US010476349B2

(12) United States Patent
Toliyat et al.

(10) **Patent No.: US 10,476,349 B2**
(45) **Date of Patent: Nov. 12, 2019**

(54) **METHOD AND APPARATUS FOR COMPACT AXIAL FLUX MAGNETICALLY GEARED MACHINES**

(71) Applicant: **The Texas A&M University System**, College Station, TX (US)

(72) Inventors: **Hamid A. Toliyat**, College Station, TX (US); **Matthew C. Johnson**, Mesquite, TX (US); **Matthew C. Gardner**, Austin, TX (US)

(73) Assignee: **The Texas A&M University System**, College Station, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 375 days.

(21) Appl. No.: **15/287,493**

(22) Filed: **Oct. 6, 2016**

(65) **Prior Publication Data**

US 2017/0104388 A1 Apr. 13, 2017

Related U.S. Application Data

(60) Provisional application No. 62/239,695, filed on Oct. 9, 2015.

(51) **Int. Cl.**

H02K 7/116	(2006.01)
H02K 15/02	(2006.01)
H02K 16/02	(2006.01)
H02K 7/11	(2006.01)
H02K 49/10	(2006.01)

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

CPC ***H02K 7/116*** (2013.01); ***H02K 7/11*** (2013.01); ***H02K 15/02*** (2013.01); ***H02K 16/02*** (2013.01); *H02K 49/102* (2013.01)

(58) **Field of Classification Search**

CPC H02K 7/116; H02K 7/11; H02K 16/02; H02K 15/02; H02K 49/102

USPC 310/3, 83

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2013/0099501	A1	4/2013	Focchi et al.	
2016/0134180	A1*	5/2016	Tchervenkov	H02K 21/24 310/156.37
2017/0005560	A1*	1/2017	Bird	H02K 49/102
2017/0104388	A1*	4/2017	Toliyat	H02K 7/116
2017/0110956	A1*	4/2017	Morris	H02K 49/102

FOREIGN PATENT DOCUMENTS

CN	101976905	A	2/2011	
DE	102014210299	A1 *	12/2015	H02K 49/102
WO	WO-2012014596	A1 *	2/2012	H02K 49/108
WO	WO-2015/117231	A1	8/2015	
WO	WO-2016104919	A1 *	6/2016	H02K 49/102

OTHER PUBLICATIONS

Thomas, Shane, "International Search Report", prepared for PCT/US2016/055806, dated Jan. 9, 2017, 2 pages.

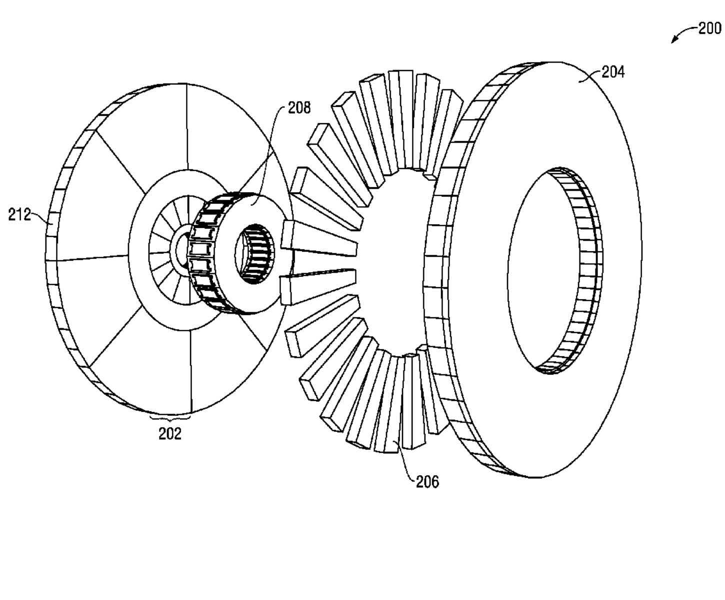
* cited by examiner

Primary Examiner — Forrest M Phillips
(74) *Attorney, Agent, or Firm* — Winstead PC

(57) **ABSTRACT**

An axial flux magnetic geared machine includes a high speed magnetic rotor and a low speed magnetic rotor maintained in a spaced relationship from the high speed magnetic rotor. A modulating structure is disposed between the high speed magnetic rotor and the low speed magnetic rotor. A stator is disposed in a radially central bore of one or more of the high speed magnetic rotor, the low speed magnetic rotor, and the modulating structure.

