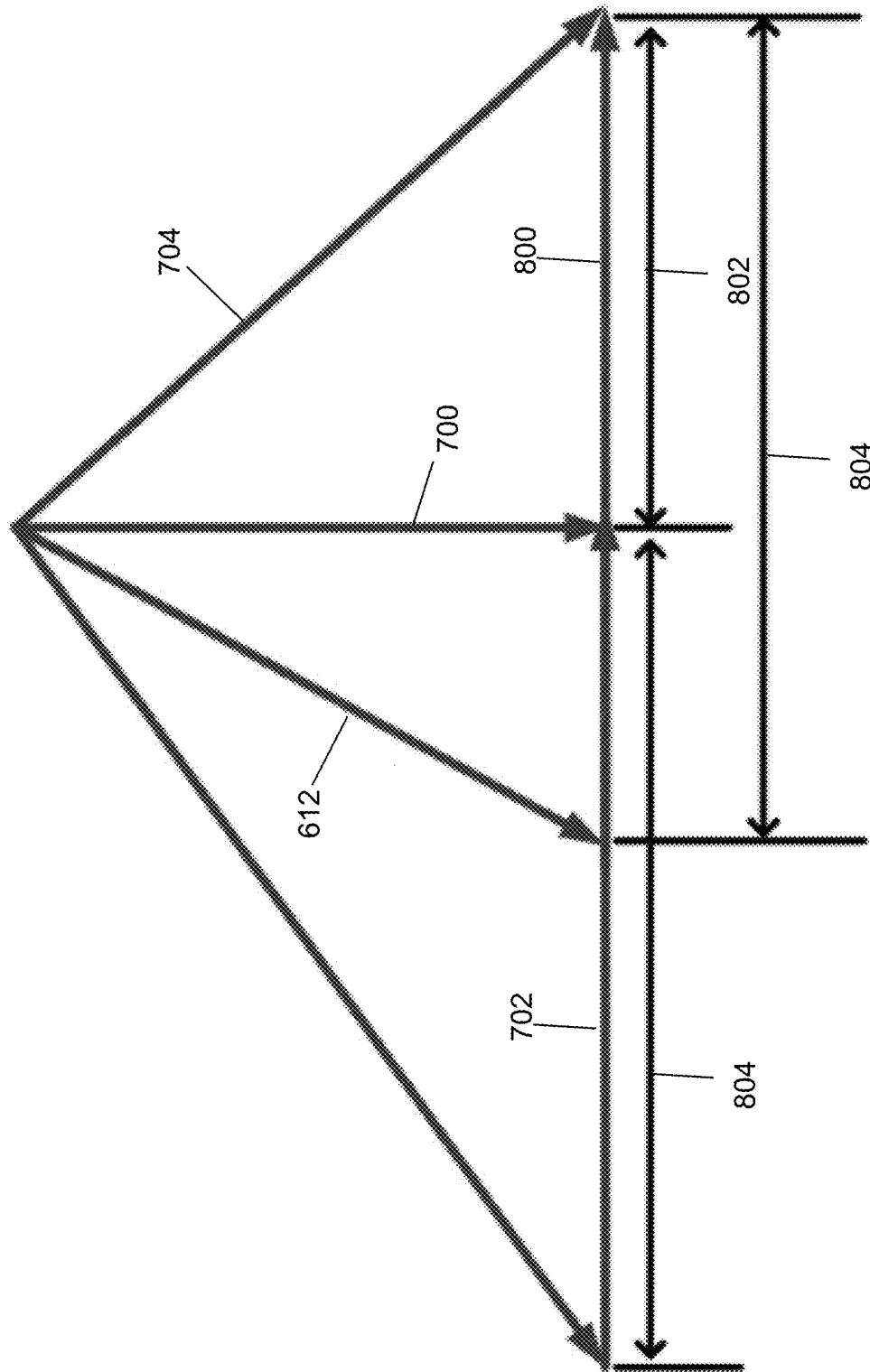


Fig. 8

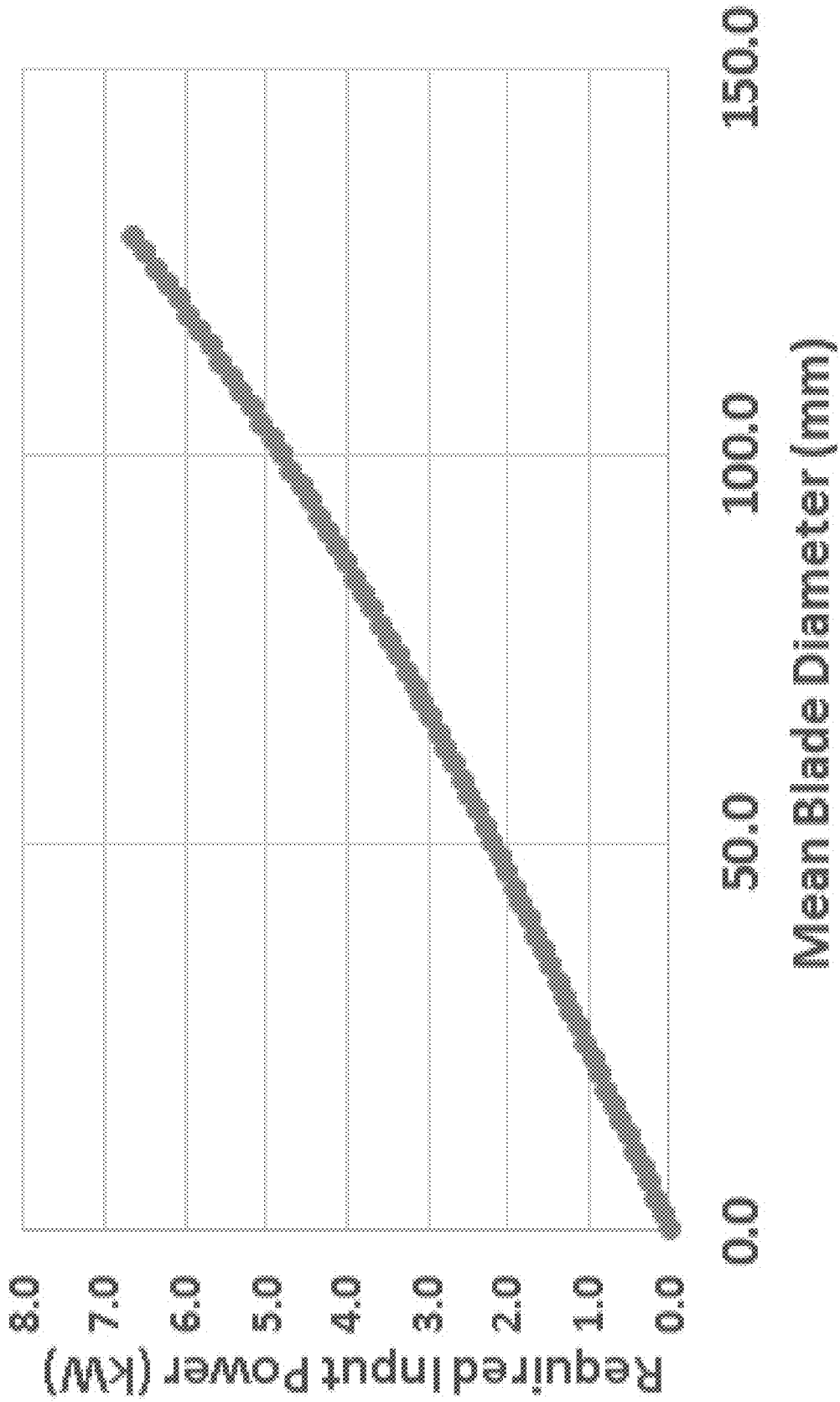


Fig. 9

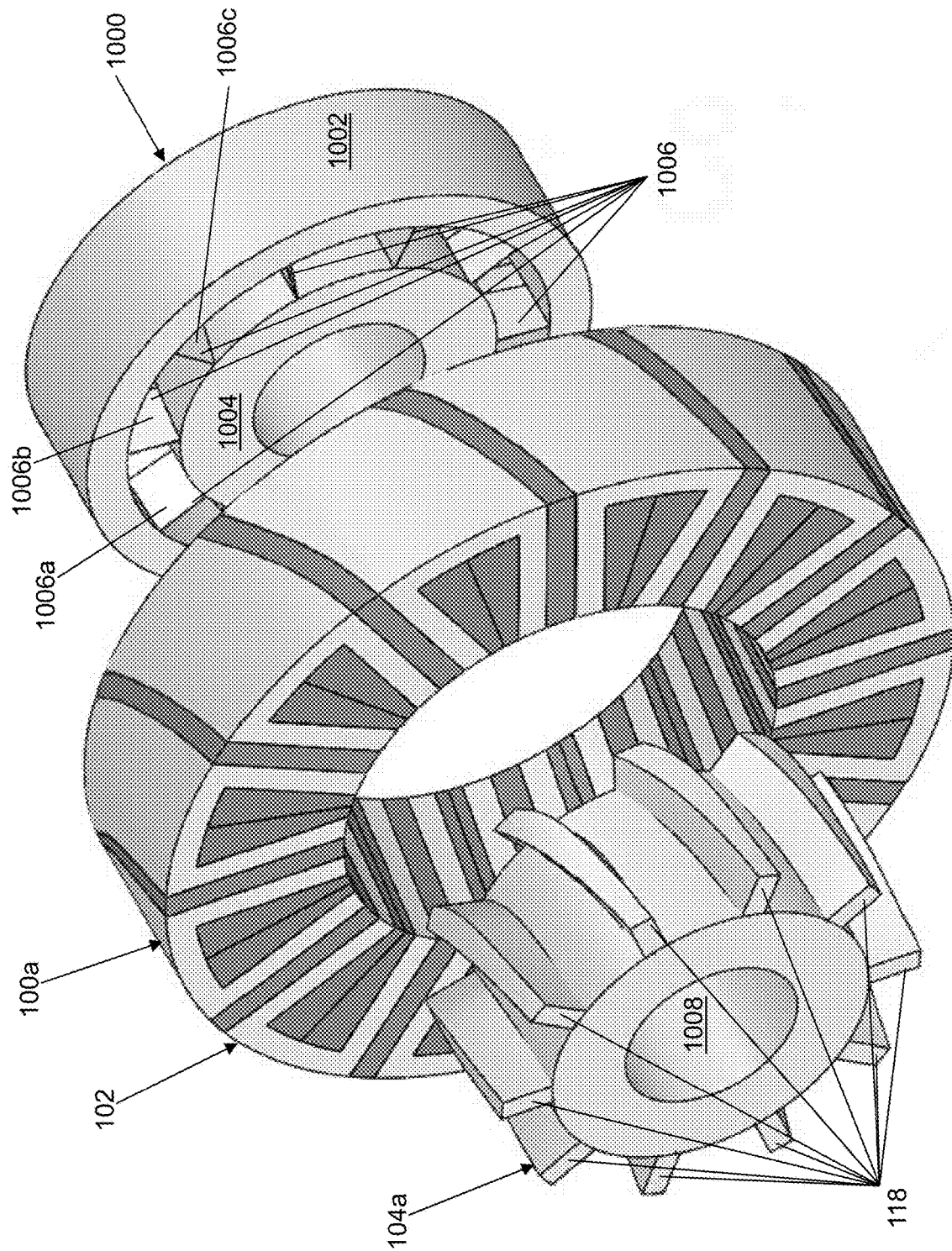


Fig. 10

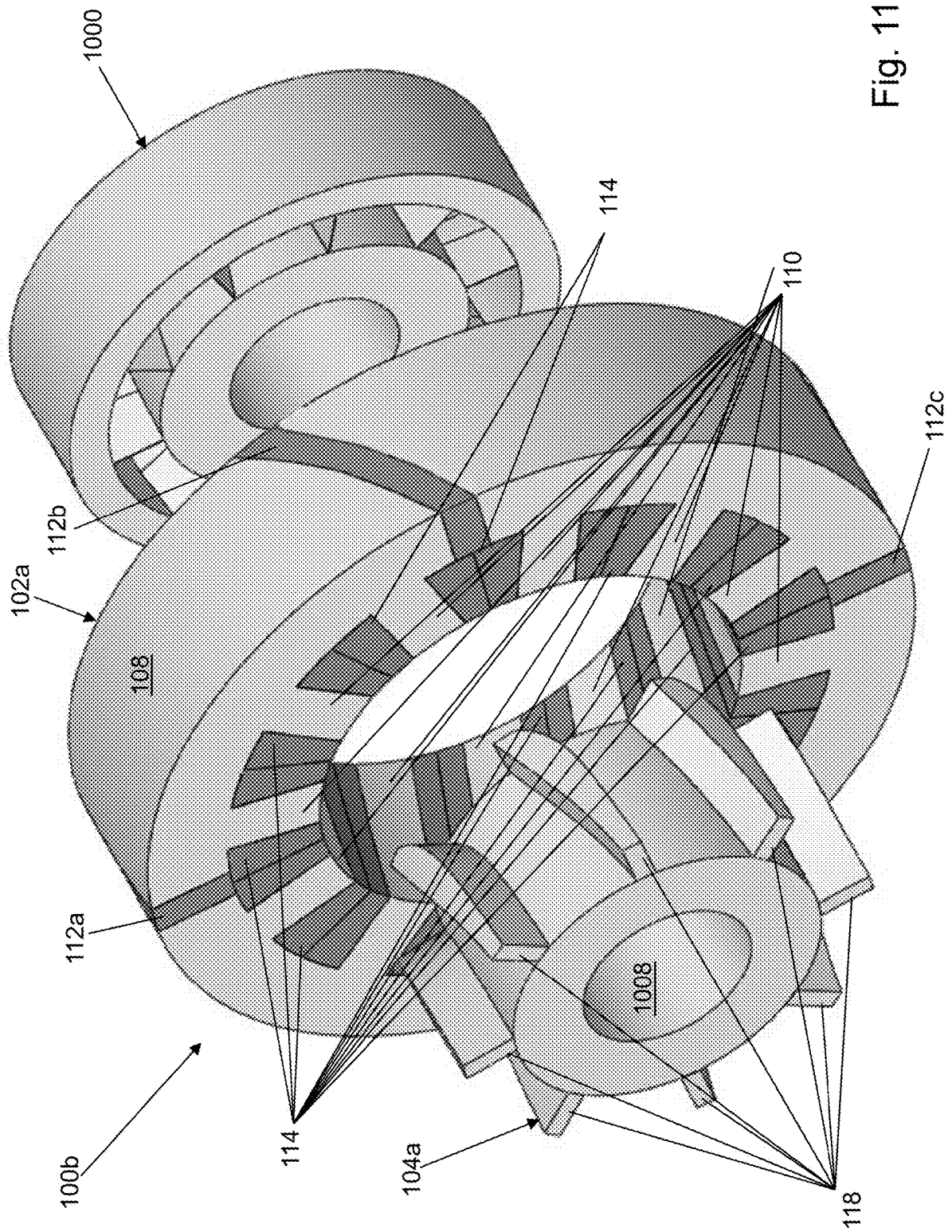


Fig. 11

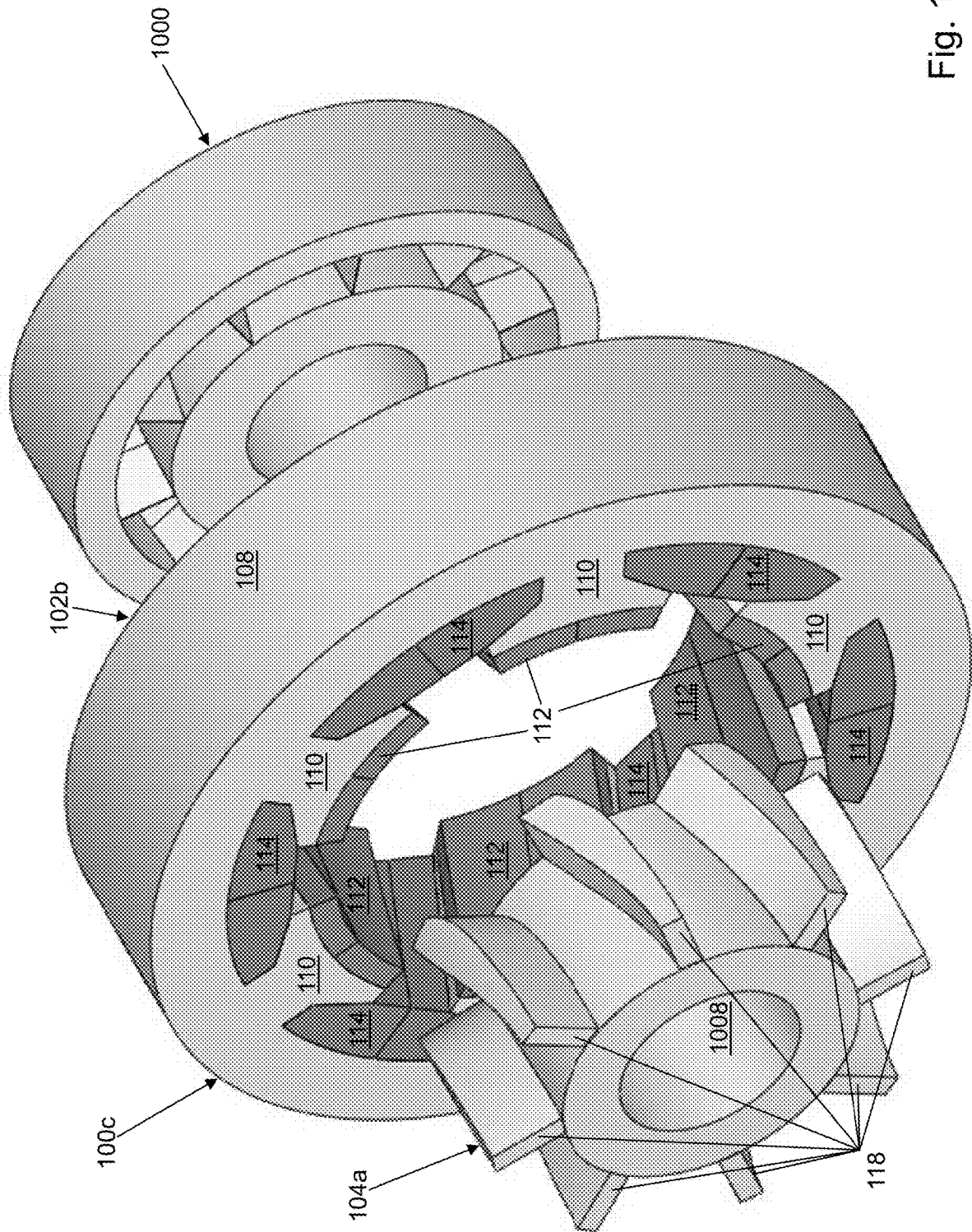


Fig. 12

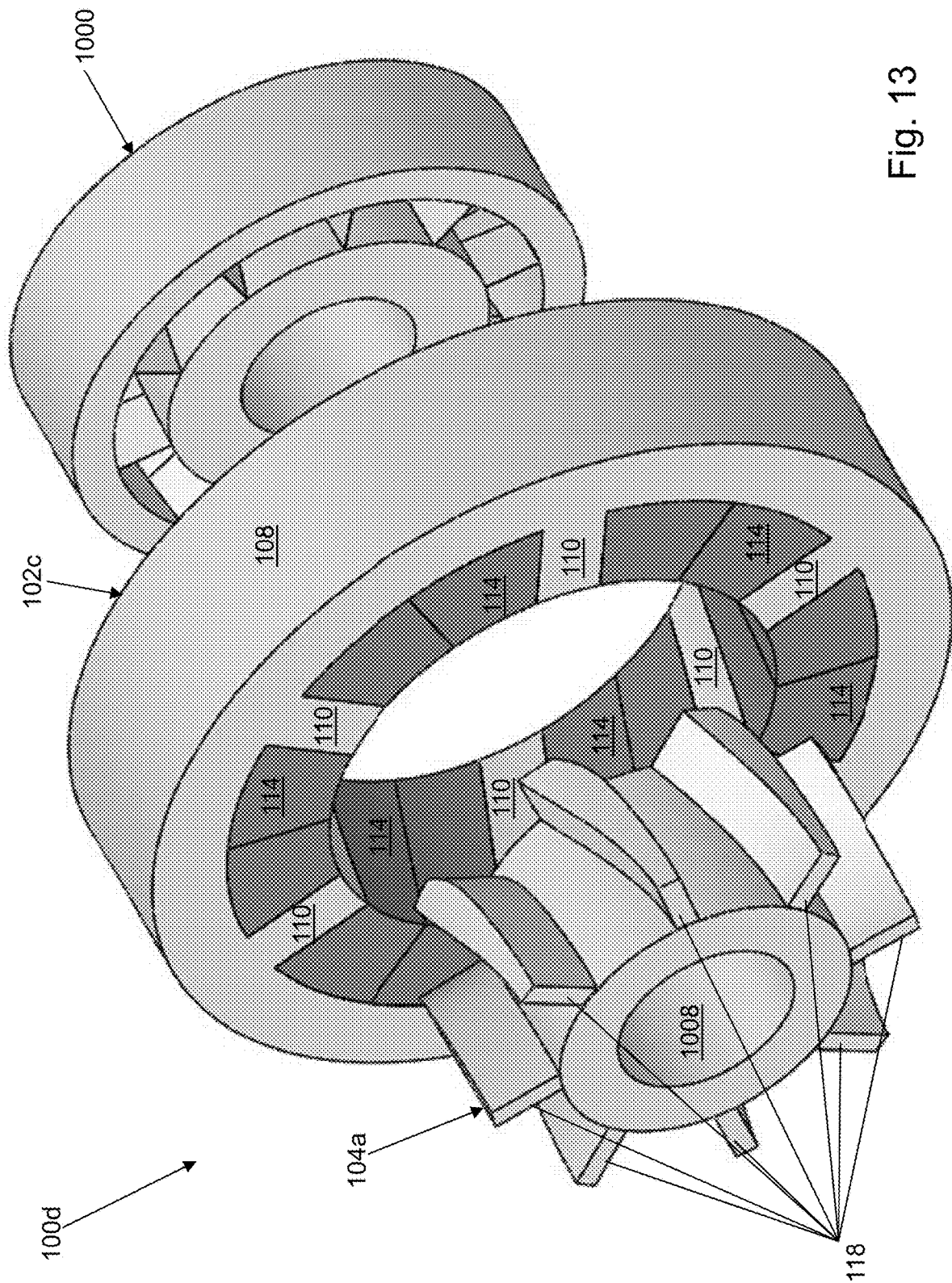


Fig. 13

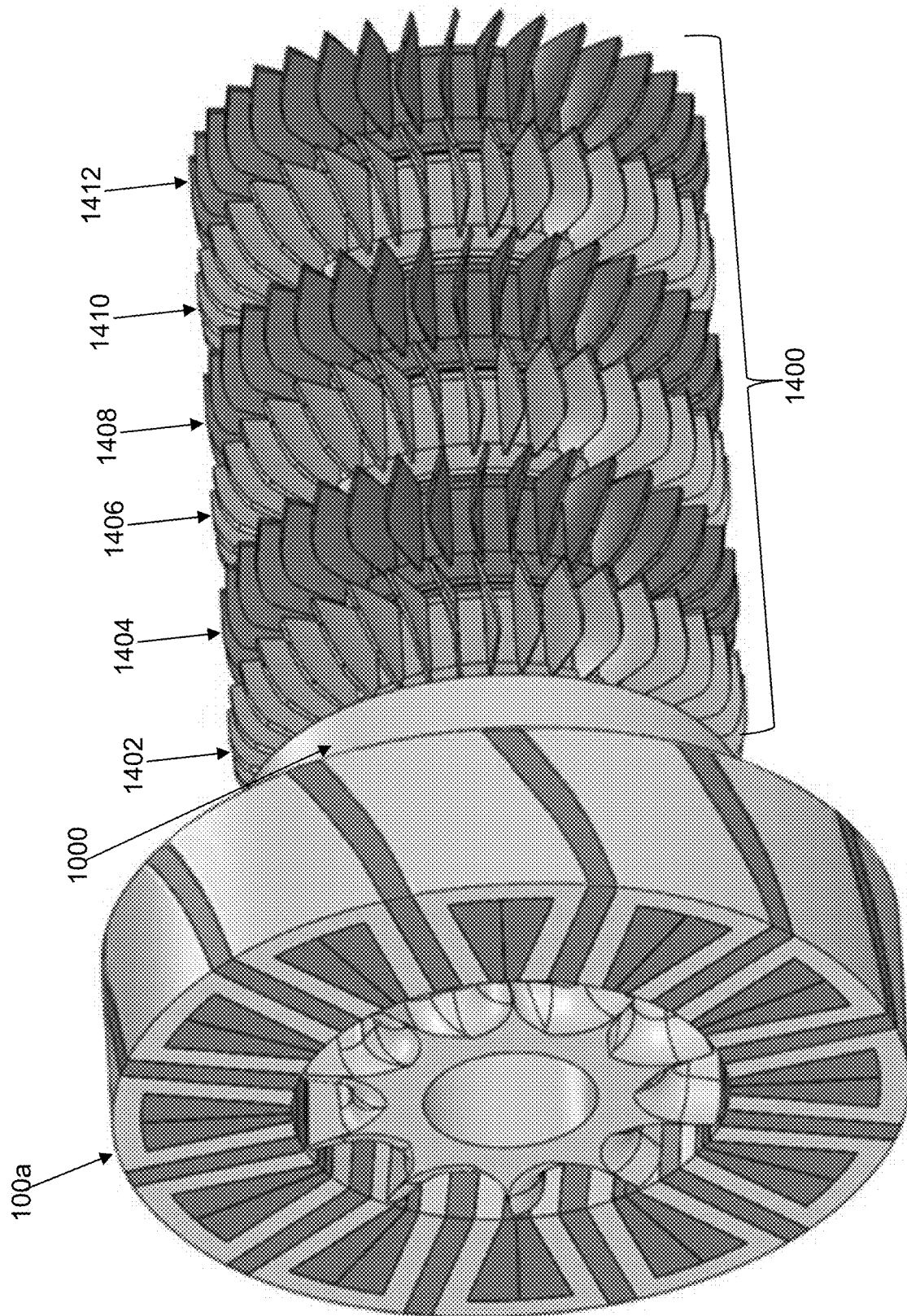


Fig. 14

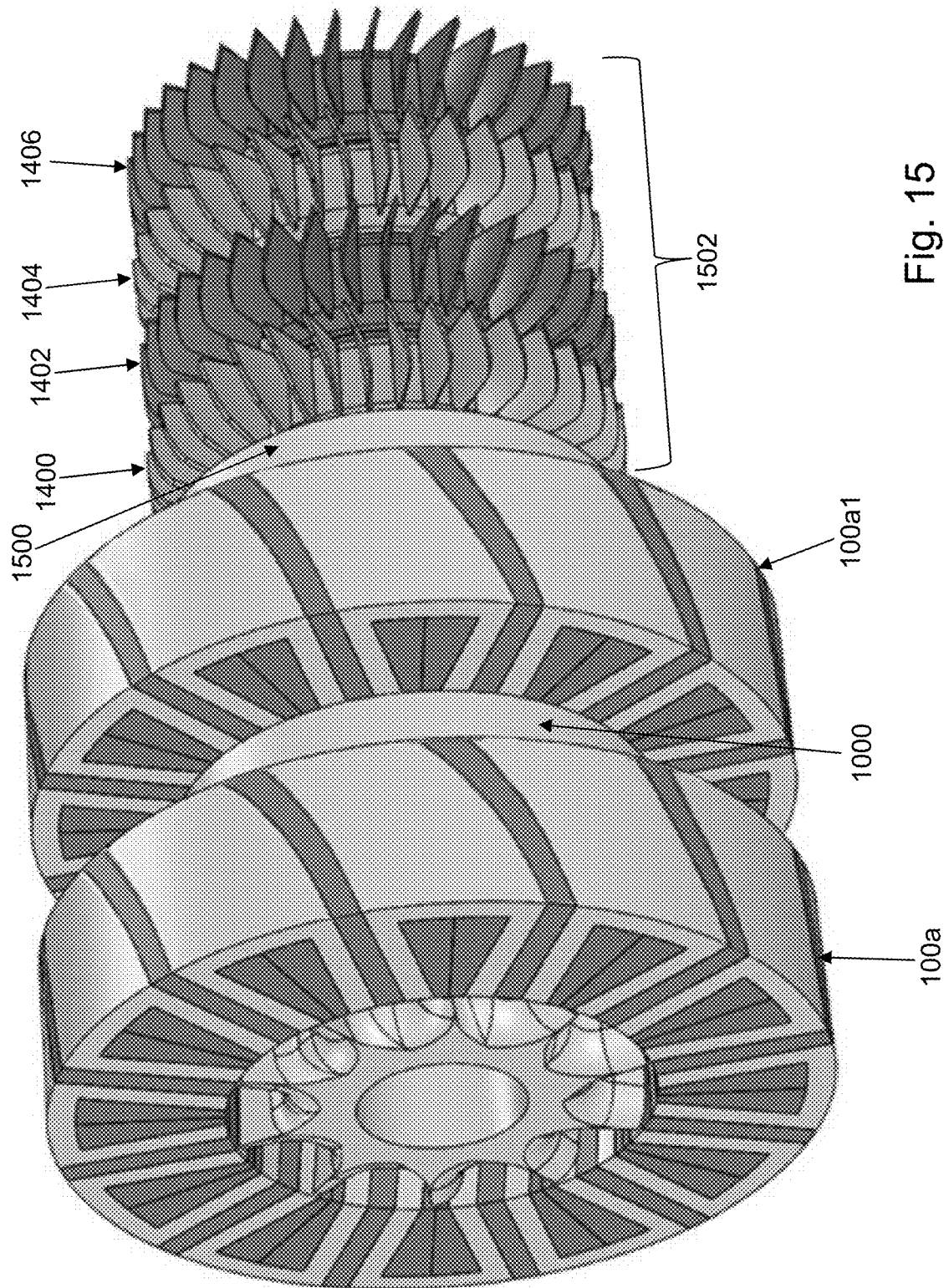


Fig. 15

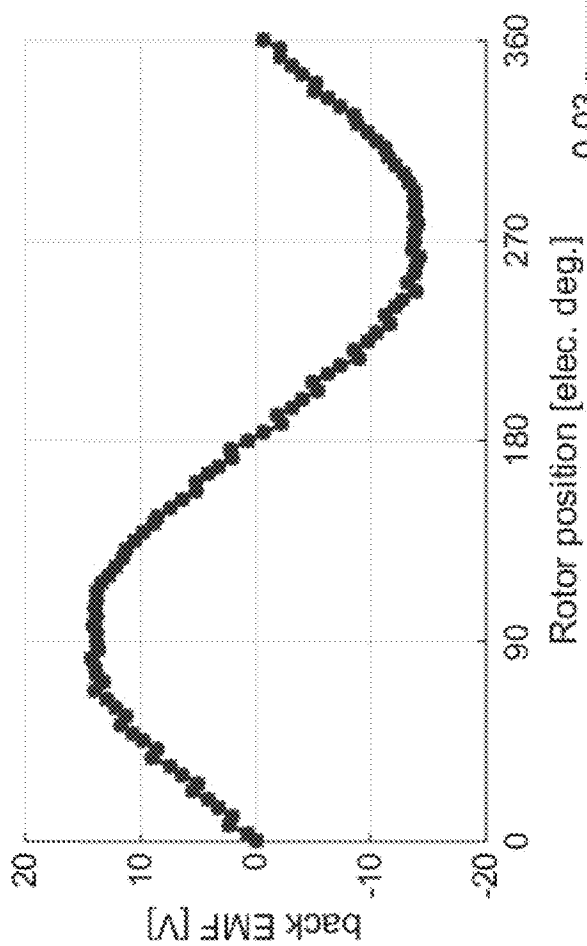


Fig. 16

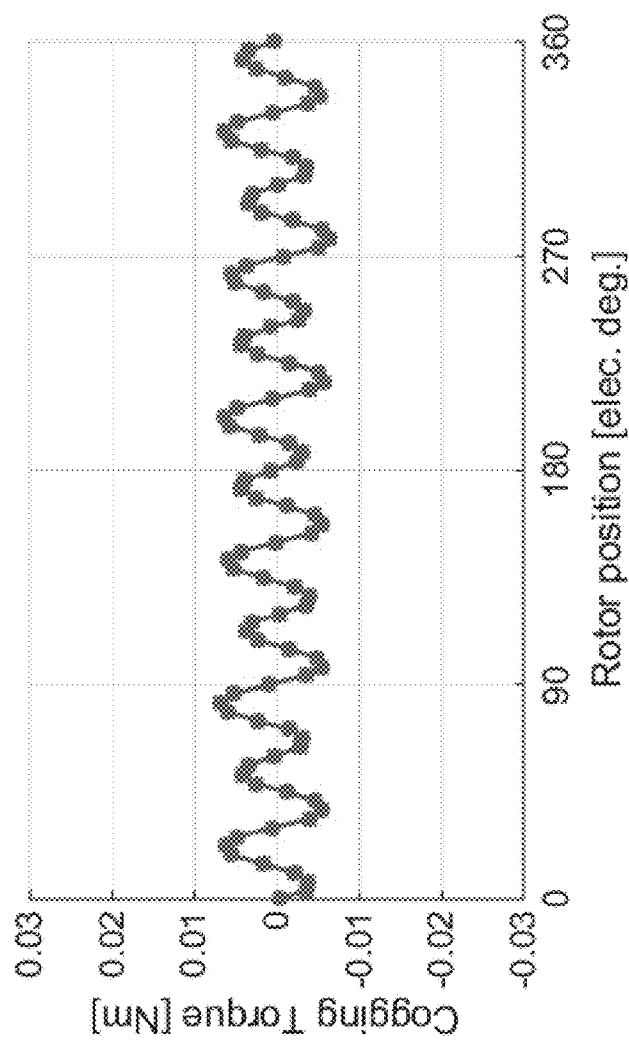


Fig. 17

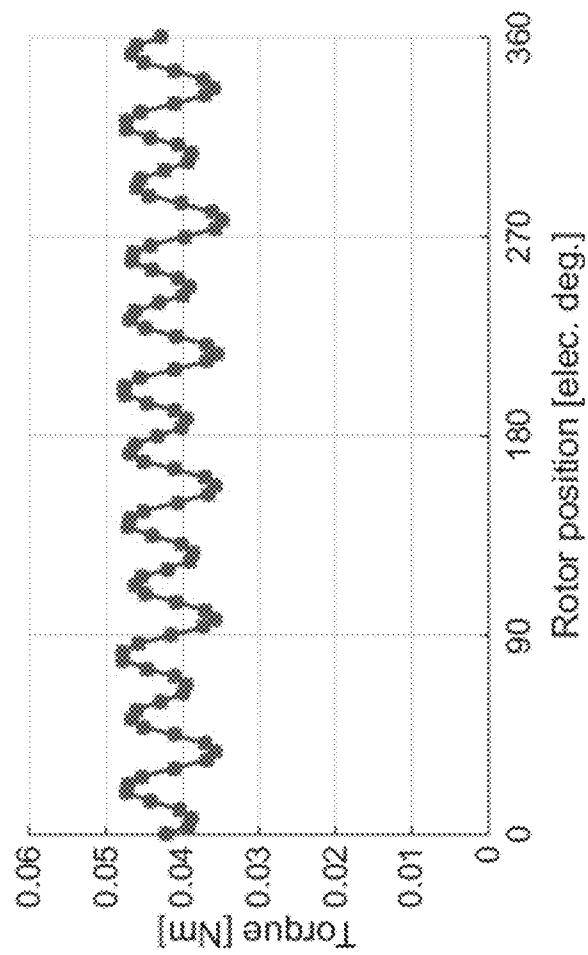
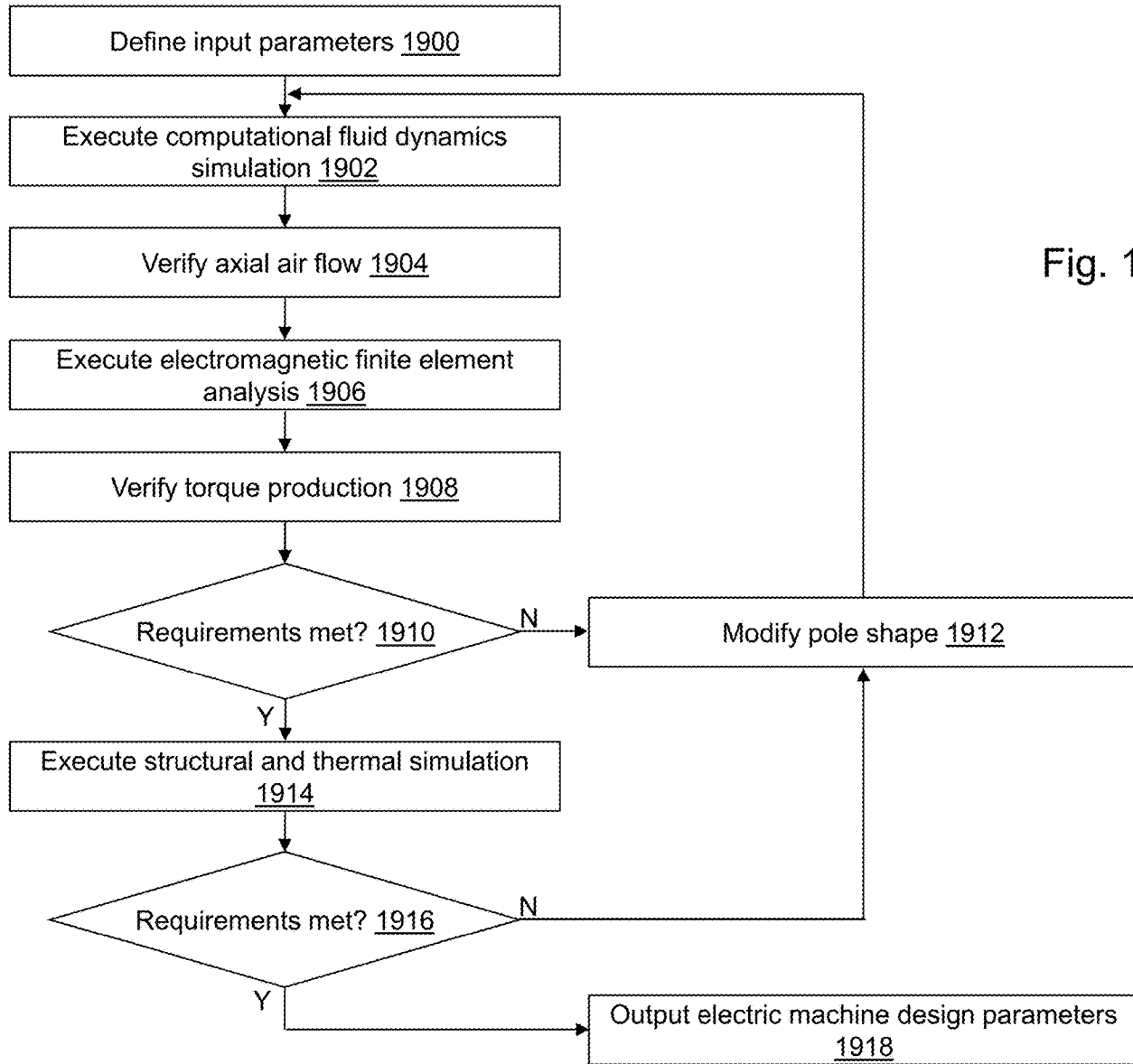


Fig. 18



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INTEGRATED ROTOR FOR AN ELECTRICAL MACHINE AND COMPRESSOR

BACKGROUND

A gas compressor increases a pressure of a gas by reducing its volume. An air compressor is a specific type of gas compressor designed to compress air. Though a gas compressor and a fluid pump both increase the pressure on the