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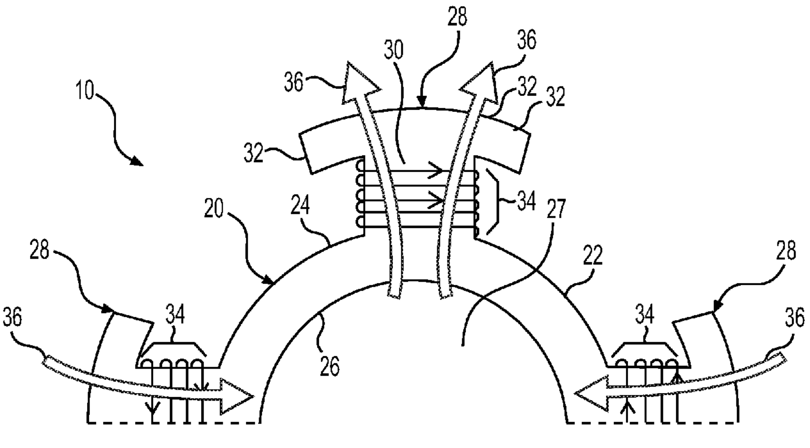

FIG. 1

(57) Abstract: A rotor for a wound-field synchronous machine (WFSM) comprises a core having a base with a ring-shaped cross-section extending between an outside surface and an inside surface defining a bore. The rotor also comprises a plurality of field windings spaced apart from one another at regular angular intervals and each extending around the base of the core, adjacent the outside surface and through the bore. Rotor field windings having radial, or spoke configurations are provided. Rotor field windings having V-shaped arrangements, in which two field windings each contribute to the production of each pole, are also provided. Rotors having permanent magnets in addition to field windings are also provided.

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WOUND-FIELD SYNCHRONOUS MACHINES AND CONTROL

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This PCT International Patent Application claims the benefit of and priority to U.S. Provisional Patent Application Serial No. 62/909,882 filed on October 3, 2019, and titled "Wound-Field Synchronous Machines And Control" and U.S. Provisional Patent Application Serial No. 62/924,840 filed on October 23, 2019, and titled "Wound-Field Synchronous Machines And Control," the entire disclosures of which are hereby incorporated by reference.

BACKGROUND

[0002] Wound-field synchronous machines (WFSMs) are electric machines, which can be used as motors, generators, or motor/generators, having one or more rotors with electromagnetic field windings configured to produce an induced magnetic field by passing electrical current therethrough. WFSMs present many potential advantages over permanent magnet and induction machines in common use for a variety of different applications.

SUMMARY

[0003] A rotor for an electric machine is provided in some embodiments of the present disclosure. The rotor comprises a core having a base with a ring-shaped cross-section extending between an outside surface and an inside surface defining a bore. The rotor also comprises a plurality of field windings spaced apart from one another at regular angular intervals, with each of the field windings configured to conduct current in a radial direction around the base of the core to induce a magnetic field through the core tangentially to the ring-shaped cross-section.

[0004] In some embodiments, a rotor for an electric machine comprises a core having a base with a ring-shaped cross-section extending between an outside surface and an inside surface defining a bore, with the inside surface of the base defining an interior recesses. The rotor also includes an external coil retainer disposed upon the outside surface of the base, the external coil retainer circumferentially separated from the interior recess. A field winding extends radially and circumferentially from the interior recess around the base of the core and to the external coil retainer. The interior recess is one of a plurality of interior recesses spaced apart from one another at a regular angular interval.

[0005] In some embodiments, a rotor for an electric machine comprises a core having a base and a pole extending radially therefrom, and a field winding extending about the pole for generating an induced magnetic field therein. A permanent magnet is disposed within the pole.

[0006] A method of operating an electric machine is also provided. The method comprises conducting an electrical current through a field winding disposed around a pole to produce an induced magnetic field in the pole; and generating a permanent magnetic field in the pole with a permanent magnet.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Further details, features and advantages of designs of the invention result from the following description of embodiment examples in reference to the associated drawings.

[0008] FIG. 1 shows an end-view of a rotor for a conventional salient pole wound-field synchronous machine;

[0009] FIG. 2 shows an end-view of a rotor for a wound-field synchronous machine in accordance with the present disclosure;

[0010] FIG. 3 shows an end-view of a rotor for a wound-field synchronous machine in accordance with the present disclosure;

[0011] FIG. 4 shows an end-view of a rotor for a wound-field synchronous machine in accordance with the present disclosure;

[0012] FIG. 5 shows an end-view diagram of a rotor for a wound-field synchronous machine in accordance with the present disclosure;

[0013] FIG. 6 shows an end-view diagram of a rotor for a wound-field synchronous machine in accordance with the present disclosure;

[0014] FIG. 7 shows an end-view diagram of a rotor for a wound-field synchronous machine in accordance with the present disclosure;

[0015] FIG. 8 shows an end-view diagram of a rotor for a wound-field synchronous machine in accordance with the present disclosure;

[0016] FIG. 9 shows an end-view diagram of a rotor for a wound-field synchronous machine in accordance with the present disclosure;

[0017] FIG. 10 shows an end-view diagram of a rotor for a wound-field synchronous machine in accordance with the present disclosure;

[0018] FIG. 11 shows an end-view of a rotor for a wound-field synchronous machine including a transformer winding in accordance with the present disclosure;;

[0019] FIG. 12 shows an end-view of a rotor for a wound-field synchronous machine including a transformer winding in accordance with the present disclosure;

[0020] FIG. 13 shows an end-view of a rotor for a wound-field synchronous machine including a transformer winding in accordance with the present disclosure; and

[0021] FIG. 14 shows a flow chart of steps in a method of operating an electric machine.

DETAILED DESCRIPTION

[0022] Referring to the drawings, the present invention will be described in detail in view of following embodiments. Example embodiments of a rotor **110, 210, 310, 410, 510** having various different configurations for use in a wound-field synchronous machine (WFSM) are provided.

[0023] Advantages of WFSMs include reduced costs when compared to electric machines with permanent magnets, higher system efficiencies resulting from increased power factor, enhanced loss minimization and flux weakening control because of an additional field excitation control variable, and improved safety during inverter faults since the field excitation can be de-energized. WFSMs historically have not been popular in traction applications because the field winding supply assembly (e.g., brushes, slip rings, or rotating transformers) can be large, expensive, prone to deterioration, and add extra losses to the machine. However, emerging technologies such as harmonic, inductive, and capacitive coupling for transferring power to the rotating field windings make WFSMs a noteworthy candidate for future electric vehicle powertrain applications.

[0024] The control of the field excitation is the main benefit for the WFSM. During field-weakening (FW) operation of the motor, this field excitation can be controlled rather than injecting additional d-axis current into the stator which does not provide additional torque. The reduced levels of d-axis current increase the power factor in the machine and reduce the electrical stress on the inverter and other components since the required reactive power is minimized. Therefore, the efficiency of the motor and inverter will increase in the field-weakening operating region. Also, wider constant power region can be obtained for operation in electric vehicles. Using a wound field instead of permanent magnets also eliminates the risk of demagnetization due to high rotor temperatures. Further performance improvements may be realized by using permanent magnet (PM) assisted topologies and different field winding configurations on the rotor.

[0025] The present disclosure provides different embodiments for placement of the rotor field windings. Placing the field winding in a V-shape or spoke configuration provides an enhanced utilization of the rotor core and can lead to a significant increase in the power density of the machine. The alternative WFSM configurations can also be designed to produce reluctance torque. It can also be designed with an outer rotor to provide more space for field windings. Having the field winding in a V-shaped configuration only requires half the number of conductors in each coil since two coils contribute to the production of one pole. Each field winding may require insulation, liners, and separators.

[0026] When compared with permanent magnet synchronous machines (PMSMs), wound-field synchronous machines (WFSMs) provide a number of advantages. The advantages of WFSMs include:

- WFSMs can provide a wider constant power region.
- WFSMs have increased efficiency in the field weakening (FW) region since *d*-axis current is not required to weaken the permanent magnet (PM) flux-linkage (increased power factor). This additional *d*-axis current lowers the power factor of the machine and causes increased copper losses in the motor and conduction losses in the inverter.
- Control of the field excitation provides opportunities to optimize field weakening and loss minimization across the drive-cycle.
- WFSMs do not require expensive PM material.
- WFSMs do not have a fixed flux level in the rotor, which increases safety during inverter faults.
- WFSMs may provide increased reliability by reducing or eliminating risks of demagnetizing permanent magnets (PMs), particularly in WFSMs without PMs.

[0027] Traditional WFSMs have had some disadvantages when compared with PMSMs. The disadvantages of WFSMs include:

- It can be difficult to transfer power to a rotating field winding. WFSMs previously incorporated three methods: slip rings, brushes, and rotating transformers. Recently, three other brushless methods have been developed: harmonic, inductive, and capacitive power transfer.

- Extra components, controls, and circuitry may be needed to provide for field excitation.
- Copper losses generated by the field windings on the rotor may necessitate rotor cooling.