20 Claims, 7 Drawing Sheets



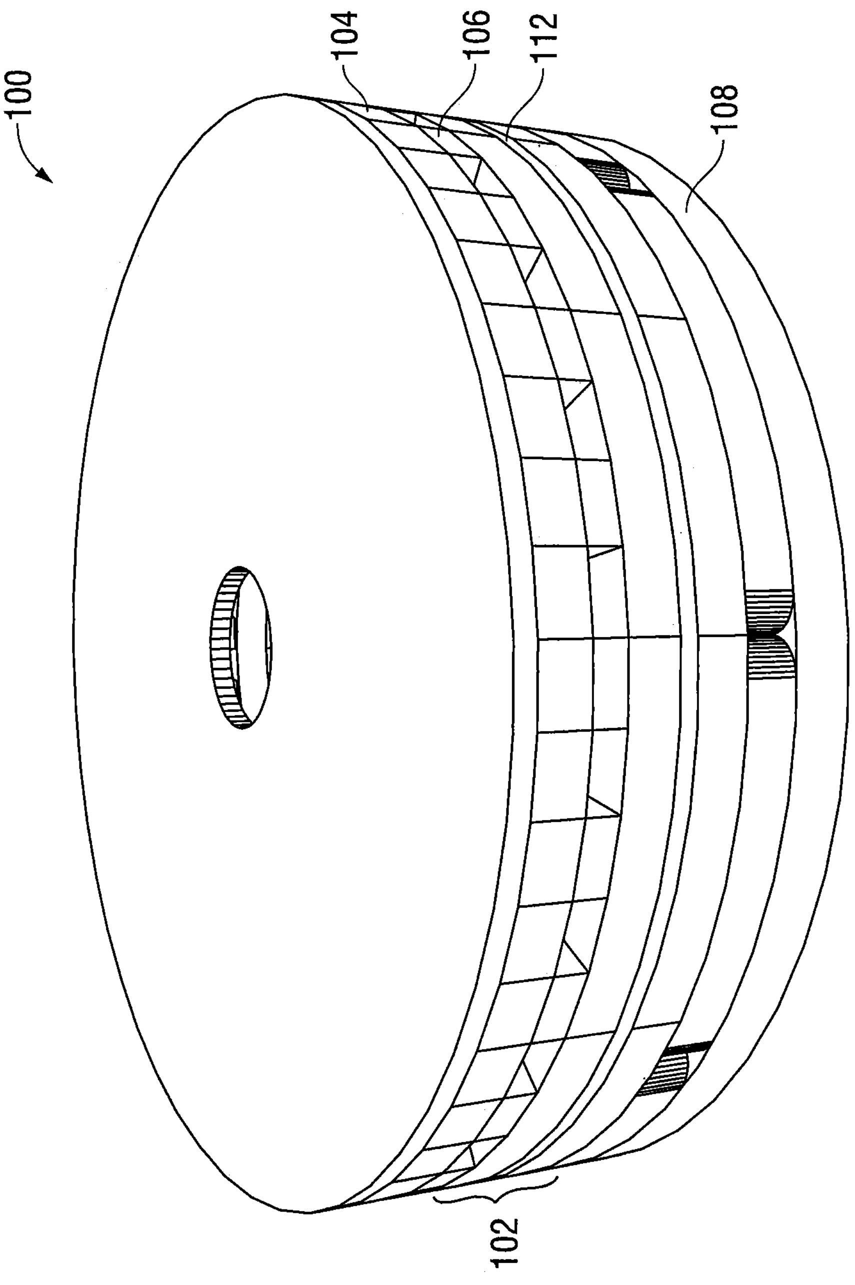


FIG. 1

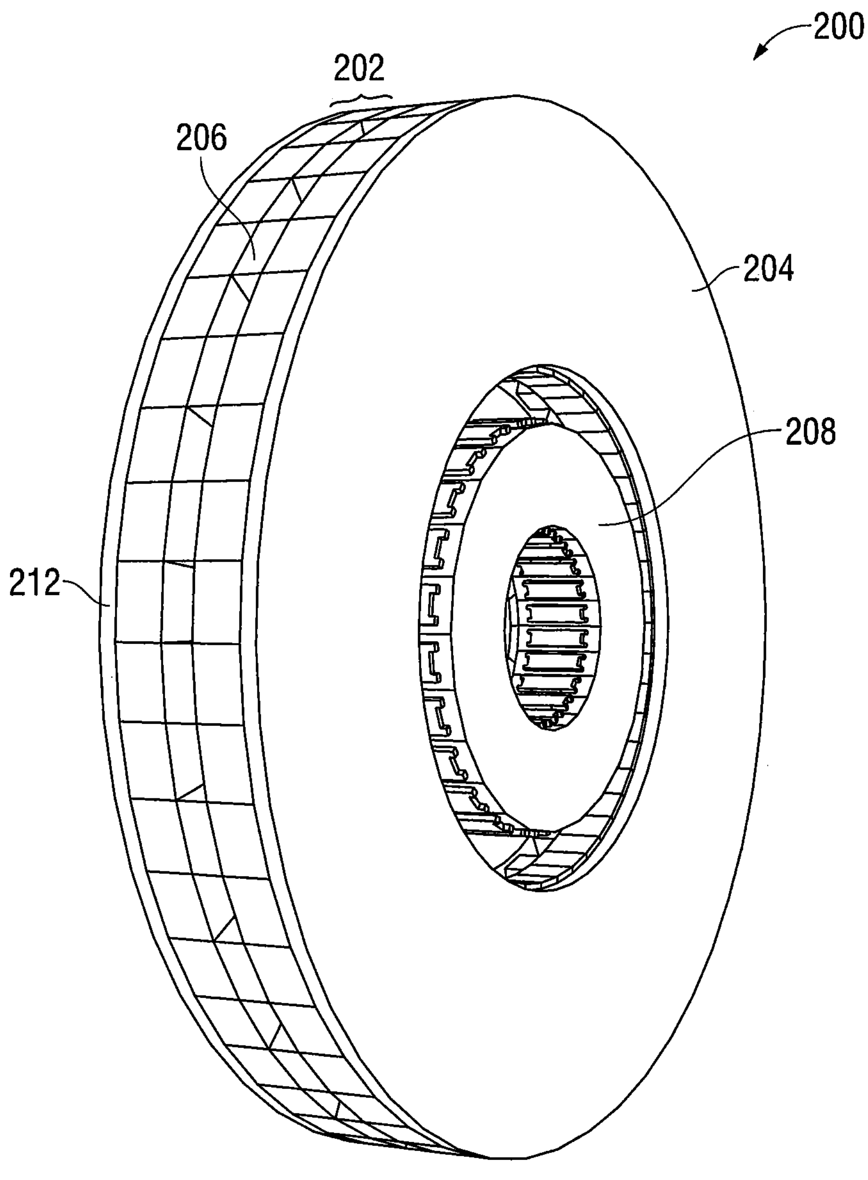


FIG. 2A

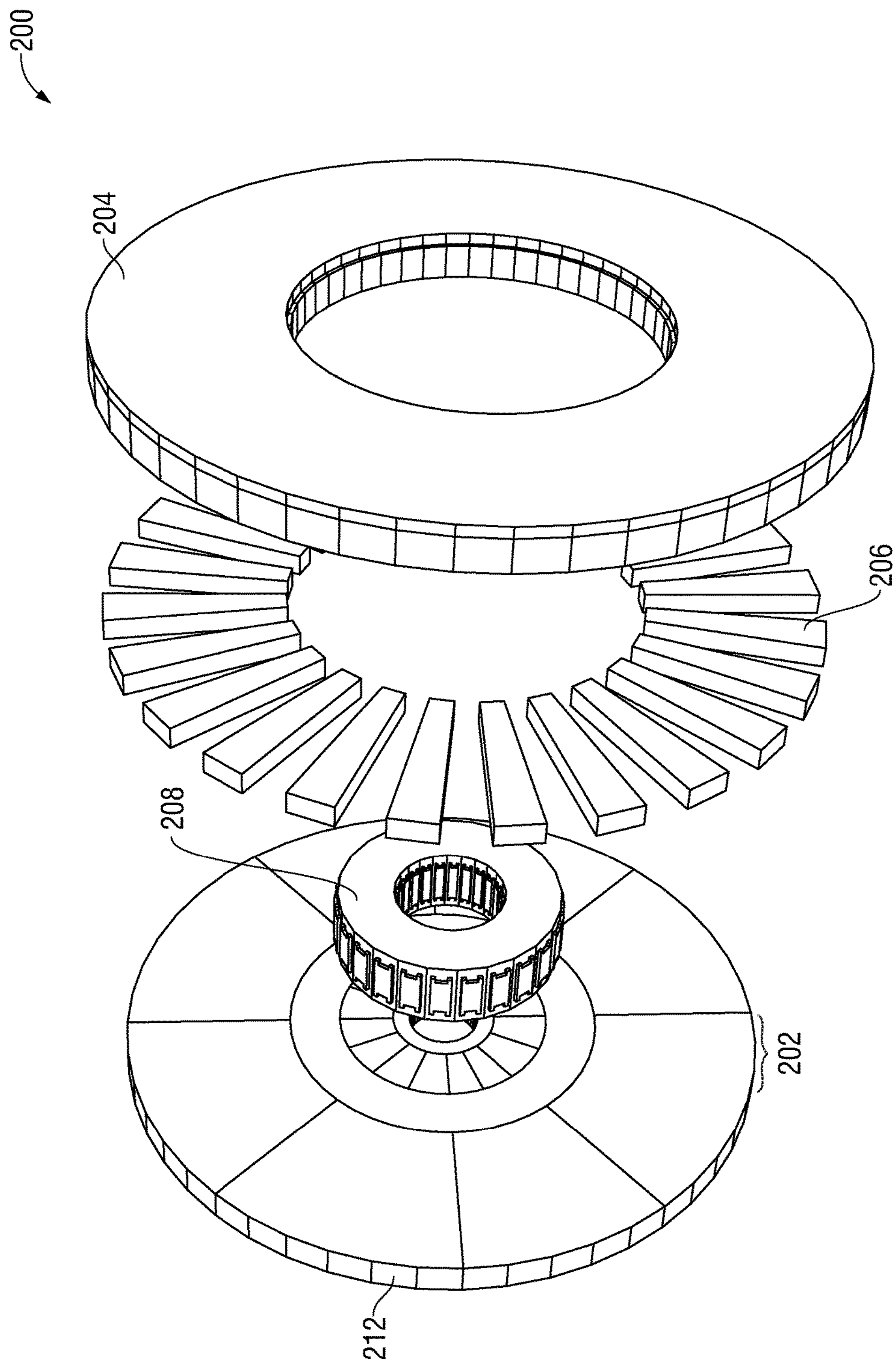


FIG. 2B

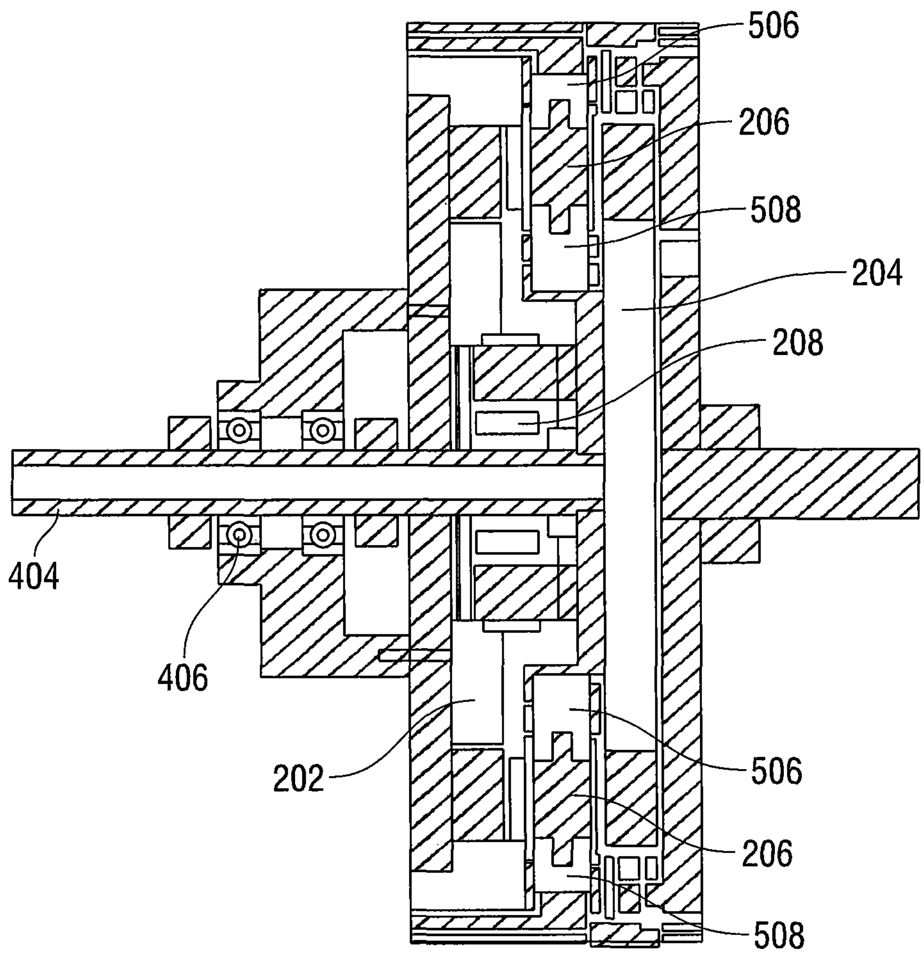


FIG. 3

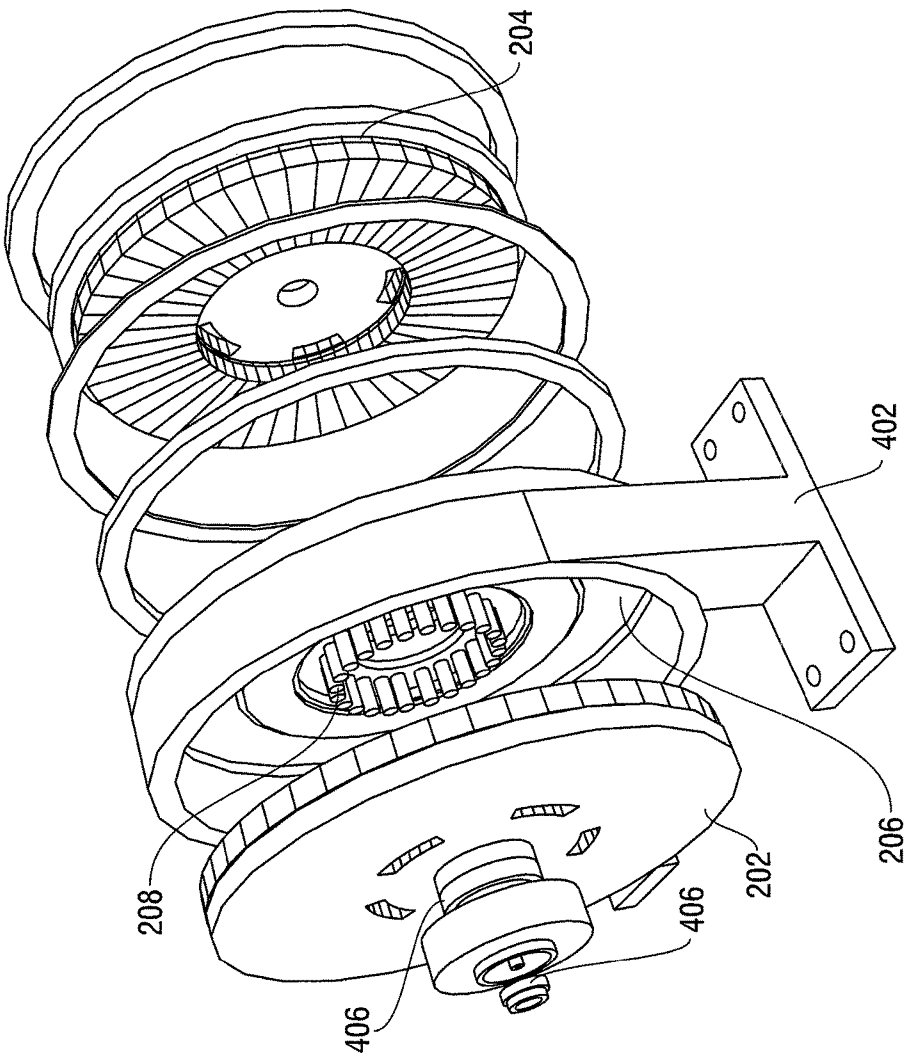


FIG. 4

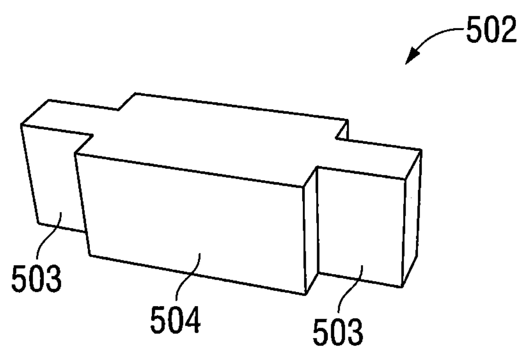


FIG. 5

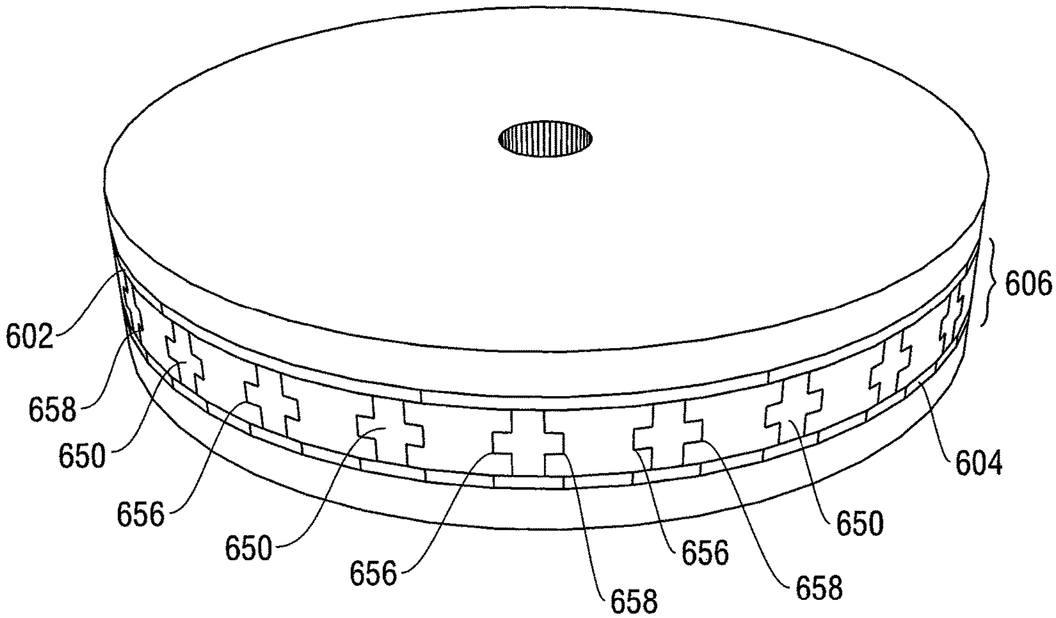


FIG. 6A

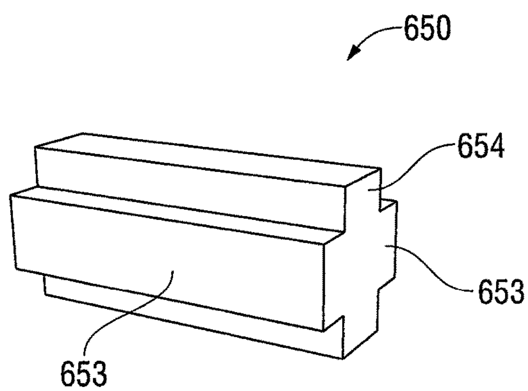


FIG. 6B

METHOD AND APPARATUS FOR COMPACT AXIAL FLUX MAGNETICALLY GEARED MACHINES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to, and incorporates by reference for any purpose, U.S. Provisional Patent Application No. 62/239,695, filed Oct. 9, 2015.

BACKGROUND

Field of the Invention