gas/fluid and transport the gas/fluid through a conduit, a gas compressor also reduces the volume of the gas. Liquids are relatively incompressible. As a result, the main action of a pump is to pressurize and transport liquids and not to compress them. Gas compression is used in heating, ventilating, and air conditioning (HVAC) systems in buildings, cars, and airplanes, in vehicle propulsion, in energy storage, in air brakes in railway and road vehicles, in scuba diving equipment, in refrigeration systems, in air start systems for aircraft engines, etc. Gas compressors place significant demands on utility generators and power distributors.

SUMMARY

In an example embodiment, an electric machine includes, but is not limited to, a rotor, a stator, and a winding. The rotor includes, but is not limited to, a rotor core and a plurality of blades extending from the rotor core. The rotor core is configured to mount to a shaft for rotation of the rotor core and shaft together. Each blade of the plurality of blades is curved in an axial direction along the rotor core and is simultaneously configured as a pole that carries a magnetic flux of the electrical machine and as an airfoil that compresses a gas when the rotor is rotated. The gas flows axially between successive blades of the plurality of blades.

The stator includes, but is not limited to, a stator core and a plurality of teeth extending from the stator core toward the plurality of blades. The plurality of teeth define a plurality of slots between successive teeth of the plurality of teeth. The winding is wound through at least two slots of the plurality of slots. The stator is mounted radially relative to the rotor so that a gap separates the plurality of blades from an exterior face of the plurality of teeth. The exterior face of the plurality of teeth is axially aligned along the stator core to follow an axial edge of a blade of the plurality of blades.

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 electric machine in accordance with an illustrative embodiment.

FIG. 2 depicts a front view of the electric machine of FIG. 1 in accordance with an illustrative embodiment.

FIG. 3 depicts a perspective view of a stator of the electric machine of FIG. 1 in accordance with an illustrative embodiment.

FIG. 4 depicts a perspective view of a first rotor of the electric machine of FIG. 1 in accordance with an illustrative embodiment.

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FIG. 5 depicts a perspective view of a second rotor of the electric machine of FIG. 1 in accordance with an illustrative embodiment.

FIG. 6 depicts a rotor blade shape and nomenclature for a rotor of the electric machine of FIG. 1 in accordance with an illustrative embodiment.

FIG. 7 depicts a velocity diagram of a flow through a rotor of the electric machine of FIG. 1 in accordance with an illustrative embodiment.

