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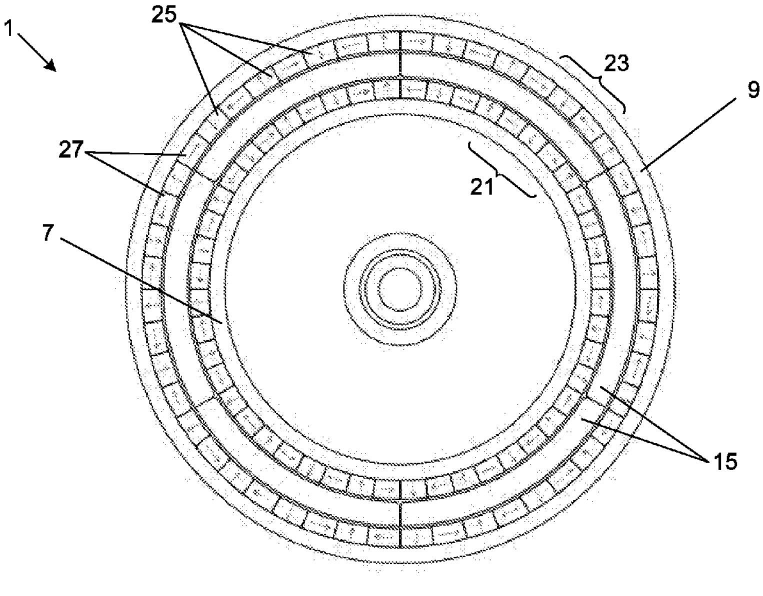


Figure 3

(57) Abstract: A radial flux permanent magnet machine (1) is provided which comprises an air-cored stator (3) positioned in an air gap (5) defined between inner (7) and outer (9) rotors mounted to a common rotor side plate (13) to operatively rotate together. The inner and outer rotors are radially spaced apart from the air-cored stator and have arrays of permanent magnets (21, 23) about their circumferences. The arrays of permanent magnets include a set of radial magnets (25) and a set of azimuthal magnets (27) circumferentially positioned in an alternating polarity arrangement along the rotor. The radial magnets provide a radial magnetic field component and the azimuthal magnets provide an azimuthal magnetic field component in the air gap.

RADIAL FLUX PERMANENT MAGNET MACHINE

CROSS-REFERENCE(S) TO RELATED APPLICATIONS

This application claims priority to South African provisional patent application number 2014/03358 filed on 12 May 2014, which is incorporated by reference herein.

FIELD OF THE INVENTION

This invention relates to permanent magnet machines. More particularly, the invention relates to a radial flux permanent magnet machine having an air-cored stator positioned between an inner and outer rotor.

BACKGROUND TO THE INVENTION

Electrical machines, which throughout this specification should be interpreted so as to include both electrical motors and electrical generators, fundamentally comprise a rotor and a stator. The rotor is a rotating part of the electrical machine and the stator is a stationary part.

One particular class of electrical machines makes use of permanent magnets mounted on either the rotor or the stator, to establish a magnetic field in the machine. These machines are referred to as permanent magnet (“PM”) machines and a variety of configurations for such machines have been developed.

Coils of conductive material, such as copper, are secured to either the stator or the rotor of the PM machine. In electrical generators, as the rotor is rotated in relation to the stator, movement of the magnetic field produced by the permanent magnets relative to the conductive material induces a current in windings thereof. Electrical motors employ the reverse process of electrical generators, utilising a force generated when current flows through the windings situated in the magnetic field produced by the permanent magnets, which in turn leads to rotation of the rotor.

One particular type of permanent magnet machine is known as a double-sided rotor, radial flux, air-cored, permanent magnet machine. The machine comprises an air-cored stator located in a magnetic air gap between two annular rotor portions which are mounted to rotate together on opposite sides of the air-cored stator.

The rotor portions are provided with arrays of permanent magnets and ferrous backing arranged so as to drive magnetic flux back and forth between the rotor portions and through the air-cored stator in a substantially radial direction in use. The air-cored stator, also referred to as an ironless stator, is substantially devoid of ferromagnetic materials and may be made up of a plurality of stator modules, each module supporting one or more compact wound conductive coils in the magnetic air gap, although the modularity of the stator is by no means a requirement for the machine to operate.

The rotor portions are ferrous and provide backing iron, or yokes, for the arrays of permanent magnets. The backing iron in each rotor portion is required to complete the magnetic flux path through the machine in use.

In a known configuration of the double-sided rotor, radial flux, air-cored, permanent magnet machine, the machine is adapted to be used as an electrical generator in a wind generator for converting kinetic energy of wind into useful electrical energy. Such a configuration is disclosed in Patent Cooperation Treaty (PCT) patent application number WO2011033370A1.

A problem associated with a radial flux permanent magnet machine of the type described above is that the machine may be relatively heavy, at least partially due to its ferrous rotor portions. This may make the machine unsuitable for certain lightweight applications. For example, the mass of such a machine may restrict its torque-to-weight ratio to the extent that it is unsuitable for use as a motor for driving relatively small battery-powered or solar-powered vehicles.

The preceding discussion of the background to the invention is intended only to facilitate an understanding of the present invention. It should be appreciated that the discussion is not an acknowledgment or admission that any of the material referred to was part of the common general knowledge in the art as at the priority date of the application.