The present application relates generally to electrical machines including, but not limited to electrical motors and electrical generators and more particularly, but not by way of limitation to electrical machines that are co-axially arranged with a magnetic gear.

History of the Related Art

Electrical machines have been utilized for a variety of purposes. Typically, the cost of an electric machine is proportional to the torque with which it must interact. For applications requiring a large torque at a low speed there are two generally accepted options. First, a high speed, low torque machine could be utilized in conjunction with a mechanical gear. Second, a larger low speed, high torque direct-drive machine could be utilized. Mechanical gears are generally viewed as unattractive options as they require considerable maintenance, produce acoustic noise, and have a shorter useful life.

Magnetic gears have attracted considerable attention as a possible replacement for traditional, mechanical gears. Unlike mechanical gears, which rely on the physical interaction between teeth, magnetic gears create a gearing action through the modulated interaction between magnetic flux generated by two means of inducing magnetic flux with different pole pair counts. Magnetic gears exhibit generally contactless operation and, as such, facilitate reduced maintenance, improved reliability, decreased acoustic noise, and physical isolation between input and output shafts.

SUMMARY

The present application relates generally to electrical machines and more particularly, but not by way of limitation to electrical machines that are co-axially arranged with a magnetic gear. In one aspect, the present invention relates to an axial flux magnetically geared machine. The axial flux magnetically geared machine includes a high speed magnetic rotor. A low speed magnetic rotor is maintained in a spaced relationship from the high speed magnetic rotor. A modulating structure is disposed between the high speed magnetic rotor and the low speed magnetic rotor. A stator is disposed in a radially central bore of one or more of the high speed magnetic rotor, the low speed magnetic rotor, and the modulating structure.

In another aspect, the present invention relates to a method of forming an axial flux magnetically geared machine. The method includes arranging a high-speed rotor in a spaced relationship from a low-speed rotor. A modulating structure is positioned between the high-speed rotor and the low-speed rotor. A stator is positioned in a radially central bore of one or more of the high speed magnetic rotor, the low speed magnetic rotor, and the modulating structure.