FIG. 8 depicts a combined velocity triangle for a rotor of the electric machine of FIG. 1 showing a velocity increase in accordance with an illustrative embodiment.

FIG. 9 depicts a required power for rotor compression work as a function of mean blade diameter for a rotor blade of a rotor of the electric machine of FIG. 1 in accordance with an illustrative embodiment.

FIG. 10 depicts an exploded perspective view of an electric machine in accordance with a second illustrative embodiment.

FIG. 11 depicts an exploded perspective view of the electric machine in accordance with a third illustrative embodiment.

FIG. 12 depicts an exploded perspective view of the electric machine in accordance with a fourth illustrative embodiment.

FIG. 13 depicts an exploded perspective view of the electric machine in accordance with a fifth illustrative embodiment.

FIG. 14 depicts a perspective view of the electric machine of FIG. 10 with a cascaded connection of multi-stage compressors in accordance with an illustrative embodiment.

FIG. 15 depicts a perspective view of a cascaded connection of two electric machines of FIG. 10 with a cascaded connection of multi-stage compressors in accordance with an illustrative embodiment.

FIG. 16 depicts a back-electromotive force generated by the electric machine of FIG. 1 as a function of the rotor position in accordance with an illustrative embodiment.

FIG. 17 depicts a cogging torque generated by the electric machine of FIG. 1 as a function of a rotor position in accordance with an illustrative embodiment.

FIG. 18 depicts a torque generated by the electric machine of FIG. 1 as a function of the rotor position in accordance with an illustrative embodiment.

FIG. 19 depicts a flow diagram illustrating examples of operations performed to determine parameters for the electric machines of FIGS. 1 and 10-13 in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

Referring to FIG. 1, a perspective view of an electric machine 100 is shown in accordance with an illustrative embodiment. In the illustrative embodiment of FIG. 1, electric machine 100 is a radial flux switching permanent magnet machine (FSPM). Electric machine 100 may include a stator 102, a rotor 104, and a plurality of windings 114. In the illustrative embodiment, electric machine 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, electric machine 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 orienta-

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

Electric machine **100** may be used in various orientations. A shaft **106** may be mounted to extend parallel to a z-axis (shown referring to FIGS. **3** and **5**) that is perpendicular to an x-axis and a y-axis (shown referring to FIGS. **2**, **3**, and **5**). The x-axis and the y-axis are perpendicular to each other so that the x-axis, y-axis, and z-axis form an orthonormal coordinate system. The z-axis defines an axial direction that extends through a center of rotor **104**. In the illustrative embodiment of FIG. **1**, rotor **104** is mounted radially within stator **102**, and rotor **104** is mounted to shaft **106** for rotation. Rotor **104** is separated from stator **102** by an air gap **120**. In an alternative embodiment, stator **102** may be mounted radially within rotor **104**, and shaft **106** may or may not extend through a center of electric machine **100**.

As used in this disclosure, the term “mount” includes join, unite, connect, couple, associate, insert, hang, hold, affix, attach, fasten, bind, paste, secure, bolt, screw, rivet, 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.

Stator **102** may include a stator core **108**, a plurality of teeth **110**, and a plurality of magnets **112** that form a plurality of stator poles. Stator **102** has a generally circular cross section with a hollow core sized to accommodate shaft **106** and rotor **104**. Stator core **108** and the plurality of teeth **110** may be formed of a ferromagnetic material such as lamination steel, iron, cobalt, nickel, etc. Stator core **108** and the plurality of teeth **110** may be formed of laminations stacked in the axial direction. The laminations may be punched or laser cut. In the illustrative embodiment, the number of stator slots or stator poles of stator **102** is $p_s=12$ though stator **102** may include a fewer or a greater number of stator poles.

Rotor **104** has a generally circular cross section with a hollow core sized to accommodate shaft **106**. Rotor **104** may include a rotor core **116** and a plurality of blades **118** that form a plurality of rotor poles. The number of rotor poles may depend on the number of phases supported by electric machine **100**. In the illustrative embodiment, the number of rotor blades or rotor poles of rotor **104** is $p_r=10$ though rotor **104** may include a fewer or a greater number of rotor poles. Rotor core **116** and the plurality of blades **118** may be formed of a ferromagnetic material such as lamination steel, iron, cobalt, nickel, etc. Rotor core **116** and the plurality of blades **118** may be formed of laminations stacked in the axial direction that is parallel to the z-axis. The laminations may be punched or laser cut.

Rotor **104** may control rotation of shaft **106** when electric machine **100** is acting as a motor, and shaft **106** may control rotation of rotor **104** when electric machine **100** is acting as a generator. Electric machine **100** may be configured to act as both a generator and a motor or as a generator or as a motor.

The excitation frequency, f_e , of an FSPM machine is proportional to the number of rotor poles (p_r) as

$$f_e = \frac{np_r}{60},$$

where n is a rotational speed, for example, in revolutions per minute (RPM). A typical FSPM machine has $p_s=12$ and $p_r=10$ though a minimum number of stator slots is six for a three-phase machine because the number of stator slots is an even number and a multiple of the number of phases. The number of rotor poles can be 4, 5, 7, 8, etc. though not all of these combinations may be suitable for practical use.

Referring to FIG. **2**, a front view of electric machine **100** is shown in accordance with an illustrative embodiment. Stator core **108** and the plurality of teeth **110** form a plurality of slots in which the plurality of windings **114** are wound. A winding of the plurality of windings **114** is wound over at least one magnet of the plurality of magnets **112** and through at least two slots of the plurality of slots. For example, in the illustrative embodiment of FIG. **2**, a first winding **114a** is wound over a first magnet **112a** and defines a first phase “A” winding. A second winding **114b** is wound over a second magnet **112b** and defines a second phase “A” winding. A third winding **114c** is wound over a third magnet **112c** and defines a third phase “A” winding. A fourth winding **114d** is wound over a fourth magnet **112d** and defines a fourth phase “A” winding. First winding **114a** and second winding **114b** may be connected in series. Third winding **114c** and fourth winding **114d** may be connected in series. First winding **114a**, second winding **114b**, third winding **114c**, and fourth winding **114d** may be connected in series in various orders. Similarly, the remaining windings are wound over the remaining magnets to form four phase “B” windings and four phase “C” windings. Each of the plurality of windings **114** may form a concentrated coil. Each winding of the plurality of windings **114** conducts a current in a positive or a negative direction.

The plurality of magnets **112** are permanent magnets formed of non-rare or rare earth elements such as ferrite, samarium-cobalt, neodymium-iron-boron, etc. The plurality of magnets **112** may be cast, sintered, molded, etc. Each magnet of the plurality of magnets **112** 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 circumferential direction from the first side to the second side of the magnet relative to the generally circular cross section of stator **102**. The plurality of magnets **112** are mounted with N poles adjacent N poles and S poles adjacent S poles to form pole pairs. The pole pairs are formed at a regular pitch circumferentially around stator **102**. In the illustrative embodiment, the block arrows point from the north polarity to the south polarity.

Referring to FIG. **3**, a perspective view of stator **102** of electric machine **100** is shown in accordance with an illustrative embodiment. Stator **102** has a hollow cylindrical shape with an aperture through a center of the cylinder. Stator core **108** and the plurality of teeth **110** may form a plurality of core pieces. In the illustrative three-phase embodiment, the plurality of core pieces include four core pieces for each phase such that the plurality of core pieces includes a first core piece **108a**, a second core piece **108b**, a third core piece **108c**, a fourth core piece **108d**, a fifth core piece **108e**, a sixth core piece **108f**, a seventh core piece **108g**, an eighth core piece **108h**, a ninth core piece **108i**, a tenth core piece **108j**, an eleventh core piece **108k**, and a twelfth core piece **108l**. In the illustrative embodiment, each core piece of the plurality of core pieces has the same size

and shape. In the illustrative embodiment, each core piece has a "C"-shape distributed circumferentially at a regular pitch around the z-axis and open towards rotor 104. For example, third core piece 108c has a first tooth 300c, a second tooth 302c, and a core section 304c, and fourth core piece 108d has a first tooth 300d, a second tooth 302d, and a core section 304d. First tooth 300c and second tooth 302c extend from core section 304c to form a C-shaped face that opens towards the z-axis and rotor 104. First tooth 300d and second tooth 302d extend from core section 304d to form a C-shaped face that opens towards the z-axis and rotor 104. The hollow of the C-shape of each core piece defines a stator slot within which the plurality of windings 114 is wound. The slots are distributed at equal angles around a circumference of stator 102.

In the illustrative embodiment of FIG. 3, the plurality of magnets 112 are mounted between the teeth of adjacent core pieces. For example, a third magnet 112c fits in a slot formed between a first tooth 300c of third core piece 108c and second tooth 302d of fourth core piece 108d. The remaining magnets are similarly mounted and distributed circumferentially around stator core 108. For example, a first magnet 112a fits in a slot formed between first core piece 108a and second core piece 108b; a second magnet 112b fits in a slot formed between second core piece 108b and third core piece 108c; a fourth magnet 112d fits in a slot formed between fourth core piece 108d and fifth core piece 108e; a fifth magnet 112e fits in a slot formed between fifth core piece 108e and sixth core piece 108f; a sixth magnet 112f fits in a slot formed between sixth core piece 108f and seventh core piece 108g; a seventh magnet 112g fits in a slot formed between seventh core piece 108g and eighth core piece 108h; an eighth magnet 112h fits in a slot formed between eighth core piece 108h and ninth core piece 108i; a ninth magnet 112i fits in a slot formed between ninth core piece 108i and tenth core piece 108j; a tenth magnet 112j fits in a slot formed between tenth core piece 108j and eleventh core piece 108k; an eleventh magnet 112k fits in a slot formed between eleventh core piece 108k and twelfth core piece 108l; and a twelfth magnet 112l fits in a slot formed between twelfth core piece 108l and first core piece 108a.

In the illustrative embodiment, each magnet of the plurality of magnets 112 has the same size and shape. For example, each magnet of the plurality of magnets 112 has a rectangular shape in the x-y-plane though each magnet of the plurality of magnets 112 may have a truncated wedge shape or other polygonal and/or elliptical shape in the x-y-plane in alternative embodiments. The plurality of core pieces and the plurality of magnets 112 form the circular cross section of stator 102 in the x-y-plane with the z-axis extending axially through a center of the circular cross section of stator 102.

Each magnet of the plurality of magnets 112 is curved in the x-y-plane in the direction of the z-axis to axially align the plurality of magnets 112 with an axially extending edge or face of a blade of the plurality of blades 118. Being curved in the x-y-plane in the direction of the z-axis means that a location of each magnet of the plurality of magnets 112, such as third magnet 112c, is at a different (x,y) coordinate value at each location along the z-axis. The (x,y) coordinate variation follows a continuous curve with a non-zero curvature value (not a straight line) between a front face of stator 102 and a back face of stator 102. The continuous curve may be monotonic.