SUMMARY OF THE INVENTION

In accordance with the disclosure there is provided a radial flux permanent magnet machine, comprising:

an air-cored stator positioned in an air gap defined between generally annular inner and outer rotors mounted to operatively rotate together, the inner and outer rotors being radially spaced apart from the air-cored stator and at least one of the rotors having an array of permanent magnets about its circumference, the machine being characterised in that

the array of permanent magnets provides substantially radial and substantially azimuthal magnetic field components to operatively complete a magnetic flux path through the machine.

Further features provide for the rotors to be manufactured from materials that are substantially free of ferromagnetic material; and for the array of permanent magnets to include a set of radial magnets and a set of azimuthal magnets circumferentially positioned in an alternating polarity arrangement along each of the rotors, the radial magnets providing radial magnetic field components and the azimuthal magnets providing azimuthal magnetic field components.

Yet further features provide for the array of permanent magnets to be provided on the outer rotor; alternatively, for the array of permanent magnets to be provided on the inner rotor; alternatively, for both the inner and outer rotor to have an array of permanent magnets about its circumference; and for the array of permanent magnets to be substantially arranged in a Halbach magnet array.

Still further features provide for the set of azimuthal magnets of a particular array of permanent magnets to be radially offset from the set of radial magnets of the same array and positioned radially further from the air-cored stator than the set of radial magnets of the same array; for the set of azimuthal magnets of each array to be substantially embedded in its associated rotor; and for the set of radial magnets of the inner rotor to be provided on a radially outer surface thereof and for the set of radial magnets of the outer rotor to be provided on a radially inner surface thereof.

Further features provide for the outer rotor and/or the inner rotor to define magnet receiving slots; for one or both of the azimuthal magnets and the radial magnets to be received in the magnet receiving slots; and for the inner surface of the outer rotor and the outer surface of the inner rotor to define a series of grooves and ridges, the grooves forming magnet receiving slots for receiving the set of azimuthal magnets and the radial magnets being received against the ridges such that, for each rotor, the radial magnets are radially offset from the azimuthal magnets.

Yet further features provide for the permanent magnets making up the array of permanent magnets to be magnetised so as to provide a series of generally rotating patterns of magnetisation for operatively driving magnetic flux back and forth between the rotors and through the air-cored stator in a substantially radial direction; and for at least one of the permanent magnets to have an alternating magnetisation to provide radial and azimuthal magnetic field components.

Still further features provide for the air-cored stator to include a series of wound coils; for the coils to be non-overlapping; for the coils to be held in a polymeric resin; and for the machine to include a central shaft.

Further features provide for one or both of the rotors to be formed by a plurality of axially stacked rings which are secured together; and for the machine to further comprises a rotor side plate, the inner rotor and outer rotor being secured to the rotor side plate, and a stator side plate secured to the air-cored stator.

Even further features provide for a hub to be secured to the central shaft to form a hub drive arrangement; and for the hub drive arrangement to permit the machine to be connected to a complementary external direct drive mechanism.

The disclosure extends to a rotor for a radial flux permanent magnet machine comprising a generally annular body and an array of permanent magnets about its circumference, the array of permanent magnets being configured to provide substantially radial and substantially azimuthal magnetic field components to operatively complete a magnetic flux path through the machine.

Further features provide for the rotor to be manufactured from materials that are substantially free of ferromagnetic material; and for the array of permanent magnets to include a set of radial magnets and a set of azimuthal magnets circumferentially positioned in an alternating polarity arrangement along the rotor, the radial magnets providing the radial magnetic field component and the azimuthal magnets providing the azimuthal magnetic field component.

In order for the invention to be more fully understood, implementations thereof will now be described with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described, by way of example only, with reference to the accompanying representations in which:

Figure 1	is an exploded three-dimensional view of a first embodiment of a radial flux permanent magnet machine;
Figure 2	is a side view of the permanent magnet machine of Figure 1;

Figure 3	is a cross-sectional view of the permanent magnet machine of Figure 1, taken along the line A-A in Figure 2;
Figure 4	is the cross-sectional view of Figure 3, further indicating an approximate mean magnetic flux path through the machine in use;
Figure 5A	is a magnetic circuit equivalent for one pole pair, representing the embodiment shown in Figure 1;
Figure 5B	is a representation of an alternative to the circuit of Figure 5A, wherein an array of permanent magnets is provided on an outer rotor portion only;
Figure 6	is an exploded three-dimensional view of a second embodiment of a radial flux permanent magnet machine;
Figure 7	is a front view of the permanent magnet machine of Figure 6, wherein a rotor plate of the machine is illustrated;
Figure 8	is a sectional view of the permanent magnet machine of Figure 6, taken along the line B-B in Figure 7;
Figure 9	is a side view of the permanent magnet machine of Figure 6;
Figure 10	is a cross-sectional view of the permanent magnet machine of Figure 6, taken along the line C-C in Figure 9, and wherein an approximate mean magnetic flux path through the machine, in use, is indicated;
Figure 11A	is a magnetic circuit equivalent for one pole pair, representing a conventional permanent magnet configuration which includes steel backing;
Figure 11B	is a magnetic circuit equivalent for one pole pair, representing a permanent magnet configuration of the permanent magnet machine of Figures 6;
Figure 11C	is a magnetic circuit equivalent for one pole pair, representing an alternative permanent magnet configuration for a machine;
Figure 11D	is a magnetic circuit equivalent for one pole pair, representing an alternative permanent magnet configuration for a machine;