In another aspect, the present invention relates to an axial flux magnetically geared machine. The axial flux magnetically geared machine includes a high speed magnetic rotor. A low speed magnetic rotor is maintained in a spaced relationship from the high speed magnetic rotor. A modulating structure is disposed between the high speed magnetic rotor and the low speed magnetic rotor. The modulating structure includes a plurality of modulator segments. Each segment of the plurality of modulator segments includes a pair of oppositely-extending segments that extend laterally from opposed lateral sides of the modulator segment. A stator is disposed in a radially central bore of one or more of the high speed magnetic rotor, the low speed magnetic rotor, and the modulating structure.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and for further objects and advantages thereof, reference may now be had to the following description taken in conjunction with the accompanying drawings in which:

FIG. **1** is a perspective view of a series-connected axial flux magnetically geared machine;

FIG. **2**A is a perspective view of a compact axial flux magnetically geared machine according to an exemplary embodiment;

FIG. **2**B is an exploded view of the compact axial flux magnetically geared machine of FIG. **2**A;

FIG. **3** is a cross-sectional view of a compact axial flux magnetically geared machine according to an exemplary embodiment;

FIG. **4** is an exploded view of a compact axial flux magnetically geared machine according to an exemplary embodiment;

FIG. **5** is a perspective view of a modulator segment having stepped ends according to an exemplary embodiment;

FIG. **6**A is a perspective view of an axial flux magnetically geared machine utilizing interlocking modulator segments according to an exemplary embodiment; and

FIG. **6**B is a perspective view of an interlocking modulator segment according to an exemplary embodiment.

DETAILED DESCRIPTION

Various embodiments of the present invention will now be described more fully with reference to the accompanying drawings. The invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

FIG. **1** is a perspective view of a series-connected axial flux magnetically geared machine **100**. Typical existing axial flux magnetically geared machines such as, for example, the magnetically geared machine **100**, include a high speed rotor **102**, a low speed rotor **104**, and a modulating structure **106**. The high speed rotor **102** typically includes a back iron **112** disposed between permanent magnets. A stator **108** disposed beyond the high speed rotor **102**. Such an arrangement causes the stator **108** to increase the overall size of the machine **100**.

FIG. **2**A is a perspective view of a compact axial flux magnetically geared machine **200**. FIG. **2**B is an exploded view of the compact axial flux magnetically geared machine **200**. Referring to FIGS. **2**A and **2**B collectively, the compact axial flux magnetically geared machine **200** includes a high speed rotor **202**, a low speed rotor **204**, and a modulating structure **206** positioned in a spaced relationship between the high speed rotor **202** and the low speed rotor **204**. A back iron **212** comprises a portion of the high speed rotor **202**. In a typical embodiment, the high speed rotor **202** and the low speed rotor **204** include a structure for inducing magnetic flux with a given pole pair count. For example, in various embodiments, the high speed rotor **202** includes a first permanent magnet having a first pole pair count and the low speed rotor **204** includes a second permanent magnet having a second pole pair count. In a typical embodiment, the first permanent magnet and the second permanent magnet include an array of magnets; however, in other embodiments, the first permanent magnet and the second permanent magnet may be singular. In various alternative embodiments, the high speed rotor **202** includes a first set of windings that carry an electrical current or the low speed rotor **204** includes a second set of windings that carry the electrical current. In various embodiments, a third permanent magnet array, or a set of windings that carry electrical current, may also be present on the high speed rotor **202** to induce magnetic flux with a third number of pole pairs, such that the high speed rotor **202** induces two sets of magnetic fluxes with pole pair counts that may be different from each other. One of the two sets of magnetic fluxes may, in various embodiments, interact with the modulating structure **206** and the low speed rotor **204** magnetic flux. The second of the two sets of magnetic fluxes interacts with the stator **208**.

Still referring to FIG. **2**A, the high speed rotor **202** and the low speed rotor **204**, in a typical embodiment, include a disk of magnetically permeable steel with multiple permanent magnets attached to a surface of the magnetically permeable steel. Alternatively, the permanent magnets may be embedded within the magnetically permeable steel. In various alternative embodiments, the high speed rotor **202** and the low speed rotor **204** include a magnetically impermeable material having multiple permanent magnets attached to a surface of the magnetically impermeable material. In still other embodiments, the high speed rotor **202** and the low speed rotor **204** include alternating sections of permanent magnets and magnetically permeable steel. Magnetic flux induced by the high speed rotor **202** interacts with the modulating structure **206** and the magnetic flux induced by the low speed rotor **204**. Magnetic flux induced by the high speed rotor **202** also interacts with a stator **208**. The stator **208** is disposed in a radially central bore of one or more of the high speed rotor **202**, the low speed rotor **204**, and the modulating structure **206**.

Still referring to FIGS. **2**A and **2**B, in a typical embodiment, the modulating structure **206** is constructed of any magnetically permeable material such as, for example, solid steel, electrical steel laminations, soft magnetic composites, or any other magnetically permeable material as dictated by design requirements. In a typical embodiment, the modulator segments of the modulating structure **206** are evenly spaced in a circular configuration. The width and length of the modulator segments as well as any modulator support structure may vary with design requirements. In various embodiments, the modulator segments may be separated by a magnetically impermeable material such as, for example, air, polyoxymethylene, fiberglass, or other magnetically-impermeable material as dictated by design requirements.

Still referring to FIGS. **2**A and **2**B, when the compact axial flux magnetically geared machine **200** is operated as a generator, an external motion source (not shown) rotates at least one of the low speed rotor **204** or the modulating structure **206**. The magnetic flux of the low speed rotor **204** interacts with the magnetic flux of the high speed rotor **202** through the modulating structure **206** to produce rotation of the high speed rotor **202**. Rotation of the high speed rotor **202** causes rotation of the magnetic flux of the high speed rotor **202**. The magnetic flux of the high speed rotor **202** interacts with the stator **208**, which produces electrical energy.