[0028] FIG. 1 shows an end-view of a first rotor **10** for a conventional salient pole wound-field synchronous machine. Specifically, the first rotor **10** is a salient pole type rotor having a core **20** of electrical steel that includes a base **22** having a ring-shaped cross-section between an outside surface **24** and an inside surface **26** defining a bore **27** and extending annularly about an axis of rotation of the first rotor **10**. The first rotor **10** also includes a plurality of poles **28** extending radially outwardly from the base **22** of the core **20** at regular angular intervals thereabout. The first rotor **10** shown in FIG. 1 has four poles **28**, each spaced apart by 90-degrees. However, the first rotor **10** may include any number of the poles **28**. Each of the poles **28** has a T-shape cross-section, with a body **30** extending radially outwardly from the base **22** and a head **32** extending perpendicularly to the body **30** and spaced away from the base **22**. The head **32** defines a top surface **33** spaced apart from and facing away from the base **22**.

[0029] A field winding **34** of conductive wire wraps around the body **30** of each of the poles for carrying an electrical current and thus generating a magnetic field **36** through each of the pole **28**. The field windings **34** in adjacent ones of the poles **28** are configured to carry currents in alternating directions, thereby causing adjacent ones of the poles **28** to have magnetic fields **36** in opposite directions. The first rotor **10** shown in FIG. 1 may be used as an internal rotor motor, circumferentially surrounded by a stator (not shown) that remains stationary as the first rotor **10** rotates. Alternatively, the first rotor **10** may be configured for use in an external rotor motor, with the first rotor **10** surrounding the stator. In some embodiments, such as for external rotor configurations, the poles **28** may extend radially inwardly from the base **22** of the core **20**.

[0030] FIG. 2 shows an end-view of a second rotor **110** for a wound-field synchronous machine in accordance with some embodiments of the present disclosure. The second rotor **110** has a core **120** of electrical steel that includes a base **122** having a ring-shaped cross-section between an outside surface **124** and an inside surface **126** defining a bore **127** and extending annularly about an axis of rotation of the second rotor **110**. The second rotor **110** also includes a plurality of poles **128** at regular angular intervals thereabout, each of the poles **128** being a region of the base **122** producing a corresponding magnetic field **136**. A plurality of field windings **134** are spaced apart from one another at regular angular intervals and each extending around the base **122** of the core **120**, adjacent the outside surface **124** and through the bore **127**. The second rotor **110** shown in FIG. 2 may be called a spoke-type configuration, with each of the field windings **134** extending in a radial direction, like spokes of a wheel.

[0031] In some embodiments, and as shown in FIG. 2, the base **122** of the core **120** defines a plurality of slots **130**, with each of the slots **130** extending thereabout and within each of the outer surface **124** and the inner surface **126** and receiving a corresponding one of the plurality of field windings **134**. In some embodiments, each of the slots **130** has a generally rectangular cross-section. However, one or more of the slots **130** may have a different shape. The slots **130** are disposed at regular angular intervals around the base **122**. There are four slots **130**, each spaced apart by 90-degrees in the example second rotor **110** shown in FIG. 2. However, the second rotor **110** may include any number of slots **126**.

[0032] In the second rotor **110** shown in FIG. 2, the field windings **134** are each configured to conduct current in a radial direction around the base **122** of the core **120** to induce a magnetic field **136** through the core **120** tangentially to the ring-shaped cross-section of the core. In other words, the field windings **134** generate magnetic fields **136** in the base **122**, thus defining the poles **128** as regions of the base **122** between adjacent ones of the field windings **134**. The magnetic field **136** induced by the current in the field windings **134** extends tangentially to a circle within and coaxially with the ring-shaped core **120**. The field windings **134** in adjacent ones of the slots **130** are configured to carry currents in alternating directions, thereby causing each of the poles **128** to have a common magnetic field **136** that is generated by a combination of the field windings **134** in each of the two slots **130** adjacent thereto. Likewise, the magnetic fields **136** in each of the slots **130** has a polarity opposite to the magnetic field **136** in the next adjacent ones of the poles **124**. The magnetic fields **136** are configured to interact with fields from a stator (not shown) to produce torque.

[0033] In some embodiments, and as shown in FIG. 2, each of the field windings **134** comprises a conductor **135**, such as a copper wire, extending substantially radially relative to an axis of rotation of the second rotor **110** or extending substantially parallel to a radius relative to the axis of rotation. In other words, the conductors **135** extend for a substantial length (e.g., substantially larger than a cross-section of the conductor) in a radial direction, or parallel to a radius.

[0034] FIG. 3 shows an end-view of a third rotor **210** for a wound-field synchronous machine in accordance with some embodiments of the present disclosure. The third rotor **210** of FIG. 3 is similar to the second rotor **110** of FIG. 2, with some modifications. Specifically, the third rotor **210** has a core **120** of electrical steel that includes a base **122** having a ring-shaped cross-section between an outside surface **124** and an inside surface **126** defining a bore **127** and extending annularly about an axis of rotation of the third rotor **210**. The third rotor **210** also includes a plurality of poles **128** at regular angular intervals thereabout, each of the poles **128** being a region of the base **122** producing a corresponding magnetic field **136**. The example third rotor **210** shown in FIG. 3 has four poles **128**, each spaced apart by 90-degrees. However, the third rotor **210** may include any number of poles **128**. A plurality of field windings **134** are spaced apart from one another at regular angular intervals and each extending around the base **122** of the core **120**, adjacent the outside surface **124** and through the bore **127**. The inside surface **126** of the base **122** defines a plurality of interior recesses **230** spaced apart from one another at a regular angular intervals. In the example third rotor **210** shown in FIG. 3, the interior recesses **230** are formed as notches having a V-shaped cross-section, however, the interior recesses **230** may have different shapes or configurations. An external coil retainer **232** is disposed upon the outside surface **124** of the base **122**. The external coil retainer **232** is circumferentially separated from a corresponding one of the interior recesses **230**.

[0035] In some embodiments, and as shown in FIG. 3, each of the external coil retainers **232** are circumferentially offset midway between two adjacent ones of the interior recesses **230**. A field winding **234** extends radially and circumferentially from one of the interior recesses **230** around the base **122** of the core **120** and to a corresponding one of the external coil retainers **232**. In some embodiments, and as shown in FIG. 3, each of the external coil retainers **232** is formed as a groove having a V-shaped cross-section in the outside surface **124** of the base **122**. In other embodiments, one or more of the external coil retainers **232** may be formed as a protrusion extending radially outwardly from the outside surface **124** of the base **122**. The external coil retainers **232** may take other forms, such as portions or regions of a material, such as a potting material, that hardens to secure the field winding **134** at a predetermined position upon the outside surface **124** of the base **122**.

[0036] The V-shaped configuration of the field windings **134** may use less conductors when compared with conventional designs, since two coils contribute to the induced magnetic field **136** of each pole **128**. For example, each field winding **134** may use half the number of turns when compared with a conventional design.

[0037] As shown in FIG. 3, the base **122** defines a first angle **α1** between adjacent ones of the external coil retainers **232**, and each of the external coil retainers **232** defines a second angle **α2**, with the field windings **134** disposed within the second angle **α2** adjacent to the outside surface **124** of the base **122**. The first angle **α1** is substantially larger than the second angle **α2**.

[0038] In some embodiments, and as shown in FIG. 3, the inside surface **126** of the base **122** has a generally circular cross-section. FIG. 4 shows a fourth rotor **310** having a similar configuration to the third rotor **210** of FIG. 3. In some embodiments, and as shown in FIG. 4, the inside surface **126** of the base **122** defines a convex curve extending radially inwardly between adjacent ones of the plurality of interior recesses **230**, thus providing the bore **127** with a star-shaped cross-section. The inside surface **126** of the base **122** may define other shapes. For example, inside surface **126** of the base **122** may define straight lines between adjacent ones of the plurality of interior recesses **230**, thus providing the bore **127** with a cross-sectional shape of a regular polyhedron, such as a hexagon or an octagon.

[0039] The example embodiments of FIGS. 3-4 each include the field windings **234** arranged in a V-shape. The field windings **234** are wrapped axially around the rotor core **120** where two field windings **234** contribute to the production of a single pole **128**. The small arrows on the field windings **234** indicate the direction of current to form the poles **128** of the machine. The shape of the rotor core **120** can be configured as shown in FIGS 2 and 3 to decrease saturation and torque ripple as well as enhancing the mechanical integrity of the rotor structure **120** and/or field windings **234**.

[0040] FIG. 5 shows an end-view diagram of a fifth rotor **410** for a wound-field synchronous machine in accordance with some embodiments of the present disclosure. The fifth rotor **410** is similar in construction to the third rotor **210** of FIG. 3, but with the field windings **234** not contacting either of the outside surface **124** or the inside surface **126** of the base **122** of the core **120**. Instead, the base **122** of the fifth rotor **410** defines a plurality of first holes **420** extending therethrough at regular circumferential intervals and disposed radially inwardly from the outside surface **124**. Each of the first holes **420** has a wedge shape, with a point facing radially inwardly, but the first holes **420** may have other shapes, such as, for example, a triangle, a square, or a circle. The base **122** of the fifth rotor **410** also defines a plurality of second holes **422** extending therethrough at regular circumferential intervals and disposed radially inwardly from the first holes **420**. Each of the second holes **422** has a triangular shape, with a point facing radially outwardly, but the second holes **422** may have other shapes, such as, for example, a wedge, a square, or a circle. Each of the second holes **422** is disposed circumferentially mid-way between two corresponding ones of the first holes **420**. The field windings **234** extend radially and circumferentially between each of the first holes **420** and next circumferentially adjacent ones of the second holes **422**. Unless explicitly defined otherwise, the term “regular circumferential intervals” is intended to mean a same circumferential arc length between each of any two circumferentially adjacent structures.