A stator pole width may or may not have the same value in the axial direction, i.e. the width may change, for example, as a trade-off between manufacturability and

torque production. Each magnet of the plurality of magnets 112 and each core piece may be segmented in the axial direction such that the segmentation follows the curvature line.

Referring to FIG. 4, a perspective view of rotor 104 is shown in accordance with an illustrative embodiment. Rotor core 116 has a hollow cylindrical shape with an aperture through a center of the cylinder. Rotor core 116 may include a rotor front face 400, a rotor back face (not shown), a rotor interior face 1008 (shown with reference to FIG. 10), and a rotor exterior face 402. Rotor exterior face 402 and rotor interior face 1008 extend between rotor front face 400 and the rotor back face. Rotor front face 400 and the rotor back face are in the x-y-plane. Rotor interior face 1008 and rotor exterior face 402 extend parallel to the z-axis or in the axial direction. Shaft 106 mounts to rotor interior face 1008. The plurality of blades 118 extend from rotor exterior face 402. Of course, if stator 102 is mounted interior of rotor 104 instead of exterior as in the illustrative embodiment, the plurality of blades 118 would extend from rotor interior face 1008. The plurality of blades 118 extend from rotor exterior face 402 at a regular pitch circumferentially around rotor core 116.

The plurality of blades 118 includes a first blade 118a, a second blade 118b, a third blade 118c, a fourth blade 118d, a fifth blade 118e, a sixth blade 118f, a seventh blade 118g, an eighth blade 118h, a ninth blade 118i, and a tenth blade 118j that each has the same size and shape. In alternative embodiments, the plurality of blades 118 may have a different size or shape. For example, sixth blade 118f includes a front face 404f, a back face (not shown), a first side face 406f, a second side face (not shown), and an exterior face 408f. First side face 406f, the second side face, and exterior face 408f extend between front face 404f and the back face. Front face 404f extends from rotor exterior face 402, and the back face extends from the rotor back face. First side face 406f and the second side face extend from rotor exterior face 402. Exterior face 408f extends between first side face 406f and the second side face and defines an axial edge of sixth blade 118f. In the illustrative embodiment of FIG. 4, a rotor pole width of exterior face 408f changes in an axial direction with a curvature.

Air gap 120 is defined between exterior face 408f of sixth blade 118f and inner edges of each tooth of stator 102. Air gap 120 is similarly defined between an exterior face 408f of each of first blade 118a, second blade 118b, third blade 118c, fourth blade 118d, fifth blade 118e, seventh blade 118g, eighth blade 118h, ninth blade 118i, and tenth blade 118j and the inner edges of each tooth of stator 102.

Each blade of the plurality of blades 118 is shaped, sized, and/or positioned to carry a magnetic flux of electric machine 100. Each blade of the plurality of blades 118 is simultaneously shaped, sized, and/or positioned to act as an airfoil that compresses a gas when rotor 104 is rotated. Rotor 104 may be used as part of a gas compressor stage. The gas flows axially between successive blades of the plurality of blades 118.

Referring to FIG. 5, a perspective view of a second rotor 104a of electric machine 100 is shown in accordance with an illustrative embodiment. Rotor core 116 has a hollow cylindrical shape with an aperture through a center of the cylinder. Rotor core 116 may include a rotor front face 400, a rotor back face (not shown), and rotor interior face 1008. The plurality of blades 118 include a first airfoil blade 118a', a second airfoil blade 118b', a third airfoil blade 118c', a fourth airfoil blade 118d', a fifth airfoil blade 118e', a sixth airfoil blade 118f', a seventh airfoil blade 118g', an eighth

airfoil blade **118h'**, a ninth airfoil blade **118i'**, and a tenth airfoil blade **118j'** that each has the same size and shape. First airfoil blade **118a'**, second airfoil blade **118b'**, third airfoil blade **118c'**, fourth airfoil blade **118d'**, fifth airfoil blade **118e'**, sixth airfoil blade **118f'**, seventh airfoil blade **118g'**, eighth airfoil blade **118h'**, ninth airfoil blade **118i'**, and tenth airfoil blade **118j'** form fan-like airfoils to progressively compress the gas that flows between successive blades of the plurality of blades **118**.

The plurality of blades **118** are designed such that there is simultaneous energy conversion in both the electromagnetic domain and the fluid dynamic domain. The electromagnetic part of the blade design creates efficient energy conversion between electric energy supplied/generated by currents applied to the plurality of windings **114** and mechanical energy generated/supplied by rotating shaft **106**. The fluid dynamic design converts the kinetic energy from rotation of rotor **104** directly into a pressure rise in the gas that flows between successive blades of the plurality of blades **118**. The synergized design approach uses electric machine sizing equations and fluid dynamic equations to determine the power converted in each domain. The output power from electric energy is calculated based on the electric machine sizing equation below:

$$P_{out} = \frac{\sqrt{2}}{2} \pi^3 K_{av} K_t K_{curve} \eta \left(\frac{f_e}{p_s} \right) B_{g,pk} A_{s,rms} D_{is}^2 L_e, \quad (1)$$

where K_{av} is a coefficient to scale peak flux density to average flux density, K_t is a stator tooth ratio number, K_{curve} is a curve factor, η is an efficiency value, $B_{g,pk}$ is a peak airgap flux density, $A_{s,rms}$ is an electric loading measured based on a root mean square (rms) current, D_{is} is an inner diameter of stator **102**, and L_e is an effective length of electric machine **100**. A preliminary geometry of electric machine **100** may be determined by choosing appropriate values of the key parameters, such as a diameter and a length of electric machine **100**, $A_{s,rms}$, and $B_{g,pk}$, once a power and a speed rating are provided for electric machine **100**. $B_{g,pk}$ may be limited by the saturation of steel, and $A_{s,rms}$ may be limited by the cooling of electric machine **100**.

The plurality of blades **118** are shaped with a specific curvature with a specific input (angle of attack) and output angle. Referring to FIG. 6, a rotor blade shape (curvature) and nomenclature is shown for rotor **104** or second rotor **104a** of electric machine **100** in accordance with an illustrative embodiment. For illustration, first blade **118a** or first airfoil blade **118a'** of the plurality of blades **118** is curved with an inlet attacking angle **600**, a chord length **602** of a chord line **603**, a turn angle **604**, an outlet attacking angle **606**, and a stagger angle **608**. Stagger angle **608** is an angle between chord line **603** and the z-axis (axial direction). Turn angle **604** of first blade **118a** or first airfoil blade **118a'** redirects an inlet flow velocity vector **610** to an outlet flow velocity vector **612**. Inlet flow velocity vector **610** is an inlet flow velocity of the gas with respect to first blade **118a** or first airfoil blade **118a'**. Outlet flow velocity vector **612** is an outlet flow velocity of the gas with respect to first blade **118a** or first airfoil blade **118a'**. A blade pitch **614** is a distance between a center of successive blades of the plurality of blades **118**. A rotation direction **616** defines a direction of rotation of the plurality of blades **118** resulting in a pressure side **618** and a suction side **620** for each blade of the plurality of blades **118**.

Referring to FIG. 7, a velocity diagram of a gas flow through rotor **104** or second rotor **104a** of electric machine **100** is shown in accordance with an illustrative embodiment. A gas flow velocity vector **700** flowing into first blade **118a** or first airfoil blade **118a'** is assumed to have only an axial component. A blade speed vector **702** defines a blade speed at a middle blade diameter of each blade of the plurality of blades **118**. A gas flow outlet velocity vector **704** is an actual velocity of the gas exiting rotor **104** or second rotor **104a**. It may be assumed that gas flow velocity vector **700** remains constant. The torque, T_{shaft} , required in shaft **106** to compress the gas is proportional to a difference between tangential blade velocity and mass flow rate as shown below

$$T_{shaft} = r(V_{1.5} - V_1) \frac{dm}{dt} \quad (2)$$

where m is the mass flow rate, r is a mean radius of first blade **118a** or first airfoil blade **118a'**, and V_1 is gas flow velocity vector **700**, which is the tangential velocity of the mean blade for the rotor inlet, and $V_{1.5}$ is gas flow outlet velocity vector **704**, which is the tangential velocity of the mean blade for the rotor outlet.

Referring to FIG. 8, a combined velocity triangle showing a velocity increase is shown for rotor **104** or second rotor **104a** of electric machine **100** in accordance with an illustrative embodiment. A delta vector **800** completes the velocity triangle between gas flow velocity vector **700** and gas flow outlet velocity vector **704**. A magnitude **802** of delta vector **800** indicates a net increase of rotor tangential velocity provided by first blade **118a** or first airfoil blade **118a'**. Blade speed vector **702** has a blade speed magnitude **804**. The outlet gas also has a higher stagnation temperature as compared to an inlet stagnation temperature.

Referring to FIG. 9, a required power for rotor compression work is shown as a function of mean blade diameter for first blade **118a** or first airfoil blade **118a'** in accordance with an illustrative embodiment.

Referring to FIG. 10, an exploded perspective view of a second electric machine **100a** is shown in accordance with an illustrative embodiment. Second electric machine **100a** includes stator **102** and second rotor **104a**. A diffuser **1000** is mounted to second electric machine **100a** to receive the gas compressed by the plurality of blades **118**. Diffuser **1000** is a stationary diffuser that reduces the speed of the gas and increases the pressure on the gas to further compress the gas.

Diffuser **1000** may include an outer core **1002**, an inner core **1004**, and a plurality of diffuser blades **1006**. For example, diffuser **1000** may include a first stator blade **1006a**, a second stator blade **1006b**, a third stator blade **1006c**, etc. The plurality of diffuser blades **1006** are mounted between outer core **1002** and inner core **1004** to receive the gas output from second rotor **104a** (or rotor **104**), to reduce the speed of the gas, to further increase the pressure on the gas, and to output the further compressed gas. The gas from the output of the diffuser can be guided to another stage of compression such as another axial or centrifugal compressor.

Referring again to FIG. 8, the kinetic energy of the gas is converted into static pressure in diffuser **1000** where an outlet velocity **706** of the gas from diffuser **1000** is slowed down while the pressure is increased. To evaluate how much the pressure is increased by second rotor **104a** and diffuser **1000**, a pressure ratio is calculated as

$$\frac{p_{o1.5}}{p_{o1}} = \left(\frac{T_{o1.5}}{T_{o1}} \right)^{k/(k-1)} \quad (3)$$

where $p_{o1.5}$ is a total diffuser outlet pressure, p_{o1} is a total rotor inlet pressure, T_{o1} is a total rotor inlet temperature of the gas, $T_{o1.5}$ is a total diffuser outlet temperature of the gas, and k is a ratio of specific heat. The two temperatures can be calculated as

$$T_{o1} = T_1 + \frac{V_1^2}{2c_p} \quad (4)$$

$$T_{o1.5} = T_{o2} = T_{o1} - \frac{1w_2}{2c_p} \quad (5)$$

where c_p is a constant pressure specific heat of the gas, T_1 is an inlet gas temperature, $1w_2$ is a work per unit mass done by rotor **104** and diffuser **1000** from an inlet to second rotor **104a** to an outlet from diffuser **1000**.