Still referring to FIGS. **2**A and **2**B, the modulating structure **206** modulates the magnetic field of the low speed rotor **204** to produce a magnetic field with a spatial frequency component that is the same as the magnetic field produced by the high speed rotor **202**. Additionally, the modulating structure **206** modulates the magnetic field of the high speed rotor **202** to produce a magnetic field with a spatial frequency component that is the same as the magnetic field produced by the low speed rotor **204**. This interaction between the magnetic field of the high speed rotor **202**, the modulating structure **206**, and the magnetic field of the low speed rotor **204** facilitates transmission of non-zero average torques between the high speed rotor **202** and the low speed rotor **204** or the modulating structure **206**. The resulting steady state rotational speeds are determined by the pole pair count of the high speed rotor **202**, the pole pair count of the low speed rotor **204**, and the pole pair count of the modulating structure **206**. This relationship is illustrated in Equation 1.

$$\omega_{HS} = \frac{-P_{LS}}{P_{HS}} \times \omega_{LS} + \frac{Q_M}{P_{HS}} \times \omega_M \qquad \text{Equation 1}$$

Where P_{LS} is the pole pair count of the low speed rotor **204**, P_{HS} is the pole pair count of the magnetic flux of the high speed rotor **202** that interacts with the modulating structure **206** and the low speed rotor **204**, Q_M is the number of modulator pole pieces, ω_{HS} is the rotational velocity of the high speed rotor **202**, ω_{LS} is the rotational velocity of the low speed rotor **204**, and ω_M is the rotational velocity of the modulating structure **206**. The pole piece count of the modulating structure **206** is determined by Equation 2.

$$Q_M = P_{LS} + P_{HS} \qquad \text{Equation 2:}$$

As indicated by Equation 1, there are multiple viable modes of operation, A few examples are given for clarification and it should not be construed that these examples limit the potential modes of operation. One example is to include a fixed modulating structure **206** and a rotatable low speed rotor **204** and high speed rotor **202**. In this case, the gear ratio is determined by Equation 3.

$$G_r = \frac{-P_{LS}}{P_{HS}} \qquad \text{Equation 3}$$

In a second example, the low speed rotor **204** is fixed and the modulating structure **206** and the high speed rotor **202** rotate. In this case, the gear ratio is given by Equation 4.

$$G_r = \frac{Q_M}{P_{HS}} \qquad \text{Equation 4}$$

In various embodiments, the compact axial flux magnetically geared machine **200** could be driven in the inverse direction to operate as a motor. When operated as a motor, positive electrical energy flows into the compact axial flux magnetically geared machine **200** through terminals on the stator **208** and positive rotational energy flows out of the compact axial flux magnetically geared machine **200** through rotation of the low speed rotor **204** or rotation of the modulating structure **206**.

Still referring to FIGS. **2**A and **2**B, placing the stator **208** inside the bore of the compact axial flux magnetically geared machine **200** prevents the increase in volume often associated with series connections as illustrated in FIG. **1** and makes use of empty space inside the axial flux magnetically geared machine **200** that was previously unused or poorly used. As a result of this feature, the total volume consumed by the axial flux magnetically geared machine **200** is reduced from the arrangement shown and described in FIG. **1**. Furthermore, the compact topology of the axial flux magnetically geared machine **200** facilitates use of a smaller outer radius for the stator **208**. Finally, the high speed rotor back iron **212** of the axial flux magnetically geared machine **200** may be constructed from thinner material than that utilized in FIG. **1** as the high speed rotor back iron **212** no longer must isolate magnetic flux from magnets located on both sides of the high speed rotor back iron **212**. Reduction of a thickness of the high speed rotor back iron **212** results in consumption of less material thereby allowing less expensive construction of the compact axial flux magnetically geared machine **200**.

FIG. **3** is a cross-sectional view of a compact axial flux magnetically geared machine **200**. FIG. **4** is an exploded view of a compact axial flux magnetically geared machine **200**. Referring to FIGS. **3-4** together, the compact axial flux magnetically geared machine **200** includes a stationary sub-assembly **402**. The stationary sub-assembly **402** includes the stator **208** and, in various embodiments, may also include the modulating structure **206** as dictated by design requirements. A support shaft **404** is positioned through the high speed rotor **202**. In a typical embodiment, the support shaft **404** is stationary and rotation of the high speed rotor **202** is facilitated by bearings **406**.

FIG. **5** is a perspective view of a segment **502** having stepped ends of the modulating structure **206**. In a typical embodiment, the modulating structure **206** comprises a plurality of the segments **502**. The segment **502** includes a central area **504** and a pair of oppositely extending sections **503**. The oppositely extending sections **503** extend radially from the central area **504** and are thinner than the central area **504**. The increased thickness of the central area **504** imparts increased strength to the segment **502** and improves magnetic performance. During operation, the modulating structure **506** and the segments **502** are subjected to strong magnetic forces. Thus, the segments **502** must be supported by a structure capable of withstanding such forces. As shown in FIG. **5**, the segments **502** are gripped by an inner retaining ring **506** (shown in FIG. **3**) and an outer retaining ring **508** (shown in FIG. **3**). The inner retaining ring **506** and the outer retaining ring **508** are clamped onto the oppositely extending sections **503**. In various embodiments, the inner retaining ring **506** and the outer retaining ring **508** may be comprised of multiple rings.