[0041] FIG. 6 shows an end-view diagram of a sixth rotor **510** for a wound-field synchronous machine in accordance with some embodiments of the present disclosure. The sixth rotor **510** is similar in construction to the third rotor **210** of FIG. 3, but with the field windings **234** not contacting the inside surface **126** of the base **122** of the core **120**. The sixth rotor **510** is also similar to the fifth rotor **410** of FIG. 5 in that they both include a plurality of regularly spaced second holes **422**. Each of the second holes **422** of the sixth rotor **510** is disposed circumferentially mid-way between two corresponding ones of the external coil retainers **232**, and the field windings **234** each extend radially and circumferentially between each of the second holes **422** and next circumferentially adjacent ones of the external coil retainers **232**.

[0042] FIG. 7 shows an end-view diagram of a seventh rotor **610** for a wound-field synchronous machine in accordance with some embodiments of the present disclosure. The seventh rotor **610** is similar in construction to the third rotor **210** of FIG. 3, but with the field windings **234** not contacting the outside surface **124** of the base **122** of the core **120**. The seventh rotor **610** is also similar to the fifth rotor **410** of FIG. 5 in that they both include a plurality of regularly spaced first holes **420**. Each of the first holes **420** of the seventh rotor **610** is disposed circumferentially mid-way between two corresponding interior recesses **230** in the inside surface **126** of the base **122**, and the field windings **234** each extend radially and circumferentially between each of the first holes **420** and next circumferentially adjacent ones of the interior recesses **230**.

[0043] The rotors **210, 310, 410, 510, 610** of FIGS. 3-7 all function similarly to the second rotor **110** of FIG. 2, with the field windings **234** each configured to conduct current in a radial direction around at least a portion the base **122** of the core **120** to induce a magnetic field **136** through the core **120** tangentially to the ring-shaped cross-section of the core. This results in current through the field windings **234** generating magnetic fields **136** in the base **122**, thus defining the poles **128** as regions of the base **122** between adjacent ones of the field windings **134**. The magnetic field **136** induced by the current in the field windings **234** extends tangentially to a circle within and coaxially with the ring-shaped core **120**. As shown in FIG. 3, the field windings **234** are configured to carry currents in alternating directions, thereby causing each of the poles **128** to have a common magnetic field **136** that is generated by a combination of the field windings **134** in each of the two slots **130** adjacent thereto. The poles **128** have alternating polarity around a circumference of the core **120**.

[0044] FIGS. 8-10 show example configurations for permanent magnet (PM) assisted WFSMs. FIG. 8 shows an end-view diagram of an eighth rotor **710** for a wound-field synchronous machine in accordance with some embodiments of the present disclosure. The an eighth rotor **710** of FIG. 8 is similar to the conventional salient pole first rotor **10** of FIG. 1, but with the addition of a permanent magnet **440** disposed within each of the poles **24**. More specifically, FIG. 8 shows a particular embodiment of an eighth rotor **710** in which the permanent magnet **440** is recessed within a top surface **33** of each of the poles **24** opposite from the base **22**. In some embodiments, and as shown in FIG. 8, the an eighth rotor **710** each of the poles **28** extends radially outwardly from the base **22** away from an axis of rotation of the eighth rotor **710**. In some alternative embodiments, such as, for example in an external rotor electric machine, each of the poles **28** extends radially inwardly from the base **22** toward the axis of rotation of the eighth rotor **710**.

[0045] In other embodiments, the permanent magnet **440** may have a different arrangement within the poles **24**. For example, a rotor **110**, **210**, **310** having a design as shown in FIGS. 2-4 may be provided with one or more permanent magnet **440** within each of the poles.

[0046] FIG. 9 shows an end-view diagram of a ninth rotor **810** for a wound-field synchronous machine in accordance with some embodiments of the present disclosure. The sixth rotor **510** of FIG. 9 is similar to the eighth rotor **710** of FIG. 8, except each of the permanent magnets **540** is disposed between two adjacent ones of the poles **28**. More specifically, each of the permanent magnets **540** extend circumferentially between a head **32** of the pole **28** and a head **32** of the next adjacent one of poles **28**, with the heads **32** of each of the plurality of poles **28** radially spaced apart from the base **22** of the core **20**. In some embodiments, and as shown in FIG. 9, the each of the poles **28**, extends radially outwardly from the base **22** away from an axis of rotation. In some alternative embodiments, such as, for example in an external rotor electric machine, each of the poles **28** extends radially inwardly from the base **22** toward the axis of rotation of the rotor **710**.

[0047] FIG. 10 shows an end-view diagram of a tenth rotor **910** for a wound-field synchronous machine in accordance with some embodiments of the present disclosure. The tenth rotor **910** of FIG. 10 is similar to the second rotor **110** of FIG. 2, except for the addition of a permanent magnet **840** in each of the poles **128**. In some embodiments, and as shown in FIG. 10, each of the permanent magnets **840** is shaped as an arcuate segment of an annular ring that is recessed within the base **122** of the core **120** and flush with the outside surface **124** of the base **122**. However, the permanent magnets **840** may have a different shape, orientation, and/or configuration.

[0048] FIGS. 11-13 show rotors **240, 250, 260** each with a transformer winding **242, 252, 262** in addition to the field windings **134, 234**, described above. The transformer winding **242, 252, 262** may be one of a plurality of transformer windings **242, 252, 262**, which may be equal in number to the number of poles **128**. The transformer windings **242, 252, 262** and field windings **134** can be configured differently than as shown in the figures. In addition to the fundamental current fed to the stator windings, harmonic current is also fed to the stator windings. An AC voltage is induced in the transformer windings **242, 252, 262** due to a harmonic current excitation in the stator windings. The AC voltage output of the transformer windings **242, 252, 262** may be rectified to a DC power, which may then be supplied to the field windings **134, 234**. For example, a rotating rectifier located on the shaft of the WFSM (not shown in the FIGS) may be used to rectify the AC voltage output of the transformer windings **242, 252, 262**. Such a rotating rectifier may be built on a circular PCB spinning along with the rotor. The DC output of the rectifier may be fed to the field windings **134, 234** of the rotor. Controlling the harmonic current magnitude in the stator can control the DC current magnitude in the field winding. The transformer windings **242, 252,**

262 could be configured as 1-phase or 3-phase windings. An electric machine incorporating such a rotor **240, 250, 260** could be called a self-excited or harmonic excited WFSM.

[0049] FIG. 11 shows an end-view diagram of an eleventh rotor **240** for a wound-field synchronous machine. The eleventh rotor **240** has a similar configuration to the third rotor **210** of FIG. 3, with the field windings **234** extending radially and circumferentially around the base **122** of the core **120** in a V-shaped configuration. FIG. 11 also includes a first transformer winding **242** disposed within one of the poles **128**. The first transformer winding **242** shown in FIG. 11 is disposed around the core **120** of the rotor **240**, extending in a generally radial direction between two third holes **244** in the core **120** of the rotor **240**. This is merely one example, and the first transformer winding **242** may be wound around all or part of the core **120**. For example, the first transformer winding **242** may be disposed around either or both of the outside surface **124** and/or the inside surface **126**. In some embodiments, the first transformer winding **242** may be disposed within an interior recess **230** in the inside surface **126**. In some embodiments, the first transformer winding **242** may be disposed within an external coil retainer **232**, such as a rectangular or V-shaped notch in the outside surface **124**. In some embodiments, the first transformer winding **242** may be disposed within a same interior recess **230** and/or external coil retainer **232** with one or more of the field windings **34, 134, 234**.

[0050] FIG. 12 shows an end-view diagram of an twelfth rotor **250** for a wound-field synchronous machine. The twelfth rotor **250** has a similar configuration to the third rotor **210** of FIG. 3, with the field windings **234** extending radially and circumferentially around the base **122** of the core **120** in a V-shaped configuration. FIG. 12 also includes a second transformer winding **252** disposed within one of the poles **128**. The second transformer winding **252** shown in FIG. 12 is disposed around the core **120** of the rotor **240**, wound radially and circumferentially between an external coil retainer **232**, such as a V-shaped notch, and an interior recess **230** in the inside surface **126**. The second transformer winding **252** may be arranged in an alternating pattern with the field windings **234**, as shown in FIG. 12. This is merely one example, and the second transformer winding **252** may be wound around all or part of the core **120**. For example, the second transformer winding **252** may be disposed around either or both of the outside surface **124** and/or the inside surface **126**.