Figure 11E	is a magnetic circuit equivalent for one pole pair, representing an alternative permanent magnet configuration for a machine;
Figure 11F	is a magnetic circuit equivalent for one pole pair, representing an alternative permanent magnet configuration for a machine;
Figure 12A	is a simulation output illustrating output torque generated by a machine using the magnet configuration of the permanent magnet machine of Figure 6;
Figure 12B	is a simulation output illustrating output torque generated by a traditional steel-backed permanent magnet machine;
Figure 13A	is a simulation output illustrating output torque generated by a machine using the magnet configuration of Figure 11D;
Figure 13B	is a simulation output illustrating output torque generated by a machine using the magnet configuration of Figure 11B;
Figure 14	is a simulation output illustrating radial flux produced a machine using the magnet configuration of the permanent magnet machine of Figure 6;
Figure 15A	is a simulation output illustrating output torque generated by a traditional steel-backed permanent magnet machine;
Figure 15B	is a simulation output illustrating output torque generated by a machine using the magnet configuration of the permanent magnet machine of Figure 6; and,
Figure 15C	is a simulation output illustrating output torque generated by a machine using the magnet configuration of the permanent magnet machine of Figure 1.

DETAILED DESCRIPTION WITH REFERENCE TO THE DRAWINGS

A first embodiment of a radial flux permanent magnet machine (1) is illustrated in Figures 1 to 4. The machine (1) comprises an air-cored stator (3) positioned in a magnetic air gap (5) defined between an inner rotor (7) and an outer rotor (9).

The air-cored stator (3) is secured to a stator side plate (11), and the inner rotor (7) and outer rotor (9) are secured to a rotor side plate (13) such that they operatively rotate together. Figures 1 and 2 illustrate the stator side plate (11) and the rotor side plate (13), with the machine in exploded (Figure 1) and collapsed (Figure 2) configuration, respectively.

As the inner and outer rotors rotate together, they may conveniently be seen as a single rotor. In the remainder of this specification the term “rotor” will be used to refer to the inner and outer rotors in combination and the term “rotor portion” will conveniently be used to refer to the inner and outer rotors separately.

The inner rotor portion (7) and outer rotor portion (9) are radially spaced apart from the air-cored stator (3) such that one vacant portion of the magnetic air gap (5) is situated between an inner surface of the outer rotor portion (9) and the stator (3), and another vacant portion of the magnetic air gap is situated between an outer surface of the inner rotor portion (7) and the stator (3). In the embodiments described herein, each vacant air gap portion has a radial dimension of approximately 1 mm, although it should immediately be noted that the dimension of the vacant air gap can be altered and does not have to be 1 mm for the machine to work.

The air-cored stator (3) includes a series of coils (not shown) held in a polymeric resin. In this embodiment, the coils are non-overlapping wound copper coils and are held in an Ampreg 21 epoxy resin. The stator (3) is circular in cross-section and is formed from six separately moulded, arcuate stator portions (15). The arcuate portions (15) are mounted such that their end regions abut to form the annular stator (3), and each portion (15) is provided with a radially inwardly extending stator flange (17) by which it is secured to a ring (19), which is in turn secured to the stator side plate (11).

Both the inner rotor portion (7) and the outer rotor portion (9) are provided with an array of permanent magnets (21, 23) which are magnetised so as to provide substantially radial and substantially azimuthal magnetic field components to operatively complete a magnetic flux path through the permanent magnet machine (1).

Although the terms “radial” and “azimuthal”, when used in relation to permanent magnet machines, will be well understood by those skilled in the art, it should specifically be noted that throughout this specification the term “radial” should be interpreted so as to include a direction generally radial in relation to the axis of rotation of the rotor, and the phrases “radial flux” and “radial magnetic field” refer to magnetic flux and magnetic field components directed substantially in the radial direction. Furthermore, the term “azimuthal” should be interpreted so as to include the direction generally transverse to the radial direction within any given cross-sectional plane along the axis of rotation, and the term, when used in relation to magnetic flux or field components, includes components directed generally circumferentially along any radial portion or in the vicinity of the inner and outer rotor portions.

The array of permanent magnets of each rotor portion (7, 9) includes a set of radial magnets (25) and a set of azimuthal magnets (27) circumferentially positioned in an alternating polarity arrangement, as is illustrated by the directional arrows in Figures 3 and 4. In this embodiment, each array of permanent magnets (21, 23) is arranged in a Halbach magnet array, and are therefore substantially radially in line. The radial magnets (25) provide substantially radial magnetic field components and the azimuthal magnets (27) provide substantially azimuthal magnetic field components.

The rotor portions (7, 9) are manufactured from materials that are substantially free of ferromagnetic material. In this embodiment, both of the rotor portions (7, 9) and the rotor side plate (13) are manufactured from aluminium. The permanent magnet machine (1) therefore comprises both a stator and a rotor which is completely or at least substantially devoid of ferromagnetic material, also referred to as being “ironless”.

The cross-sectional view of the permanent magnet machine (1) shown in Figure 4 illustrates an approximate magnetic flux path (F) through the machine (1), in use. The directional arrows provided on each of the magnets indicate the approximate direction of their magnetic orientation. Whereas the radial magnets (25) are magnetised so as to drive magnetic flux in a substantially radial direction, the azimuthal magnets (27) are magnetised so as to drive magnetic flux in a substantially transverse direction to complete the magnetic flux path (F) through the permanent magnet machine (1).