Referring to FIG. **11**, an exploded perspective view of a third electric machine **100b** is shown in accordance with an illustrative embodiment. In the illustrative embodiment of FIG. **11**, third electric machine **100b** is a doubly salient permanent magnet machine. Third electric machine **100b** may include a second stator **102a**, second rotor **104a** (or rotor **104**), and the plurality of windings **114**. In the illustrative embodiment, third electric machine **100b** 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. Diffuser **1000** is mounted to third electric machine **100b** to receive the gas compressed by the plurality of blades **118**.

Second stator **102a** may include stator core **108**, the plurality of teeth **110**, and the plurality of magnets **112** that form a plurality of stator poles. Second stator **102a** has a generally circular cross section with a hollow core sized to accommodate shaft **106** and second rotor **104a** (or rotor **104**). The plurality of teeth **110** may have a different size and shape and number as compared to stator **102** as understood by a person of skill in the art. Unlike the plurality of magnets **112** of stator **102**, the plurality of magnets **112** of second stator **102a** are mounted to extend in a radial direction through stator core **108** in axial alignment with a slot of the plurality of slots instead of through the plurality of teeth **110**. There also may be fewer or a greater number of magnets for the plurality of magnets **112** of second stator **102a**. The plurality of windings **114** further may be wound through the plurality of slots of second stator **102a** in a different manner than the plurality of windings **114** are wound through the plurality of slots of stator **102** as understood by a person of skill in the art.

Referring to FIG. **12**, an exploded perspective view of a fourth electric machine **100c** is shown in accordance with an illustrative embodiment. In the illustrative embodiment of FIG. **12**, fourth electric machine **100c** is a flux reversal permanent magnet machine. Fourth electric machine **100c** may include a third stator **102b**, second rotor **104a** (or rotor **104**), and the plurality of windings **114**. In the illustrative embodiment, fourth electric machine **100c** 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. Diffuser **1000** is mounted to fourth electric machine **100c** to receive the gas compressed by the plurality of blades **118**.

Third stator **102b** may include stator core **108**, the plurality of teeth **110**, and the plurality of magnets **112** that form

a plurality of stator poles. Third stator **102b** has a generally circular cross section with a hollow core sized to accommodate shaft **106** and second rotor **104a** (or rotor **104**). The plurality of teeth **110** may have a different size and shape and number as compared to stator **102** as understood by a person of skill in the art. Unlike the plurality of magnets **112** of stator **102**, the plurality of magnets **112** of second stator **102a** are mounted to an exterior face of each tooth of the plurality of teeth **110** instead of through the plurality of teeth **110**. The exterior face of each tooth of the plurality of teeth **110** faces second rotor **104a** (or rotor **104**). Air gap **120** separates the plurality of blades **118** from each magnet of the plurality of magnets **112**. There also may be fewer or a greater number of magnets for the plurality of magnets **112** of third stator **102b**. The plurality of windings **114** further may be wound through the plurality of slots of third stator **102b** in a different manner than the plurality of windings **114** are wound through the plurality of slots of stator **102** as understood by a person of skill in the art.

Referring to FIG. **13**, an exploded perspective view of a fifth electric machine **100d** is shown in accordance with an illustrative embodiment. In the illustrative embodiment of FIG. **13**, fifth electric machine **100d** is a switched reluctance machine. Fifth electric machine **100d** may include a fourth stator **102c**, second rotor **104a** (or rotor **104**), and the plurality of windings **114**. In the illustrative embodiment, fifth electric machine **100d** 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. Diffuser **1000** is mounted to fifth electric machine **100c** to receive the gas compressed by the plurality of blades **118**.

Fourth stator **102c** may include stator core **108** and the plurality of teeth **110** that form a plurality of stator poles. Fourth stator **102c** has a generally circular cross section with a hollow core sized to accommodate shaft **106** and second rotor **104a** (or rotor **104**). The plurality of teeth **110** may have a different size and shape and number as compared to stator **102** as understood by a person of skill in the art. The plurality of windings **114** further may be wound through the plurality of slots of fourth stator **102c** in a different manner than the plurality of windings **114** are wound through the plurality of slots of stator **102** as understood by a person of skill in the art.

Referring to FIG. **14**, a perspective view of second electric machine **100a** and diffuser **1000** is shown with a connection to a multi-stage compressor **1400** in accordance with an illustrative embodiment. Diffuser **1000** may not be included in an alternative embodiment. Multi-stage compressor **1400** is mounted to receive compressed gas from diffuser **1000**. Arrays of airfoils of multi-stage compressor **1400** may be set in rows, usually as pairs. For example, in each pair of compressors, one compressor of the pair may be rotating and the other compressor of the pair may be stationary. In the illustrative embodiment of FIG. **14**, multi-stage compressor **1400** includes a first rotating compressor **1402** paired with a first stationary compressor **1404**, a second rotating compressor **1406** paired with a second stationary compressor **1408**, and a third rotating compressor **1410** paired with a third stationary compressor **1412**. Multi-stage compressor **1400** may include a fewer or a greater number of arrays of airfoils.

The rotating airfoils or rotor blades of first rotating compressor **1402**, second rotating compressor **1406**, and third rotating compressor **1410** accelerate the gas received from a previous stage such as diffuser **1000**, first stationary compressor **1404**, and second stationary compressor **1408**, respectively. The stationary airfoils, also known as stators or

vanes, of first stationary compressor **1404**, second stationary compressor **1408**, and third stationary compressor **1412** decelerate and redirect the flow direction of the gas, preparing it for the rotor blades of the next stage such as second rotating compressor **1406** and third rotating compressor **1410**. A cross-sectional area of a gas passage may diminish along multi-stage compressor **1400** to maintain an optimum axial Mach number. Beyond about five stages or a 4:1 design pressure ratio, a variable geometry may be used to further improve a compression of the gas.

The design for multi-stage compressor **1400** follows the same rules as outlined above for rotor **104** and second rotor **104a** such that if the mean blade diameter stays constant, the power required for each successive stage is the same as the first stage assuming turn angle **604** and inlet flow velocity vector **610** remain the same. The pressure rise ratio normally decreases slightly for the later stages while the temperature increases from stage to stage. If the blade mean diameter is allowed to change, the required power at each stage is calculated as:

$$P_{stage} = \frac{dm}{dt} r \omega \left[r \omega - V_1 \tan \left(\arctan \left(\frac{d\omega}{2V_1} \right) - \theta \right) \right] \quad (6)$$

where θ is turn angle **604**, and ω is an angular speed of rotor **104**. The required power at a second stage as a function of rotor mean blade diameter is shown in FIG. 9.

Referring to FIG. 15, a perspective view of second electric machine **100a**, diffuser **1000**, a second instance **100a1** of second electric machine **100a**, and a second diffuser **1500** is shown with a connection to a second multi-stage compressor **1502** in accordance with an illustrative embodiment. Diffuser **1000** is mounted to receive compressed gas from second electric machine **100a**. Second instance **100a1** of second electric machine **100a** is mounted to receive compressed gas from diffuser **1000**. Second diffuser **1500** is mounted to receive compressed gas from second instance **100a1** of second electric machine **100a**. Second multi-stage compressor **1502** is mounted to receive compressed gas from second diffuser **1500**. In the illustrative embodiment of FIG. 15, second multi-stage compressor **1502** includes first rotating compressor **1402** paired with first stationary compressor **1404** and second rotating compressor **1406** paired with a second stationary compressor **1408**. Second multi-stage compressor **1502** may include a fewer or a greater number of arrays of airfoils. Diffuser **1000** and/or second diffuser **1500** may not be included in alternative embodiments. A greater number of electric machines **100** of the same or different type may be included in alternative embodiments.

The various dimensions of the elements of the electric machines described herein may be determined based on desired rated performance characteristics using analytical sizing equations and finite element analysis using an electromechanical design tool. For example, referring to FIG. 16, a cogging torque generated by electric machine **100** is shown in accordance with an illustrative embodiment. Referring to FIG. 17, a back-electromotive force (back-EMF) generated by electric machine **100** as a function of a rotor position is shown in accordance with an illustrative embodiment. Referring to FIG. 18, a torque generated by electric machine **100** as a function of the rotor position is shown in accordance with an illustrative embodiment. The

cogging torque, the back-EMF, and the torque were determined using finite element analysis and the parameter values listed in Table 1 below.

TABLE 1

Parameters	Values
Electric machine power, P_{out} [kW]	40
Rotor speed n [krpm]	15
Hub diameter D_{hub} [mm]	103.2
Blade tip diameter D_{tip} [mm]	136.4
Stator curve slot pitch	1
Blade turn angle, θ [deg.]	30
Axial air flux velocity, V_1 [m/s]	170
Specific gas constant, $R_{specific}$ [J/(kg*K)]	287.1
Air pressure p_{o1} [kPa]	101.3
Air temperature, T_1 [K]	300
Mass rate of flow, m [kg/s]	1.249
Torque required, T [Nm]	7.524
Power required, P [kW]	11.82
Inlet stagnation temperature, T_{o1} [K]	314.4
Rotor outlet stagnation temperature, $T_{o1.5}$ [K]	323.8
Ideal pressure rise	10.88%

Hub diameter D_{hub} is a diameter **500** (shown referring to FIG. 5) of a yoke of rotor **104**. Blade tip diameter D_{tip} is an outer diameter **502** (shown referring to FIG. 5) of rotor **104**. Axial air flux velocity V_1 is a magnitude of gas flow velocity vector **700** at an input to diffuser **1000**. Air pressure p_{o1} is a pressure at an inlet of diffuser **1000**. Air temperature T_1 is an input air temperature. Torque required, T , and power required, P , is a torque and a power required to compress the gas. Ideal pressure rise is a percentage pressure increase at an output with respect to an inlet pressure. The airflow compression rise of rotor **104** was calculated as 10.88%, which is in a typical range of 5% to 20% for a single stage compression using subsonic tip speed blades. The power required to compress the air is calculated to be 11.82 kW, so the remaining power supplied by the electric machine can be used for additional rotating compressor stages. The proposed machine has a sinusoidal back-EMF and a small cogging torque, which is beneficial to improving efficiency.