[0051] FIG. 13 shows an end-view diagram of an thirteenth rotor **260** for a wound-field synchronous machine. The thirteenth rotor **260** has a similar configuration to the third rotor **210** of FIG. 3, with the field windings **234** extending radially and circumferentially around the base **122** of the core **120** in a V-shaped configuration. FIG. 13 also includes a third transformer winding **262** disposed between two adjacent ones of the poles **128**. The third transformer winding **262** shown in FIG. 13 is disposed around the core **120** of the rotor **240**, extending in a generally radial direction between two fourth holes **264** in the core **120** of the rotor **240**. This is merely one example, and the third transformer winding **262** may be wound around all or part of the core **120**. For example, the third transformer winding **262** may be disposed around either or both of the outside surface **124** and/or the inside surface **126**. In some embodiments, the third transformer winding **262** may be disposed within an interior recess **230** in the inside surface **126**. In some embodiments, the third transformer winding **262** may be disposed within an external coil retainer **232**, such as a rectangular or V-shaped notch in the outside surface **124**. In some embodiments, the first transformer winding **242** may be disposed within a same interior recess **230** and/or external coil retainer **232** with one or more of the field windings **34, 134, 234**.

[0052] The transformer windings **242, 252, 262** are configured to generate an induced voltage for supplying power to the field windings **34, 134, 234**. For example, one or more of the transformer windings **242, 252, 262** may be connected as an input to a rectifier, which may produce a DC output to be fed to the field windings **134, 234**, as described above.

[0053] The proposed V-shaped field windings **34, 134, 234** in the rotor **240, 250, 260** enable manufacturing feasibility and mechanical strength to the transformer winding **242, 252, 262** and core **120**. The machine can have 'n' number of phases, 'k' number of slots and 'm' number of poles. Number of the harmonic component and magnitude depends on n, k, m and winding type.

[0054] A method **1000** of operating an electric machine is shown in the flow chart of FIG. 14. The method **1000** includes conducting an electrical current through a field winding **34, 134, 234** disposed around a pole **28** of a rotor **110**, **210**, **310, 410, 510** to produce an induced magnetic field **36, 136** in the pole **28** at step **1002**. This induced magnetic field **36, 136** can be controlled or modified as a field excitation control variable. The electrical current may be transmitted to the rotor **110**, **210**, **310, 410, 510** in any one of several different ways. For example, the electric machine (i.e., the field windings **34, 134, 234)** can be self-excited or separately excited. The excitation to the rotor **110**, **210**, **310, 410, 510** can come from the stator or from a power supply assembly on the rotor. For example, in a separately excited configuration, the power supply to the rotor **110**, **210**, **310, 410, 510** can come from a capacitive coupling, an inductive coupling, brushes, a slip ring arrangement, etc. In case of self-excitation, the rotor **110**, **210**, **310, 410, 510** will have a field coil and transformer coil. The transformer coil links with the stator excitation and produces an AC supply which will be converter to DC supply to feed the field winding **34, 134, 234**. The conversion will take place using a rectifier that could be mounted on the rotor **110**, **210**, **310, 410, 510**. The transformer coils and field windings **34, 134, 234** could be placed in different ways in the rotor **110**, **210**, **310, 410, 510**. The transformer coils could be adjacent to the field windings **34, 134, 234** in different rotor poles. Alternatively, the transformer coil could be wound on the same rotor pole that the field winding **34, 134, 234** is wound on.

[0055] In some embodiments, the method **1000** also includes generating a permanent magnetic field in the pole **28** with a permanent magnet **440**, **540** at step **1004**. In some embodiments, the induced magnetic field **36, 136** is configured to additively supplement the permanent magnetic field in the pole **28**.

[0056] In some embodiments, the method **1000** also includes reducing the current in the field winding **34, 134, 234** to reduce the induced magnetic field **36, 136** in a field-weakening mode at step **1006**.

[0057] The foregoing description is not intended to be exhaustive or to limit the disclosure. Individual elements or features of a particular embodiment are generally not limited to that particular embodiment, but, where applicable, are interchangeable and can be used in a selected embodiment, even if not specifically shown or described. The same may also be varied in many ways. Such variations are not to be regarded as a departure from the disclosure, and all such modifications are intended to be included within the scope of the disclosure.

CLAIMS

What is claimed is:

Claim 1. A rotor for an electric machine comprising:

a core having a base with a ring-shaped cross-section extending between an outside surface and an inside surface defining a bore;

a plurality of field windings spaced apart from one another at regular angular intervals and each configured to conduct current in a radial direction around the base of the core to induce a magnetic field through the core tangentially to the ring-shaped cross-section.

Claim 2. The rotor of claim 1, wherein the corresponding one of the plurality of field windings extends around the core adjacent the outside surface and through the bore.

Claim 3. The rotor of claim 1, further comprising the base of the core defining a plurality of slots, with each of the slots receiving a corresponding one of the plurality of field windings.

Claim 4. The rotor of claim 1, further comprising a transformer winding disposed around the core of the rotor and configured to generate an induced voltage for supplying power to the field windings; and

wherein the plurality of field windings each extend radially and circumferentially around the base of the core.

Claim 5. A rotor for an electric machine comprising:

a core having a base with a ring-shaped cross-section extending between an outside surface and an inside surface defining a bore;

the inside surface of the base defining an interior recesses;

an external coil retainer disposed upon the outside surface of the base, the external coil retainer circumferentially separated from the interior recess

a field winding extending radially and circumferentially from the interior recess around the base of the core and to the external coil retainer;

wherein the interior recess is one of a plurality of interior recesses spaced apart from one another at a regular angular interval.

Claim 6. The rotor of claim 5, wherein the external coil retainer is formed as one of: a groove having a V-shaped cross-section in the outside surface of the base, or a protrusion extending radially outwardly from the outside surface of the base.

Claim 7. The rotor of claim 5, wherein the inside surface of the base defines one of: a generally circular cross-section, or a convex curve extending radially inwardly between adjacent ones of the plurality of interior recesses.

Claim 8. A rotor for an electric machine comprising:

a core having a base and a pole extending radially therefrom;

a field winding extending about the pole for generating an induced magnetic field therein; and

a permanent magnet disposed within the pole.

Claim 9. The rotor of claim 8, wherein the permanent magnet is recessed within a top surface of the pole opposite of the base.

Claim 10. The rotor of claim 8, wherein the pole is one of a plurality of poles; and

wherein each pole of the plurality of poles extends either radially outwardly from the base away from an axis of rotation of the rotor, or radially inwardly from the base toward an axis of rotation of the rotor.

Claim 11. A rotor for an electric machine comprising:

a core having a base and a pole extending radially therefrom;

a field winding extending about the pole for generating an induced magnetic field therein;

wherein the pole is one of a plurality of poles spaced apart from one another at regular angular intervals;

a permanent magnet disposed between the pole and a next adjacent one of the plurality of poles.

Claim 12. The rotor of claim 11, wherein the pole is one of a plurality of poles; and

wherein each pole of the plurality of poles extends either radially outwardly from the base away from an axis of rotation of the rotor, or radially inwardly from the base toward an axis of rotation of the rotor.

Claim 13. The rotor of claim 11, wherein the permanent magnet extends circumferentially between a head of the pole and a head of the next adjacent one of poles, with the heads of each of the plurality of poles radially spaced apart from the base of the core.

Claim 14. A method of operating an electric machine, comprising:

conducting an electrical current through a field winding disposed around a pole to produce an induced magnetic field in the pole; and

generating a permanent magnetic field in the pole with a permanent magnet.

Claim 15. The method of operating an electric machine of claim 14, wherein the induced magnetic field is configured to additively supplement the permanent magnetic field in the pole.

Claim 16. The method of operating an electric machine of claim 14 further comprising: reducing the current in the field winding to reduce the induced magnetic field in a field-weakening mode.