An exemplary magnetic circuit equivalents for one pole pair in the permanent magnet machine (1) is shown in Figure 5A. The following reference symbols are used therein, and also throughout the remainder of the specification:

- F indicates an approximation of the mean magnetic flux path;
- h indicates the portion of the air gap filled by the stator;
- l_g indicates the vacant air gap portions between each of the rotor portions and the stator; and
- r_n represents the nominal radius, which is the distance from the axis of rotation to the middle of the stator.

The magnetic circuit equivalent (28) of Figure 5A illustrates the permanent magnet configuration of the permanent magnet machine (1) of Figure 1. The directional arrows provided on each of the radial (29) and azimuthal (31) magnets indicate the approximate direction of their magnetic orientation.

Figure 5B illustrates an alternative magnet configuration (33), wherein only the outer rotor portion is provided with an array of permanent magnets consisting of radial (35) and azimuthal magnets (37), while the inner rotor portion is devoid of permanent magnets. Simulations performed by the applicant indicates that such a configuration may produce sufficient torque for driving the machine. Such a configuration may thus be a feasible alternative embodiment, and may potentially simplify the structure of the machine and reduce manufacturing costs. It is also envisaged that, in an alternative embodiment, only the inner rotor portion may be provided with an array of permanent magnets.

A second embodiment of a radial flux permanent magnet machine (40) is illustrated in Figures 6 to 10. In this embodiment, the permanent magnet machine (40) is configured for use as a hub drive motor.

The machine (40) comprises an air-cored stator (41) positioned in a magnetic air gap (43) defined between an inner rotor portion (45) and an outer rotor portion (47).

Similarly to the embodiment of Figure 1, the air-cored stator (41) is secured to a stator side plate (49), and the inner rotor portion (45) and outer rotor portion (47) are secured to a rotor side plate (51) such that they operatively rotate together. Figure 7 more clearly illustrates the rotor side plate (51).

The stator (41) is circular in cross-section and is formed from three separately moulded, arcuate stator portions (53). The arcuate portions (53) are mounted such that their end regions abut to form the annular stator (41), and each portion (53) is provided with a radially inwardly extending stator flange (55) by which it is secured to the stator side plate (49).

The permanent magnet machine (40) further comprises a central shaft (57). A hub (59) is secured to the shaft (57) and the rotor side plate (51) to form a hub drive arrangement, with bearings being provided between the shaft (57) and hub (59). The hub drive arrangement permits the permanent magnet machine (40) to be directly connected to a complementary external direct drive mechanism, as will be described further below. In this embodiment, the hub (59) and shaft (57) are manufactured from mild steel.

In this embodiment, the inner rotor portion (45) and the outer rotor portion (47) are formed from a plurality of axially stacked magnet rings. A plurality of inner magnet rings (61) and plurality of outer magnet rings (63) are axially secured to one another and to the rotor side plate (51) to respectively form the inner rotor portion (45) and outer rotor portion (47). The inner magnet rings (61) and outer magnet rings (63) are shown in Figures 6 and 8, and Figure 9, which shows the permanent magnet machine (40) in an assembled condition, illustrates the outer magnet rings (63).

The inner surface of the outer rotor portion (47) and the outer surface of the inner rotor portion (45) are provided with a series of axially extending grooves and ridges, as illustrated in Figure 6. These formations permit the rotor portions (45, 47) to act as permanent magnet holders. The grooves form magnet receiving slots (65) for receiving a set of azimuthal magnets, and a set of radial magnets are received against the ridges.

Similarly to the embodiment of Figure 1, both the inner rotor portion (45) and the outer rotor portion (47) is provided with an array of permanent magnets which are magnetised so as to provide substantially radial and substantially azimuthal magnetic field components to operatively complete a magnetic flux path through the permanent magnet machine (40).

The array of permanent magnets of each rotor portion (45, 47) includes a set of radial magnets (67) and a set of azimuthal magnets (69) circumferentially positioned in an alternating polarity arrangement.

Whereas each array of permanent magnets are substantially radially in line to form a Halbach magnet array in the embodiment of Figure 1, in the embodiment of Figure 6, the set of azimuthal magnets (69) of each of the rotor portions (45, 47) are radially offset from the set of radial magnets (67) of the same array and positioned radially further from the air-cored stator (41) than the set of radial magnets (67) of the same array. While the azimuthal magnets (69) are partially embedded in the rotor portions (45, 47), the radial magnets (67) of the inner rotor portion (45) are provided on the outer surface thereof and the radial magnets (67) of the outer rotor portion (47) are provided on the inner surface thereof.

Sets of spaced apart bolts (71) and parallel pins (73) secure the outer rotor portion (47) and inner rotor portion (45) to the rotor side plate (51), and machine screws (75) are used to mount the hub (59) to the rotor side plate (51), as is illustrated in Figures 7 and 8.

The cross-sectional view of the permanent magnet machine (40) shown in Figure 10 illustrates an approximate magnetic flux path (F) through the machine, in use. Whereas the radial magnets (67) are magnetised so as to drive magnetic flux in a substantially radial direction, the azimuthal magnets (69) are magnetised so as to drive magnetic flux in a substantially transverse direction to operatively complete the magnetic flux path (F) through the permanent magnet machine (40).