To further refine the parameters of the electric machines describe herein including a determination of an optimum curve angle for stator **102** and rotor **104** as well as the airfoil shape of the plurality of blades to achieve maximum pressure ratios without sacrificing the electromagnetic performance, multi-physics simulations that integrate the analysis of electromagnetic, thermal, and fluid dynamic aspects are performed for various operating stages using advanced co-simulation and analysis tools.

A flowchart for the multi-physics design is provided in FIG. 19. In an operation, input parameters are defined. For example, in an operation **1900**, initial dimensions of electric machine **100** design requirements are defined for electric machine **100** in terms of axial air flow, electromagnetic torque, structure, and thermal properties.

In an operation **1902**, a computational fluid dynamics simulation of the defined electric machine **100** is executed to determine axial air flow. In an operation **1904**, the determined axial air flow is verified against the design requirements. At this stage, fluid dynamic properties of the designed machine are validated.

In an operation **1906**, a finite element analysis simulation of the defined electric machine **100** is executed to determine a torque production. In an operation **1908**, the determined torque production is verified against the design requirements. At this stage, the electromagnetic properties of the designed machine are validated.

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In an operation **1910**, a determination is made concerning both fluid dynamics and electromagnetics to validate whether or not the determined axial air flow, compression ratio, and the determined torque production satisfy the design requirements. If the determined axial air flow, compression ratio, and the determined torque production satisfy the design requirements, processing continues in an operation **1914**. If the determined axial air flow, compression ratio, and the determined torque production do not satisfy the design requirements, processing continues in an operation **1912**.

In operation **1912**, dimensions of the plurality of blades **118** that form the plurality of rotor poles are modified, and processing continues in operation **1902** with the modified dimensions. The curvature along with input (angle of attack) angle and output angle of the plurality of blades **118** are modified. The plurality of stator poles are also modified to have the average trajectory of the rotor curvature.

In operation **1914**, structural and thermal simulation of the defined electric machine **100** is executed to determine that the structure of the machine meets various mechanical requirements such as vibration, stress, and reliability. Similarly, thermal design of electric machine **100** should be such that the machine receives adequate cooling, and the materials used in the machine do not exceed its temperature rating.

In an operation **1916**, a determination is made concerning whether or not the determined torque, air flow, compression, thermal, vibration, stress, and reliability measures satisfy the design requirements. If the determined measures satisfy the design requirements, processing continues in an operation **1918**. If the determined measures do not satisfy the design requirements, processing continues in operation **1912**.

In operation **1918**, the design parameters for electric machine **100** that satisfy the design requirements are output, for example, to a computer-readable medium or a computer display.

In conventional compressors, a drive motor is mounted separately from a compressor assembly often with additional gears or outlet casing since the motor is mounted so that the axial flow of the gas is not compromised. The drive motor along with its independent cooling mechanism adds additional losses in addition to weight and volume. The electric machines described herein provide a reduced volume and utilize the pressure and temperature difference.

By incorporating electric machine **100**, **100a**, **100b**, **100c**, **100d** at a low pressure stage of a compressor, a natural cooling mechanism is provided for electric machine **100**, **100a**, **100b**, **100c**, **100d** keeping the internal temperature and losses at a minimum. Because axial-flow compression is particularly advantageous for higher pressure ratios, multiple stages of compression can be achieved by cascading electric machine **100**, **100a**, **100b**, **100c**, **100d** with one or more diffuser **1000**. To further increase a discharge pressure, an axial flow compressor can be combined with a radial flow stage at the axial stage outlet.

The term “air” is used herein to reference any gas. 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.

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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 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 configured to mount to a shaft for rotation of the rotor core and shaft together; and

a plurality of blades extending radially away from the rotor core, wherein each blade of the plurality of blades is curved axially along the rotor core with a first non-zero radius of curvature, wherein both radially extending sides of each blade of the plurality of blades is curved with a second non-zero radius of curvature, wherein a width between the radially extending sides of a respective blade in a direction perpendicular to a radial direction from a center of the rotor core decreases away from the rotor core;

a stator comprising

a stator core; and

a plurality of teeth extending from the stator core toward the plurality of blades, wherein the plurality of teeth define a plurality of slots between successive teeth of the plurality of teeth; and

a winding wound through at least two slots of the plurality of slots;

wherein the stator is mounted radially relative to the rotor so that a gap separates the plurality of blades from an exterior face of the plurality of teeth;

wherein the exterior face of the plurality of teeth is axially aligned along the stator core to follow an axial edge of a blade of the plurality of blades.

2. The electrical machine of claim 1, further comprising: a plurality of permanent magnets, wherein a permanent magnet of the plurality of permanent magnets is mounted to extend in a second radial direction through each tooth of the plurality of teeth;

wherein the winding is wound over at least one permanent magnet of the plurality of permanent magnets and through at least two slots of the plurality of slots;

wherein the plurality of permanent magnets are axially aligned to follow the axial edge of the blade of the plurality of blades.

3. The electrical machine of claim 1, further comprising: a plurality of permanent magnets, wherein a permanent magnet of the plurality of permanent magnets is mounted to extend in a second radial direction through the stator core in axial alignment with a slot of the plurality of slots.

4. The electrical machine of claim 1, further comprising: a plurality of permanent magnets, wherein a permanent magnet of the plurality of permanent magnets is mounted to the exterior face of each tooth of the plurality of teeth, wherein a second gap within the gap

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- separates the plurality of blades from each permanent magnet of the plurality of permanent magnets.
5. The electrical machine of claim 1, further comprising: a stationary diffuser mounted to extend axially from the rotor to receive a compressed gas from the rotor, wherein the stationary diffuser is configured to further compress the received, compressed gas.
 6. The electrical machine of claim 5, further comprising: a first rotating gas compressor mounted to extend axially from the stationary diffuser to receive the further compressed gas, wherein the first rotating gas compressor is configured to still further compress the received, further compressed gas.
 7. The electrical machine of claim 6, further comprising: a second stationary diffuser mounted to extend axially from the first rotating gas compressor to receive the still further compressed gas, wherein the second stationary diffuser is configured to reduce a velocity of the received, still further compressed gas.
 8. The electrical machine of claim 1, further comprising: a first rotating gas compressor mounted to extend axially from the rotor to receive a compressed gas from the rotor, wherein the first rotating gas compressor is configured to further compress the received, compressed gas.
 9. The electrical machine of claim 8, further comprising: a first stationary diffuser mounted to extend axially from the first rotating gas compressor to receive the further compressed gas, wherein the first stationary diffuser is configured to reduce a velocity of the received, further compressed gas.
 10. The electrical machine of claim 8, wherein the first rotating gas compressor is mounted to the shaft.
 11. The electrical machine of claim 1, further comprising:
 - a second rotor comprising
 - a second rotor core configured to mount to the shaft for rotation of the second rotor core and shaft together; and
 - a second plurality of blades extending radially away from the second rotor core, wherein each blade of the second plurality of blades is curved axially along the second rotor core with a third non-zero radius of curvature, wherein both radially extending sides of each blade of the second plurality of blades is curved with a fourth non-zero radius of curvature, wherein a second width between the radially extending sides of a respective blade of each blade of the second plurality of blades in a second direction perpendicular to a second radial direction from a second center of the second rotor core decreases away from the second rotor core;
 - a second stator comprising
 - a second stator core; and
 - a second plurality of teeth extending from the second stator core toward the second plurality of blades, wherein the second plurality of teeth define a second plurality of slots between successive teeth of the second plurality of teeth; and
 - a second winding wound through at least two slots of the second plurality of slots;
 wherein the second stator is mounted radially relative to the second rotor so that a second gap separates the second plurality of blades from an exterior face of the second plurality of teeth;

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- wherein the exterior face of the second plurality of teeth is axially aligned along the second stator core to follow a second axial edge of a second blade of the second plurality of blades.
12. The electrical machine of claim 11, further comprising:
 - a plurality of permanent magnets, wherein a permanent magnet of the plurality of permanent magnets is mounted to extend in a second radial direction through each tooth of the plurality of teeth; and
 - a second plurality of permanent magnets, wherein a permanent magnet of the second plurality of permanent magnets is mounted to extend in a third radial direction through each tooth of the second plurality of teeth;
 wherein the winding is wound over at least one permanent magnet of the plurality of permanent magnets and through at least two slots of the plurality of slots;
 wherein the second winding is wound over at least one permanent magnet of the second plurality of permanent magnets and through at least two slots of the second plurality of slots;
 wherein the plurality of permanent magnets are axially aligned to follow the axial edge of the blade of the plurality of blades,
 wherein the second plurality of permanent magnets are axially aligned to follow the axial edge of the second blade of the second plurality of blades.
 13. The electrical machine of claim 11, further comprising:
 - a plurality of permanent magnets, wherein a permanent magnet of the plurality of permanent magnets is mounted to extend in a second radial direction through the stator core in axial alignment with a slot of the plurality of slots; and
 - a second plurality of permanent magnets, wherein a permanent magnet of the second plurality of permanent magnets is mounted to extend in a third radial direction through the second stator core in axial alignment with a slot of the second plurality of slots.
 14. The electrical machine of claim 11, further comprising:
 - a plurality of permanent magnets, wherein a permanent magnet of the plurality of permanent magnets is mounted to the exterior face of each tooth of the plurality of teeth, wherein a third gap within the gap separates the plurality of blades from each permanent magnet of the plurality of permanent magnets; and
 - a second plurality of permanent magnets, wherein a permanent magnet of the second plurality of permanent magnets is mounted to the exterior face of each tooth of the second plurality of teeth, wherein a fourth gap within the second gap separates the second plurality of blades from each permanent magnet of the second plurality of permanent magnets.
 15. The electrical machine of claim 11, further comprising:
 - a stationary diffuser mounted to extend axially from the rotor to receive a compressed gas from the rotor, wherein the stationary diffuser is configured to further compress the compressed gas received from the rotor.
 16. The electrical machine of claim 15, wherein the stationary diffuser is mounted between the rotor and the second rotor, and the second gas is output from the stationary diffuser.
 17. The electrical machine of claim 16, further comprising:

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a second stationary diffuser mounted to extend axially from the second rotor to receive a compressed second gas from the second rotor, wherein the second stationary diffuser is configured to further compress the compressed second gas received from the second rotor. 5

18. The electrical machine of claim **17**, further comprising:

a first rotating gas compressor mounted to extend axially from the second stationary diffuser to receive the further compressed second gas, wherein the first rotating gas compressor is configured to still further compress the received, further compressed second gas. 10

19. The electrical machine of claim **18**, further comprising:

a third stationary diffuser mounted to extend axially from the first rotating gas compressor to receive the still further compressed second gas, wherein the third stationary diffuser is configured to reduce a velocity of the received, still further compressed second gas. 15

20. The electrical machine of claim **18**, wherein the first rotating gas compressor is mounted to the shaft. 20

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