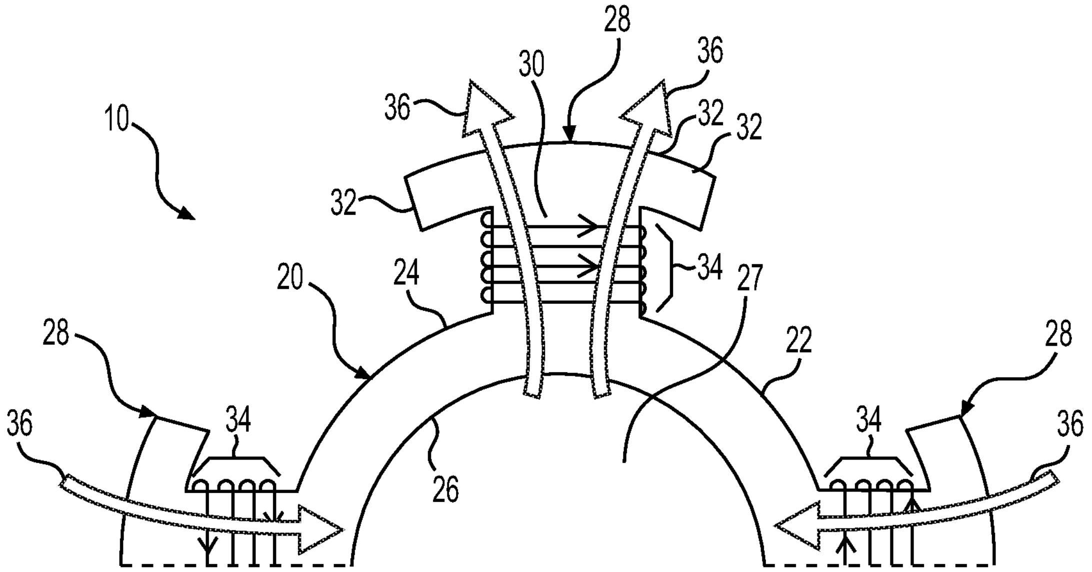
10
20
22
24
26
27
28
30
32
34
36

FIG. 1

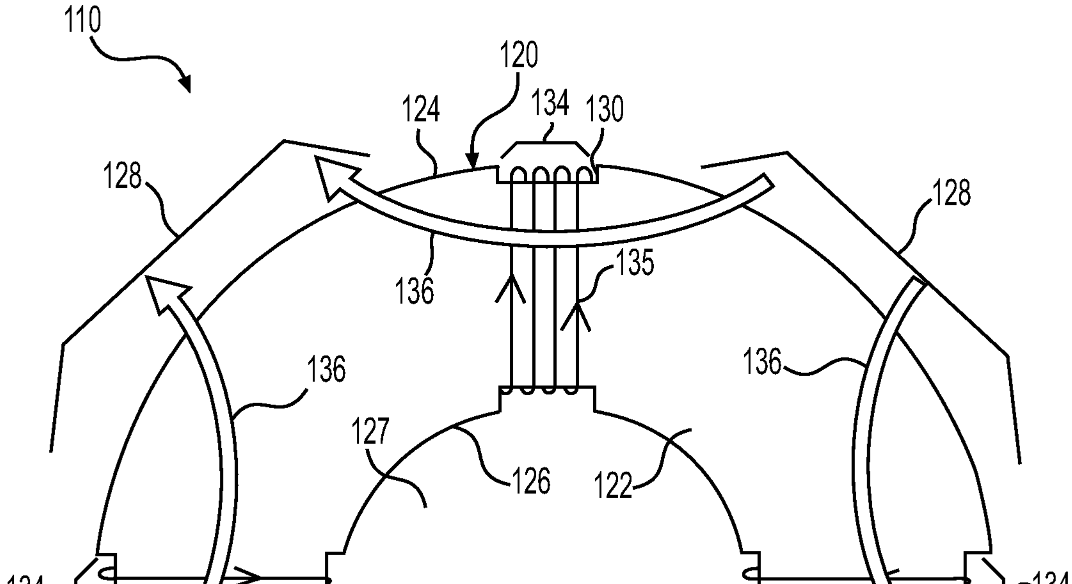
110
120
122
124
126
127
128
130
134
135
136

FIG. 2

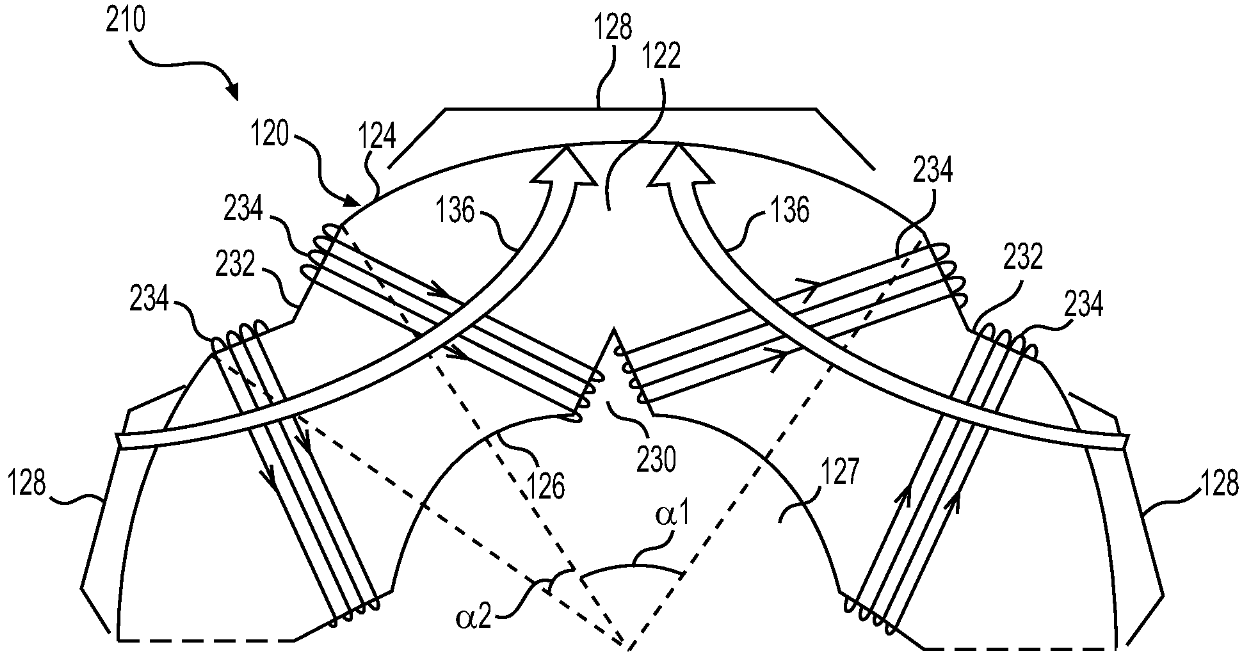
210
128
122
120
124
234
136
136
234
232
232
234
234
230
126
127
128
128
α1
α2

FIG. 3

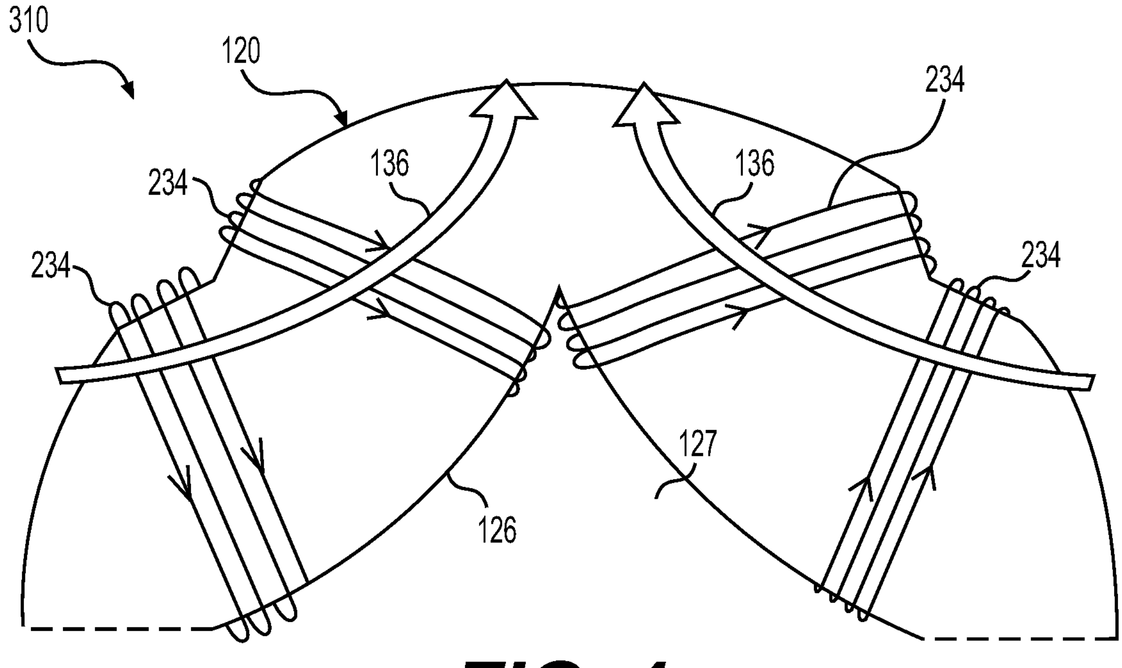
310
120
234
234
136
136
234
234
126
127

FIG. 4

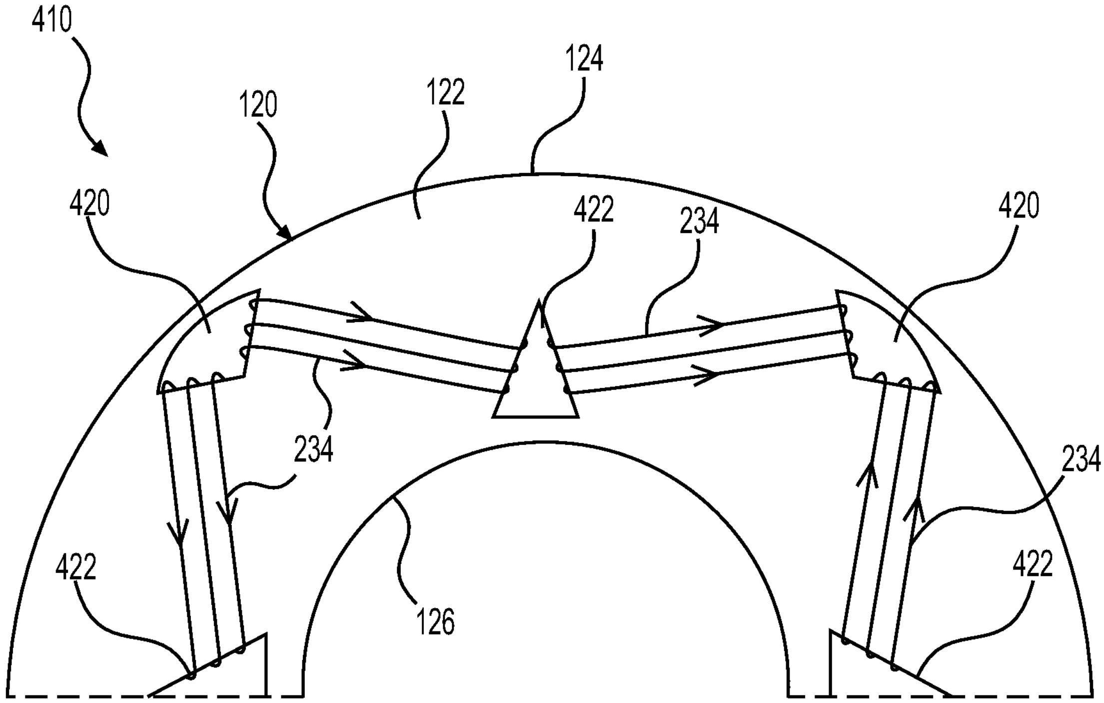
410
120
122
124
420
422
234
420
234
234
422
126
422