The arrangement of the azimuthal magnets (69) in relation to adjacent radial magnets (67) permits magnetic flux to be driven back and forth between the rotor portions (45, 47) and through the air-cored stator (41) in a substantially radial direction, in use, without requiring ferromagnetic material in either of the rotor portions (45, 47).

In the embodiments described with reference to the drawings, the permanent magnets consist of neodymium-boron-iron (NeBFe), a second generation rare-earth magnet. Specifically, N48 grade NeBFe is used. NeBFe may be preferable over other magnets such as first generation samarium-cobalt due to its cost-effectiveness and usefulness in small to medium motor applications. NeBFe typically provides comparatively high remanant flux density and coercivity.

To applicant’s knowledge, radial flux permanent magnet machines known in the prior art require some form of steel or other ferromagnetic backing to be provided in its rotor or rotor portions for operatively completing the flux path through the machine. This is commonly referred to as a “rotor iron yoke”, “backing iron”, or “steel backing” arrangement.

A number of exemplary magnetic circuit equivalents for one pole pair in a permanent magnet machine are shown in Figures 11A to 11F. The directional arrows provided on each of the magnets in Figures 11A to 11F indicate the approximate direction of their magnetic orientation.

The magnetic circuit equivalent (77) of Figure 11A illustrates a conventional permanent magnet configuration, wherein the rotor portions include steel backing (79). This configuration includes outer rotor and inner rotor radial magnets (81), and the broken line (F) indicates the flux path in use, which is completed through incorporation of ferromagnetic material, such as steel, into the rotor portions.

The magnetic circuit equivalent (83) of Figure 11B illustrates the permanent magnet configuration employed in the embodiment of the permanent magnet machine (40) of Figures 6 to 10. This configuration essentially replaces the backing iron used in the configuration of Figure 11A with a set of azimuthal magnets (85). The circumferentially alternating polarities of the permanent magnets direct the flux path (F) to form generally rotating patterns of magnetisation at each pole pair for operatively driving magnetic flux back and forth within the permanent magnet machine.

Figures 11C to 11F illustrate alternative magnetic circuit equivalents. These configurations can be used to operatively complete the magnetic flux path through the permanent magnet machine when using non-ferromagnetic rotor portions.

In the magnetic circuit equivalent (87) of Figure 11C, azimuthal magnets (89) are included which are angled in relation to the radial direction at an approximately 45 degree angle. The magnetic circuit equivalent (91) of Figure 11D illustrates a configuration wherein trapezoidal azimuthal magnets (93) are included, and the magnetic circuit equivalent (95) of Figure 11E illustrates a configuration similar to that of Figure 11B, additionally provided with azimuthal magnets (97) which are triangular in cross-section and magnetised so as to facilitate the substantially rotating pattern of magnetic flux (F) shown in Figure 11E.

It is envisaged that, in at least some embodiments, the azimuthal and/or radial magnets may be partially or completely embedded within the rotor portions.

Instead of having separate radial and azimuthal magnets, a single magnet may also, in alternative embodiments, provide both radial and azimuthal magnetic field components. Such a permanent magnet configuration (99) is illustrated in Figure 11F. In this configuration, the rotor portions of a particular pole pair are provided with a single magnet (101), instead of separate radial and azimuthal magnets. Each individual magnet (101) has an alternating magnetisation to provide the necessary radial and azimuthal magnetic field components for completing the flux path (F), as shown in Figure 11F.

The permanent magnet machine can be configured for use as a lightweight hub drive motor, and can be connected to a complementary external direct drive mechanism, for example, directly to a wheel of a lightweight vehicle.

The vehicle may, for example, have a mass of around 150kg and an average velocity of around 25km/h. A battery may be used to power the motor, for example, and the system may provide a voltage of in the region of 48V. In such a case, power is transferred directly from the direct drive motor to the vehicle without requiring other mechanisms to effect power transfer.

Figures 12A and 12B illustrate simulation outputs (103, 107) wherein output torque generated by a permanent magnet machine as described with reference to Figures 6 to 10 and Figure 11B is compared to output torque generated by a traditional, steel-backed machine, as described with reference to Figure 11A.

A portion of a sectional view (105) is shown to illustrate the permanent magnet arrangement for the permanent magnet machine of Figure 6, while a portion of a sectional view (109) is also shown to illustrate the backing iron (111) included in the steel-backed machine. The motor characteristics for these simulations are set out in Table 1 below.

Nominal radius	100mm
Active length (length of magnets in axial direction)	60mm
Number of poles	24
Number of coils	18
Number of turns per coil	102
Peak current	1.8A

Table 1: Motor characteristics for simulations in Figures 12A and 12B

As can be seen in Figures 12A and 12B, the traditional, steel-backed machine produces an average of approximately 8.4Nm of torque, while the machine described produces an average of approximately 6.8Nm of torque. Although the traditional machine produces approximately 20% more torque, it should be noted that the absence of ferromagnetic materials in the rotor portions may readily reduce the total mass of the permanent magnet machine by more than 20%. Accordingly, the permanent magnet machine according to the disclosure may provide a greater torque-to-weight ratio, or power density, than conventional machines.