FIG. **6**A is a perspective view of an axial flux magnetically geared machine **600** utilizing interlocking modulator segments **650**. FIG. **6**B is a perspective view of the interlocking modulator segment **650**. Referring to FIGS. **6**A-**6**B collectively, the compact axial flux magnetically geared machine **600** includes a high speed rotor **602**, a low speed rotor **604**, and a modulating structure **606** positioned in a spaced relationship between the high speed rotor **602** and the low speed rotor **604**. In a typical embodiment, the high speed rotor **602** and the low speed rotor **604** are similar in function and construction to the high speed rotor **202** and the low speed rotor **204** discussed above. The modulating structure **606** includes a plurality of interlocking modulator segments **650**. Each segment of the plurality of interlocking modulator segments **650** includes a central area **654** and a pair of oppositely extending sections **653**. The oppositely extending sections **653** extend laterally from the sides of the central area **654** and are thinner than the central area **654**. In a typical embodiment, the oppositely extending sections **653** interlock with a non-magnetic support member **656** disposed between adjacent segments of the plurality of interlocking modulator segments **650**. The non-magnetic support member **656** may be constructed from any magnetically impermeable material that has sufficient mechanical strength to support the modulator segments **650** against the magnetic forces produced during operation. In a typical embodiment, the non-magnetic support member **656** is constructed of an electrically non-conductive material so as to minimize losses produced in the non-magnetic support member **656** due to varying magnetic fields. In a typical embodiment, the non-magnetic support member **656** may be constructed of materials such as, for example, polyoxymethylene, fiberglass, various other polymers, or other magnetically impermeable materials as dictated by design requirements. The non-magnetic support member **656** includes oppositely disposed recesses **658**. Each oppositely disposed recess **658** is sized to receive an oppositely extending section **653** of the pair of oppositely extending sections **653**. In a typical embodiment, the non-magnetic support member **656** is constructed via, for example, over molding or other appropriate process. Such an arrangement provides structural and electromagnetic advantages. For example, the axial flux magnetically geared machine **600** offers reduced magnetic flux leakage.

Although various embodiments of the method and system of the present invention have been illustrated in the accompanying Drawings and described in the foregoing Specification, it will be understood that the invention is not limited to the embodiments disclosed, but is capable of numerous rearrangements, modifications, and substitutions without departing from the spirit and scope of the invention as set forth herein. It is intended that the Specification and examples be considered as illustrative only.

What is claimed is:

1. An axial flux magnetically geared machine, comprising:

- a high speed magnetic rotor;
- a low speed magnetic rotor maintained in a spaced relationship from the high speed magnetic rotor;
- a modulating structure disposed between the high speed magnetic rotor and the low speed magnetic rotor, so as to modulate a magnetic field of at least one of the high speed magnetic rotor and the low speed magnetic rotor; and
- a stator disposed in a radial central bore of the modulating structure and at least one of the high speed magnetic rotor and the low speed magnetic rotor.

2. The axial flux magnetically geared machine of claim **1**, wherein the stator functions as an electric generator.

3. The axial flux magnetically geared machine of claim **1**, wherein the stator functions as an electric motor.

4. The axial flux magnetically geared machine of claim **1**, wherein the modulating structure rotates in addition to, or in place of, the low speed magnetic rotor.

5. The axial flux magnetically geared machine of claim **4**, wherein the stator functions as an electric generator.

6. The axial flux magnetically geared machine of claim **4**, wherein the stator functions as an electric motor.

7. The axial flux magnetically geared machine of claim **1**, wherein the modulating structure comprises a plurality of segments.

8. The axial flux magnetically geared machine of claim **7**, wherein each segment of the plurality of segments comprise a pair of oppositely-extending segments that extend radially from a central area of the plurality of segments.

9. The axial flux magnetically geared machine of claim **8**, wherein the plurality of segments are secured by a retaining ring.

10. The axial flux magnetically geared machine of claim **7**, wherein each segment of the plurality of segments comprises a pair of oppositely-extending segments that extend laterally from opposed lateral sides of the segment.

11. The axial flux magnetically geared machine of claim **10**, wherein the plurality of segments interlock with a non-magnetic support member that is disposed between adjacent segments of the plurality of segments.

12. The axial flux magnetically geared machine of claim **11**, wherein a portion of each segment of the plurality of segments is received into a recess formed in the non-magnetic support member.

13. A method of forming an axial flux magnetically geared machine, the method comprising:

arranging a high-speed magnetic rotor in a spaced relationship from a low-speed magnetic rotor;

positioning a modulating structure between the high-speed magnetic rotor and the low-speed magnetic rotor, so as to modulate a magnetic field of at least one of the high-speed magnetic rotor and the low-speed magnetic rotor; and

positioning a stator in a radial central bore of the modulating structure and at least one of the high speed magnetic rotor and the low speed magnetic rotor.

14. The method of claim **13**, wherein the positioning the modulating structure comprises securing a plurality of modulator segments with each modulator segment of the plurality of modulator segments being in a spaced relationship from an adjacent modulator segment.

15. The method of claim **14**, wherein the securing comprises securing the plurality of modulator segments with a retaining ring.

16. The method of claim **14**, wherein the securing comprises securing the plurality of modulator segments with a non-magnetic support member.

17. The method of claim **16**, wherein the securing comprises receiving a portion of the modulator segment into a recess formed in the non-magnetic support member.

18. An axial flux magnetically geared machine, comprising:

a high speed magnetic rotor;

a low speed magnetic rotor maintained in a spaced relationship from the high speed magnetic rotor;

a modulating structure disposed between the high speed magnetic rotor and the low speed magnetic rotor, the modulating structure comprising a plurality of modulator segments each segment of the plurality of modulator segments comprises a pair of oppositely-extending segments that extend laterally from opposed lateral sides of the modulator segment, so as to modulate a magnetic field of at least one of the high speed magnetic rotor and the low speed magnetic rotor; and

a stator disposed in a radial central bore of the modulating structure and at least one of the high speed magnetic rotor and the low speed magnetic rotor.

19. The axial flux magnetically geared machine of claim **18**, wherein the plurality of modulator segments interlock with a non-magnetic support member that is disposed between adjacent segments of the plurality of segments.

20. The axial flux magnetically geared machine of claim **19**, wherein a portion of each segment of the plurality of modulator segments is received into a recess formed in the non-magnetic support member.

* * * * *