FIG. 5

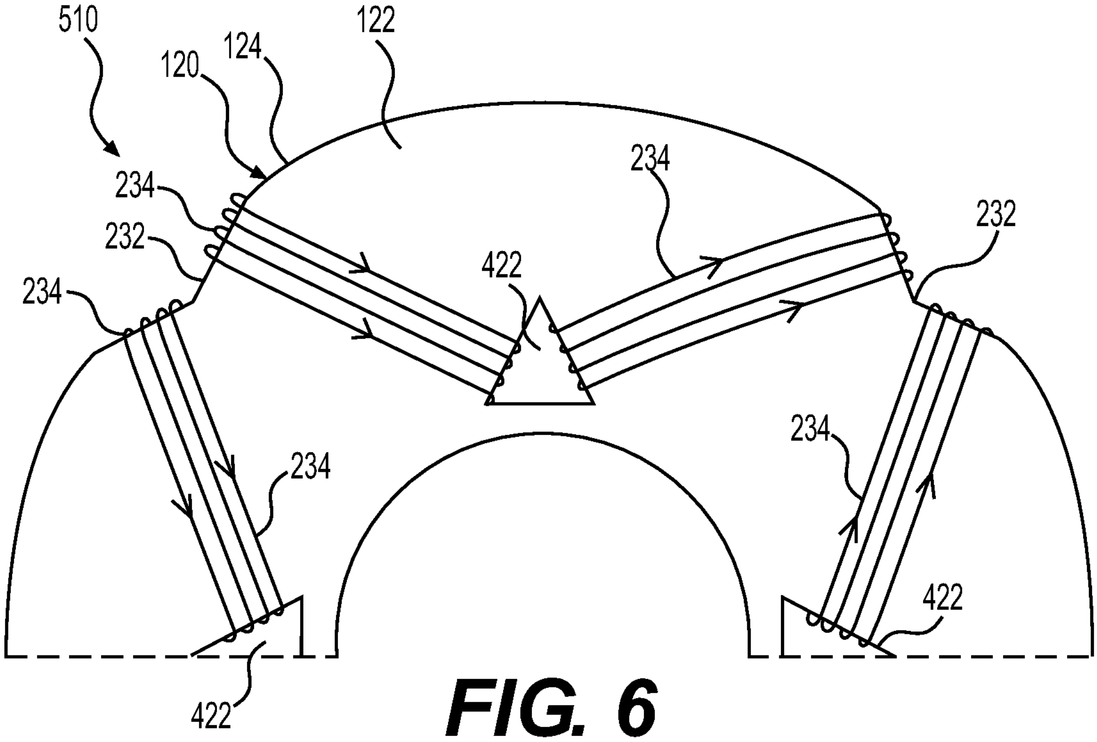
510
120
124
122
234
232
234
422
234
232
234
234
422
422

FIG. 6

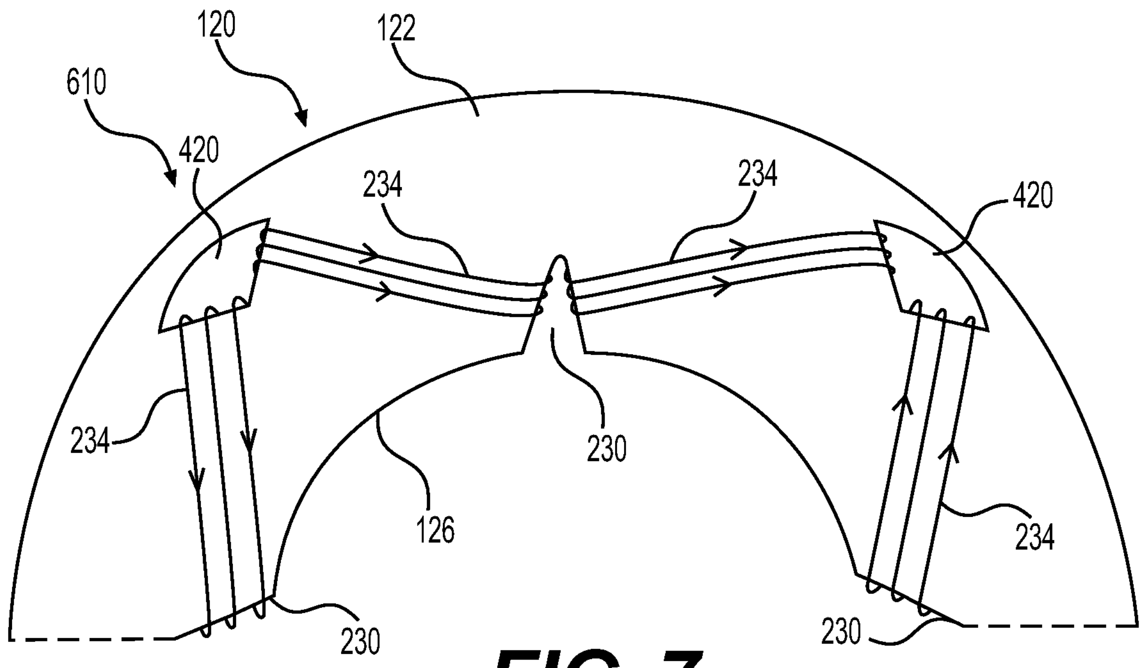
120
122
610
420
234
234
420
234
230
126
234
230
230

FIG. 7

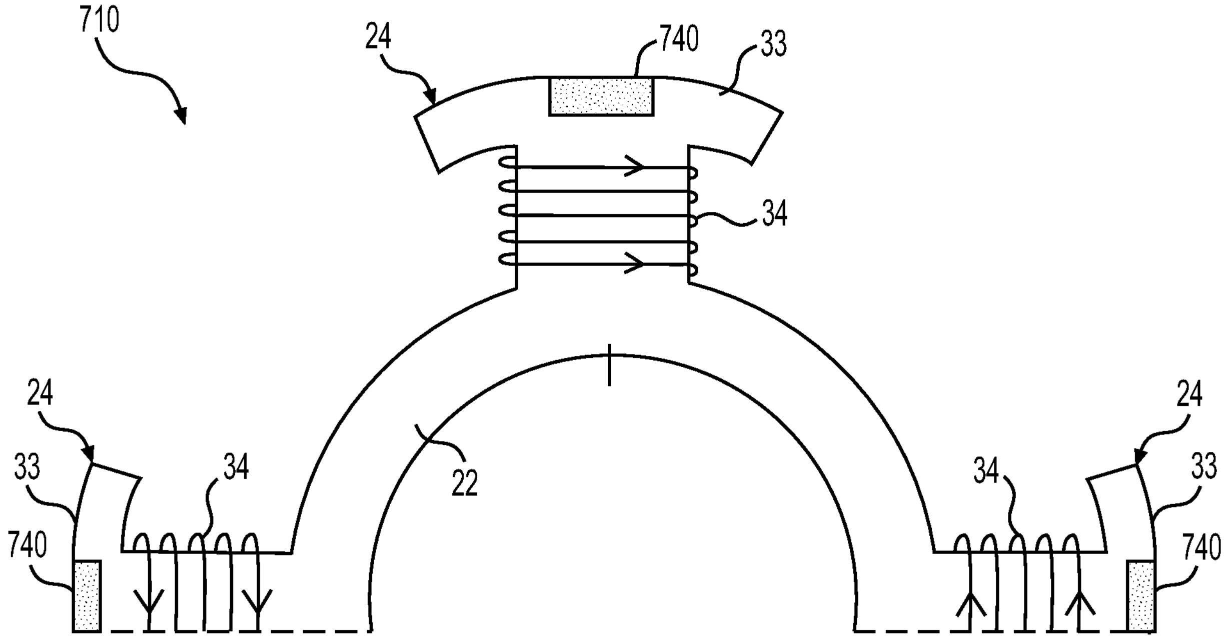
710
24
740
33
34
24
33
740
34
22
34
24
33
740