Figures 13A and 13B illustrate simulation outputs (113, 115) wherein output torque generated by a machine using trapezoidal azimuthal magnets as shown in Figure 11D is compared with the output torque generated by a machine using rectangular azimuthal magnets as shown in Figure 11B.

A portion of a sectional view (117) is shown to illustrate the trapezoidal arrangement, while a portion of a sectional view (119) is also shown to illustrate the rectangular arrangement. The motor characteristics for these simulations are set out in Table 2 below.

Nominal radius	100mm
Active length (length of magnets in axial direction)	60mm
Number of poles	24
Number of coils	18
Number of turns per coil	30
Peak current	7A

Table 2: Motor characteristics for simulations in Figures 13A and 13B

As can be seen in Figures 13A and 13B, the machine employing trapezoidal azimuthal magnets produces an average of approximately 13.7Nm of torque, while the machine employing rectangular azimuthal magnets produces an average of approximately 12.8Nm of torque. These results indicate that a trapezoidal configuration may serve to reduce flux leakage, thereby increasing torque output and further improving the torque-to-weight ratio of the machine.

Figure 14 illustrates a simulation output (121) which shows the radial flux (F) obtained by the permanent magnet machine according to the disclosure. The motor characteristics used for this simulation are set out in Table 3 below.

Nominal radius	60mm
Active length (length of magnets in axial direction)	55mm
Number of poles	24
Number of coils	18
Number of turns per coil	102
Peak current	1.8A

Table 3: Motor characteristics for simulations in Figure 14

As can be seen in Figure 14, the permanent magnet machine produces a radial flux of approximately 0.54T and displays a relatively clean sinusoidal form. This may be desirable in that space harmonics which oppose the desired direction of rotation may be avoided.

Figures 15A, 15B and 15C illustrate simulation outputs (125, 129, 133) wherein output torque generated by a machine using the traditional steel-backed configuration (125), the offset magnet configuration (129) of Figures 6 to 10, and the in line magnet configuration (133) of Figures 1 to 4, respectively, are compared. Output from a machine as represented in Figure 11A is thus shown in Figure 15A, while output from the second and first embodiments of the disclosure are shown in Figures 15B and 15C, respectively.

A portion of a sectional view (127) is shown to illustrate the conventional configuration, a further portion of a sectional view (131) is shown to illustrate the offset arrangement, and a third portion of a sectional view (135) is also shown to illustrate the in line permanent magnet arrangement. The motor characteristics for these simulations are set out in Table 4 below.

Nominal radius	84mm
Active length (length of magnets in axial direction)	20mm

Number of poles	24
Number of coils	18
Number of turns per coil	154
Peak current	2.5A

Table 4: Motor characteristics for simulations in Figures 15A, 15B and 15C

As can be seen in Figures 15A to 15C, the machine employing the in line magnet configuration of Figures 1 to 4 produces a greater output torque than the machine employing the offset magnet configuration of Figures 6 to 10 and the traditional steel-backed machine. The conventional machine of Figure 15A produces an average of about 7.35Nm of torque, the offset machine of Figure 15B produces an average of about 6.1Nm of torque, and the in line machine of Figure 15C produces an average torque of about 8.3Nm.

These results indicate that a permanent magnet machine according to the invention employing an in line magnet arrangement, or substantially or completely a Halbach magnet arrangement, may produce in excess of 30% more torque than the offset arrangement in some cases. Furthermore, such a machine may produce in excess of 10% more torque than the traditional steel-backed machine under some circumstances. The in line arrangement may therefore compare favourably to traditional steel-backed machines, while still being lighter than such machines.

A notable advantage of the present disclosure is that the mass of the machine may be significantly reduced. The use of aluminium rotor portions may reduce the mass of the machine by in the region of 20% when compared to steel-backed machines, while the use of even lighter materials such as carbon fibre may further reduce the mass.

Whereas ferrous materials are used in prior art radial flux permanent magnet machines to complete the flux path, the arrangement of permanent magnets provided facilitates completion of the flux path without the need for ferrous materials in the rotor portions.

The reduced mass and improved torque and/or torque-to-weight ratio achieved may make the radial flux permanent magnet machine useful in lightweight applications. For example, the machine may be incorporated into the rim of a wheel as a direct drive hub motor, such as for a bicycle wheel, or into the spinner of a low power wind turbine as a direct drive generator.

Exemplary implementations of the disclosure include use in small battery-powered vehicles and solar-powered vehicles, including battery operated bicycles, airplanes, quad-copters, and unmanned aerial vehicles. Generator applications may include use of the machine in small wind turbines for use in battery chargers.

The above description is by way of example only and it should be appreciated that numerous changes and modifications may be made to the embodiments described without departing from the scope of the invention.

Although the permanent magnet machine described herein includes rotor portions, a stator side plate and a rotor side plate manufactured from aluminium, any other non-ferromagnetic material may be used. It is envisaged that a lighter material such as carbon fibre or carbon fibre reinforced plastic (CFRP) may be used to further reduce mass and improve power density.

It is envisaged that a radial height of the radial magnets may be greater than a radial height of the azimuthal magnets in embodiments of the disclosure. For example, the radial height of the radial magnets may be twice that of the radial height of the radial magnets. It should also be appreciated that, as described with reference to Figure 11F, the required magnetic field components for completing the flux path through a rotor portion may be provided by a single magnet having an alternating magnetisation. It should also be noted that coils having non-overlapping or overlapping windings may be used.