FIG. 8

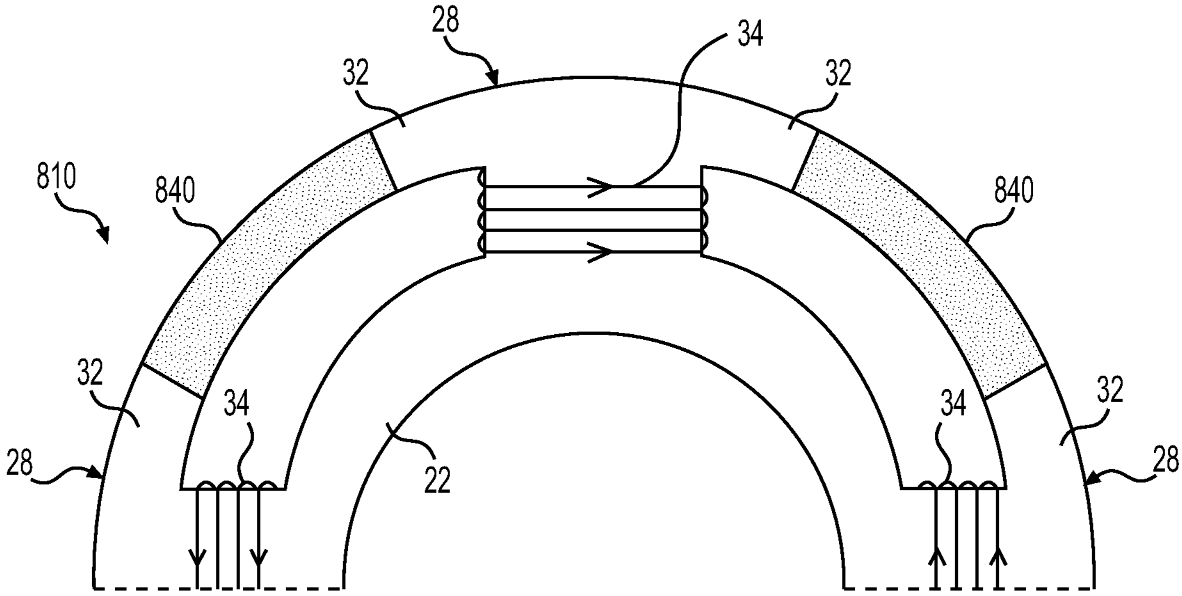
28
34
32
32
810
840
840
32
34
34
32
28
22
28

FIG. 9

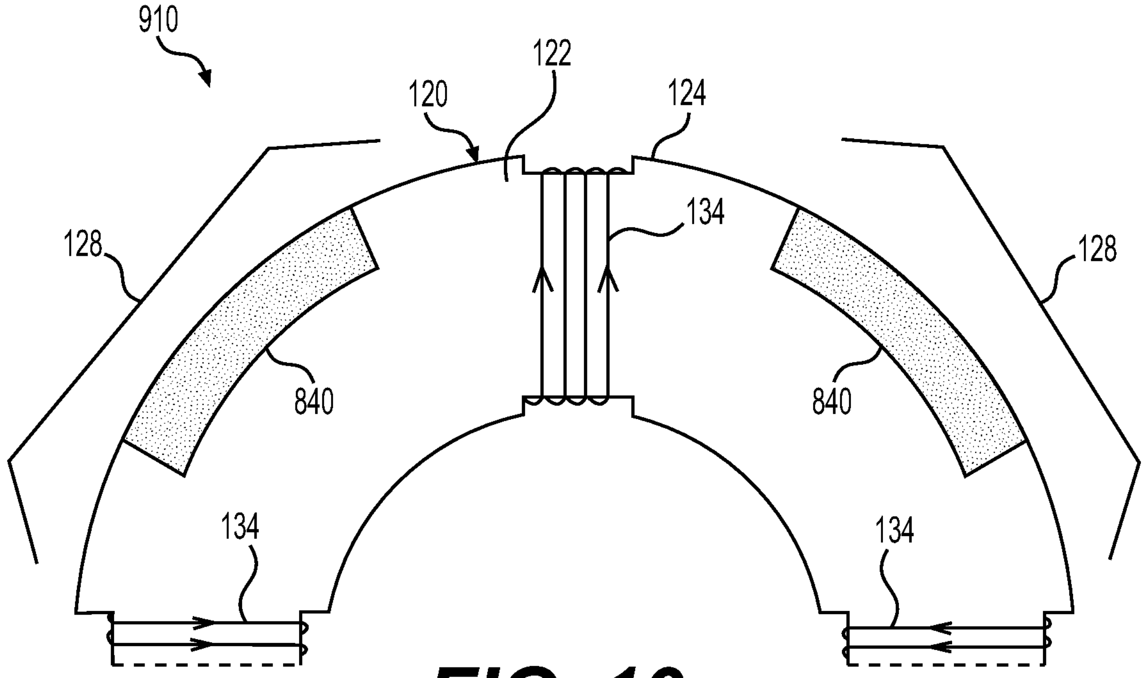
910
122
120
124
134
128
128
840
840
134
134

FIG. 10

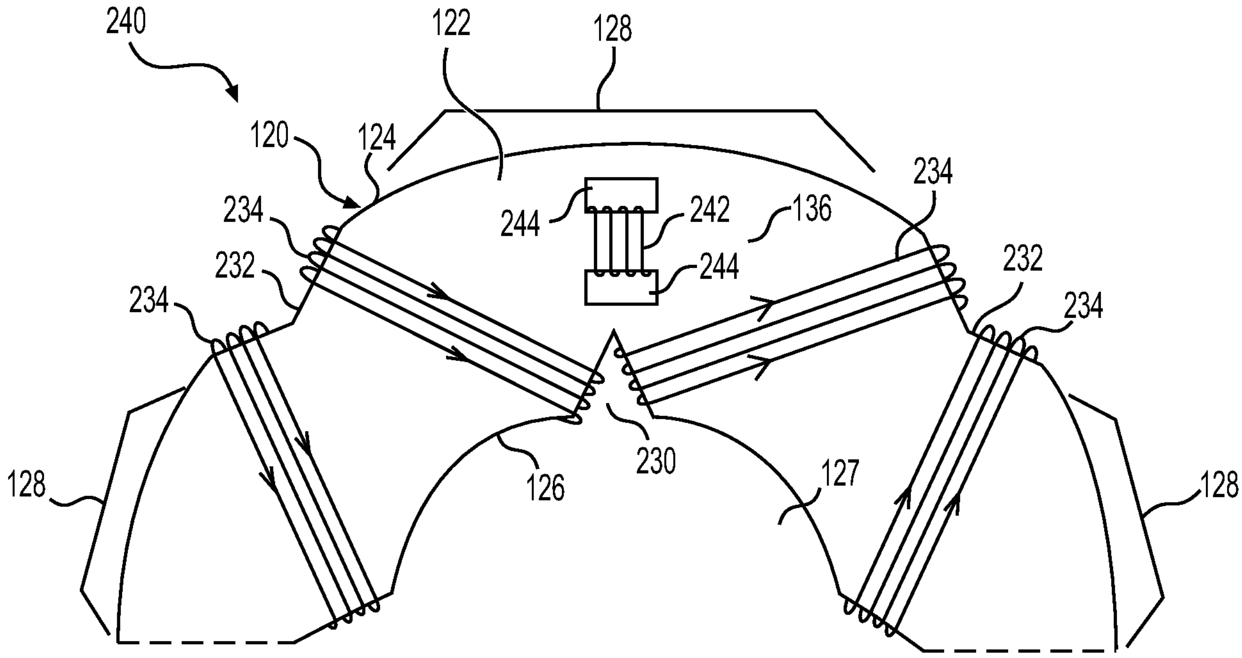
240
122
128
120
124
234
244
242
136
232
244
234
232
234
128
126
230
127
128

FIG. 11

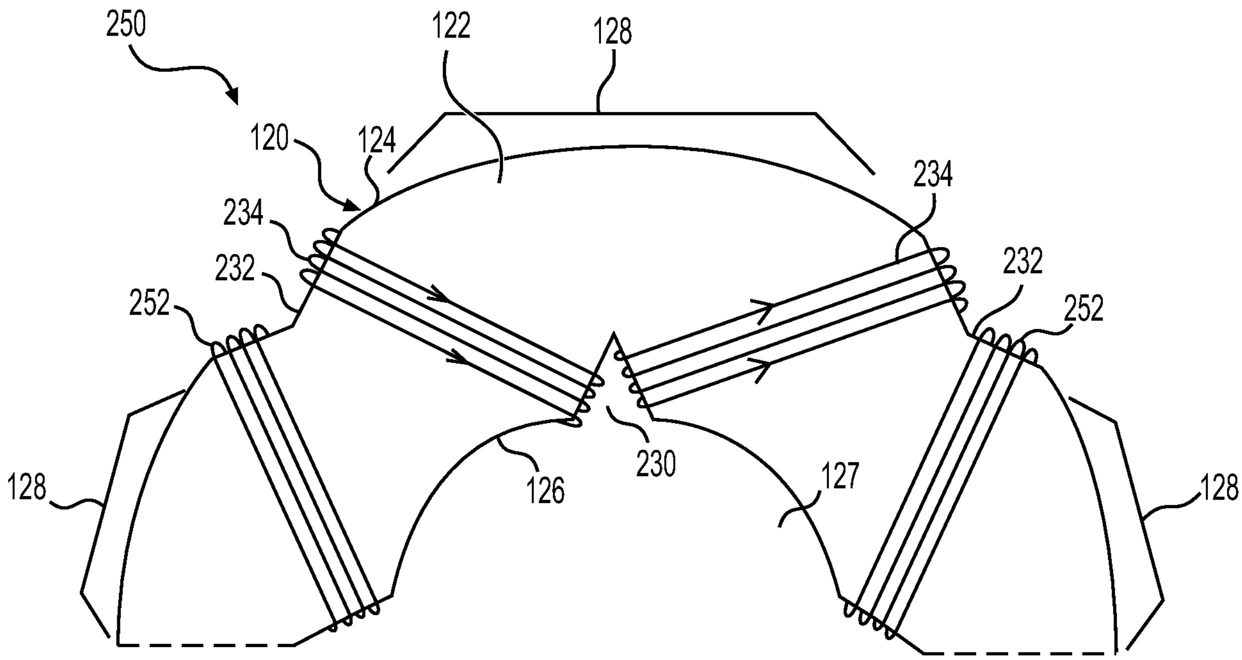
250
122
128
120
124
234
232
234
252
232
252
128
126
230
127
128

FIG. 12

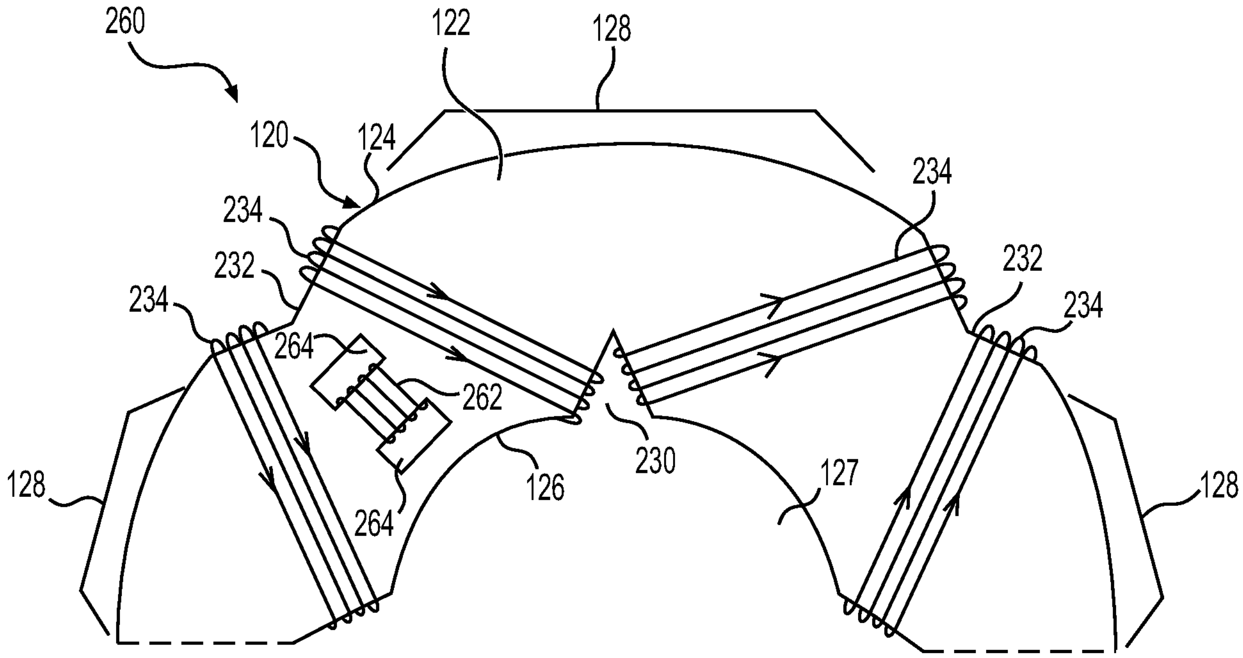
260
122
128
120
124
234
234
232
234
264
262
232
234
128
264
126
230
127
128

FIG. 13

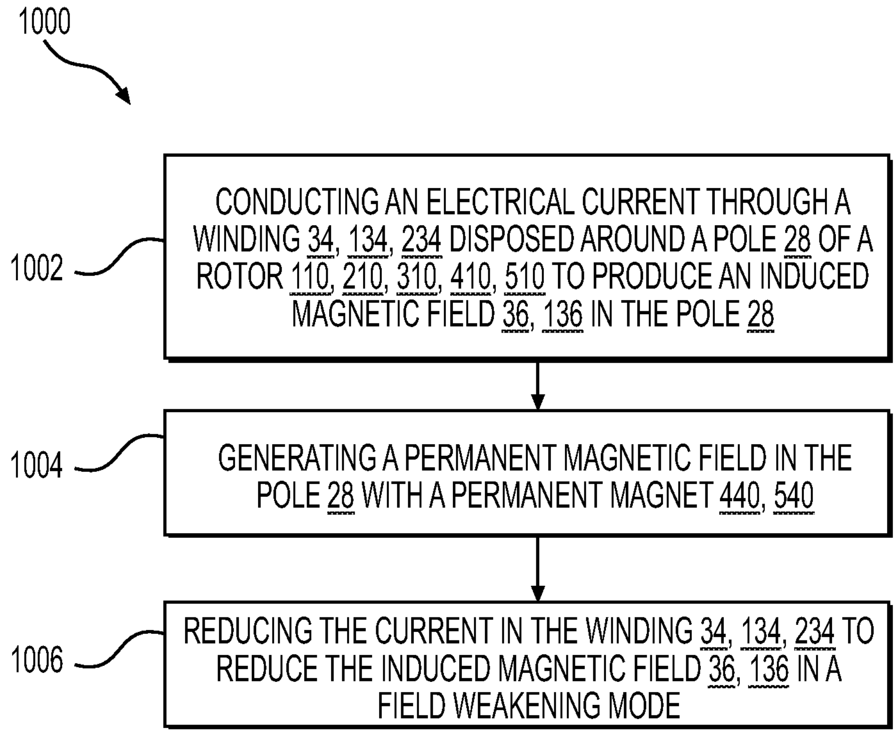
1000
1002
CONDUCTING AN ELECTRICAL CURRENT THROUGH A WINDING 34, 134, 234 DISPOSED AROUND A POLE 28 OF A ROTOR 110, 210, 310, 410, 510 TO PRODUCE AN INDUCED MAGNETIC FIELD 36, 136 IN THE POLE 28
1004
GENERATING A PERMANENT MAGNETIC FIELD IN THE POLE 28 WITH A PERMANENT MAGNET 440, 540
1006
REDUCING THE CURRENT IN THE WINDING 34, 134, 234 TO REDUCE THE INDUCED MAGNETIC FIELD 36, 136 IN A FIELD WEAKENING MODE

FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/053963

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H02K 1/27; H02K 1/14; H02K 3/18; H02K 1/17; H02K 1/20 (2021.01)

CPC - H02K 3/28; H02K 3/18; H02K 21/44; H02K 1/17; H02K 1/20 (2021.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

see Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

see Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

see Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y --- A	US 2017/0163113 A1 (MITSUBISHI ELECTRIC CORPORATION) 08 June 2017 (08.06.2017) entire document	8, 9, 11, 14 --- 1-7, 10, 12, 13, 15, 16
Y --- A	US 2004/0256935 A1 (KENNY et al) 23 December 2004 (23.12.2004) entire document	8, 9, 14 --- 10, 15, 16
Y --- A	US 8,922,087 B1 (RITTENHOUSE) 30 December 2014 (30.12.2014) entire document	11 --- 1-7, 12, 13
Y --- A	US 6,703,741 B1 (IFRIM) 09 March 2004 (09.03.2004) entire document	11 --- 12, 13
A	US 2017/0346374 A1 (MAGNA POWERTRAIN GMBH & CO KG) 30 November 2017 (30.11.2017) entire document	1-7, 10, 12
A	US 2015/0248982 A1 (DIVERGENT, INC.) 03 September 2015 (03.09.2015) entire document	16

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 January 2021	11 FEB 2021

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Blaine R. Copenheaver Telephone No. PCT Helpdesk: 571-272-4300

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/053963

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
See extra sheet(s).

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☒ No protest accompanied the payment of additional search fees.

Continued from Box No. III Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-4 and 8-16, are drawn to a rotor for an electric machine comprising a plurality of field windings spaced apart from one another at regular angular intervals.

Group II, claims 5-7, are drawn to a rotor for an electric machine comprising: the inside surface of the base defining an interior recesses.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: a plurality of field windings spaced apart from one another at regular angular intervals and each configured to conduct current in a radial direction around the base of the core to induce a magnetic field through the core tangentially to the ring-shaped cross-section as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: ; the inside surface of the base defining an interior recesses; an external coil retainer disposed upon the outside surface of the base, the external coil retainer circumferentially separated from the interior recess a field winding extending radially and circumferentially from the interior recess around the base of the core and to the external coil retainer; wherein the interior recess is one of a plurality of interior recesses spaced apart from one another at a regular angular interval as claimed therein is not present in the invention of Group I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of a rotor for an electric machine comprising: a core having a base with a ring-shaped cross-section, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2017/0163113 to Mitsubishi Electric Corporation teaches a rotor for an electric machine comprising: a core having a base with a ring-shaped cross-section (Paras. [0010], [0022-0026]).

Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.