Throughout the specification and claims unless the contents requires otherwise the word ‘comprise’ or variations such as ‘comprises’ or ‘comprising’ will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

CLAIMS:

1. A radial flux permanent magnet machine (1), comprising:

   an air-cored stator (3) positioned in an air gap (5) defined between generally annular inner (7) and outer (9) rotors mounted to operatively rotate together, the inner (7) and outer (9) rotors being radially spaced apart from the air-cored stator (3) and at least one of the rotors (7, 9) having an array of permanent magnets (21, 23) about its circumference, the machine being characterised in that

   the array of permanent magnets (21, 23) provides substantially radial and substantially azimuthal magnetic field components to operatively complete a magnetic flux path through the machine.

2. The radial flux permanent magnet machine (1) as claimed in claim 1, wherein the inner (7) and outer (9) rotors are manufactured from materials that are substantially free of ferromagnetic material.

3. The radial flux permanent magnet machine (1) as claimed in claim 1 or claim 2, wherein an array of permanent magnets (21, 23) is provided on one of the inner (7) and outer rotor (9).

4. The radial flux permanent magnet machine (1) as claimed in claim 1 or claim 2, wherein both the inner (7) and outer rotors (9) have an array of permanent magnets (21, 23) about their circumference.

5. The radial flux permanent magnet machine (1) as claimed in any one of the preceding claims, wherein each array of permanent magnets (21, 23) includes a set of radial magnets (25) and a set of azimuthal magnets (27) circumferentially positioned in an alternating polarity arrangement along the rotor (7, 9), the radial magnets (25) providing radial magnetic field components and the azimuthal magnets (27) providing azimuthal magnetic field components.

6. The radial flux permanent magnet machine (40) as claimed in claim 5, wherein the set of azimuthal magnets (69) of a particular array of permanent magnets is radially offset from the set of radial magnets (67) of the same array and positioned radially further from the air-cored stator (41) than the set of radial magnets (67) of the same array.

7. The radial flux permanent magnet machine (1, 40) as claimed in claim 5 or claim 6, wherein the set of azimuthal magnets (27, 69) of each array is substantially embedded in its associated rotor.

8. The radial flux permanent magnet machine (1, 40) as claimed in any one of claims 5 to 7, wherein the set of radial magnets (25, 67) of the inner rotor (7, 45) is provided on a radially outer surface thereof and the set of radial magnets (25, 67) of the outer rotor (9, 47) is provided on a radially inner surface thereof.

9. The radial flux permanent magnet machine (40) as claimed in any one of the preceding claims, wherein the outer rotor (47) and/or the inner rotor (45) define magnet receiving slots (65).

10. The radial flux permanent magnet machine (40) as claimed in claim 9, wherein one or both of the azimuthal magnets (69) and the radial magnets (67) are received in the magnet receiving slots (65).

11. The radial flux permanent magnet machine (40) as claimed in any one of the preceding claims, wherein an inner surface of the outer rotor (47) and an outer surface of the inner rotor (45) define a series of grooves and ridges, the grooves forming magnet receiving slots (65) for receiving a set of azimuthal magnets (69) and radial magnets (67) being received against the ridges such that, for each rotor, the radial magnets are radially offset from the azimuthal magnets.

12. The radial flux permanent magnet machine as claimed in any one of the preceding claims, wherein the permanent magnets making up the array of permanent magnets are magnetised so as to provide a series of generally rotating patterns of magnetisation for operatively driving magnetic flux back and forth between the rotors and through the air-cored stator in a substantially radial direction.

13. The radial flux permanent magnet machine as claimed in claim 12, wherein at least one of the permanent magnets has an alternating magnetisation to provide radial and azimuthal magnetic field components.

14. The radial flux permanent magnet machine as claimed in any one of the preceding claims, wherein the air-cored stator includes a series of non-overlapping, wound coils held in a polymeric resin.

15. The radial flux permanent magnet machine (40) as claimed in any one of the preceding claims, wherein one or both of the rotors (45, 47) are formed by a plurality of axially stacked rings (61, 63) which are secured together and wherein the machine further comprises a rotor side plate (51), the inner rotor (45) and outer rotor (47) being secured to the rotor side plate (51), and a stator side plate (49) secured to the air-cored stator (41).

16. The radial flux permanent magnet machine (40) as claimed in any one of the preceding claims, further comprising a hub (59) secured to a central shaft (57) to form a hub drive arrangement, the hub drive arrangement permitting the machine to be connected to a complementary external direct drive mechanism.

17. The radial flux permanent magnet machine as claimed in any one of the preceding claims, wherein each array of permanent magnets is substantially arranged in a Halbach magnet array.

18. A rotor for a radial flux permanent magnet machine comprising a generally annular body and an array of permanent magnets about its circumference, the array of permanent magnets being configured to provide substantially radial and substantially azimuthal magnetic field components to operatively complete a magnetic flux path through the permanent magnet machine.

19. A rotor as claimed in claim 18, which is manufactured from materials that are substantially free of ferromagnetic material.

20. A rotor as claimed in claim 18 or claim 19, wherein the array of permanent magnets includes a set of radial magnets and a set of azimuthal magnets circumferentially positioned in an alternating polarity arrangement along the rotor, the radial magnets providing the radial magnetic field component and the azimuthal magnets providing the azimuthal magnetic field component.

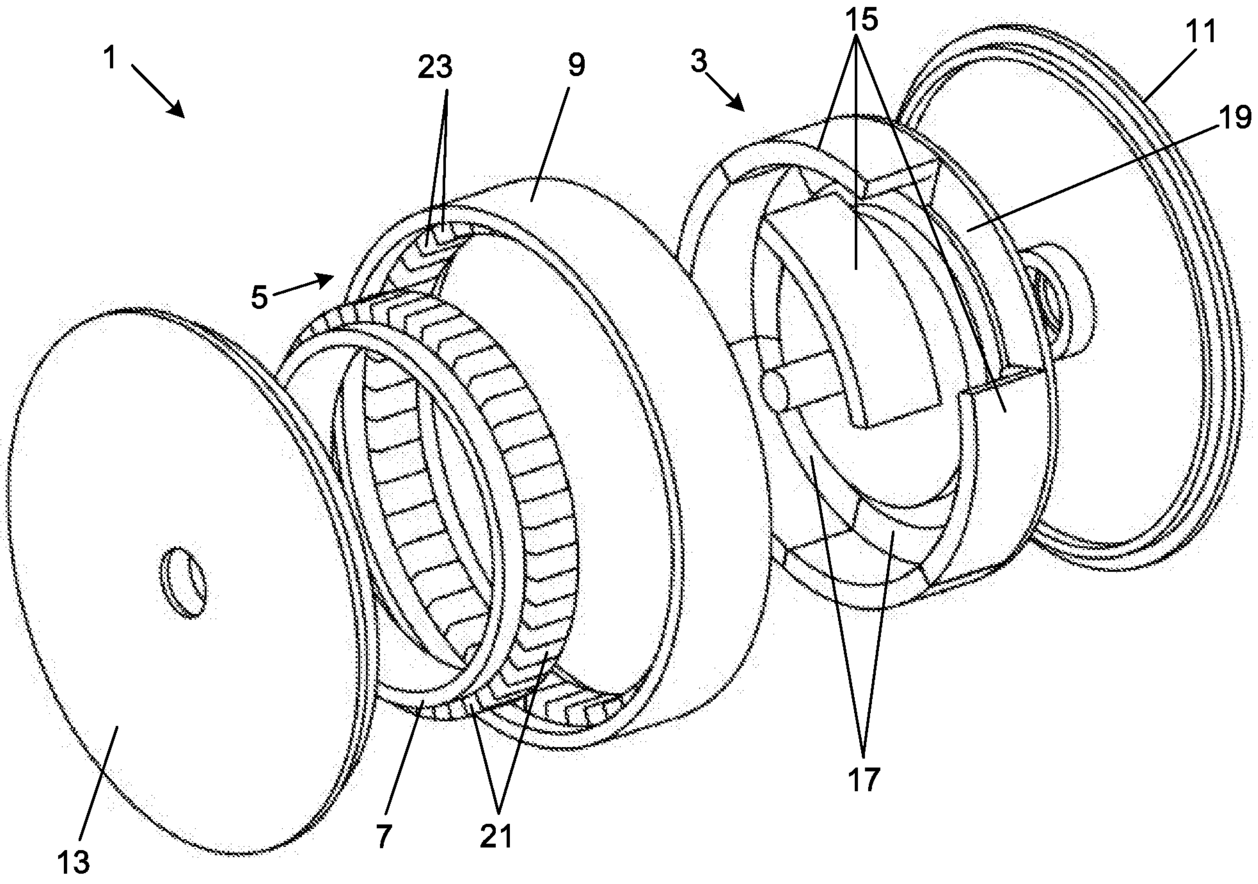
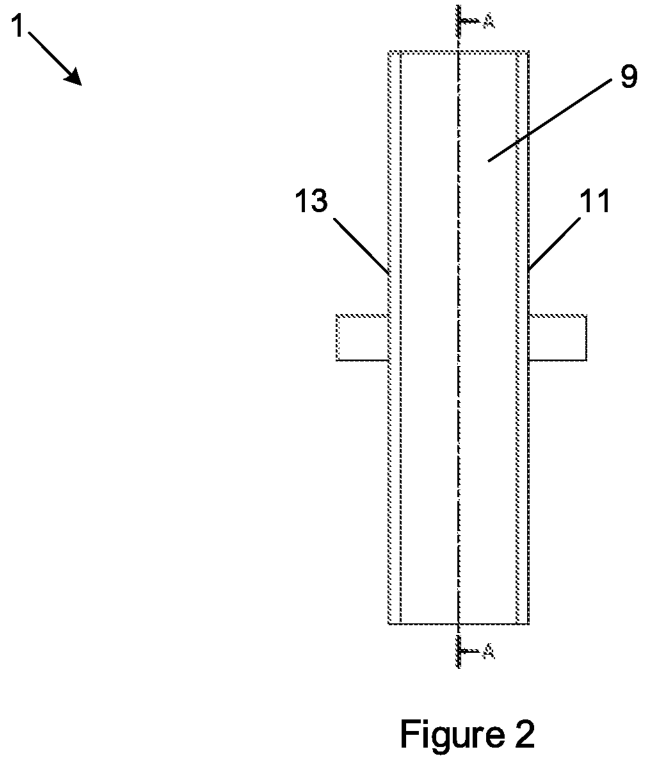


Figure 1



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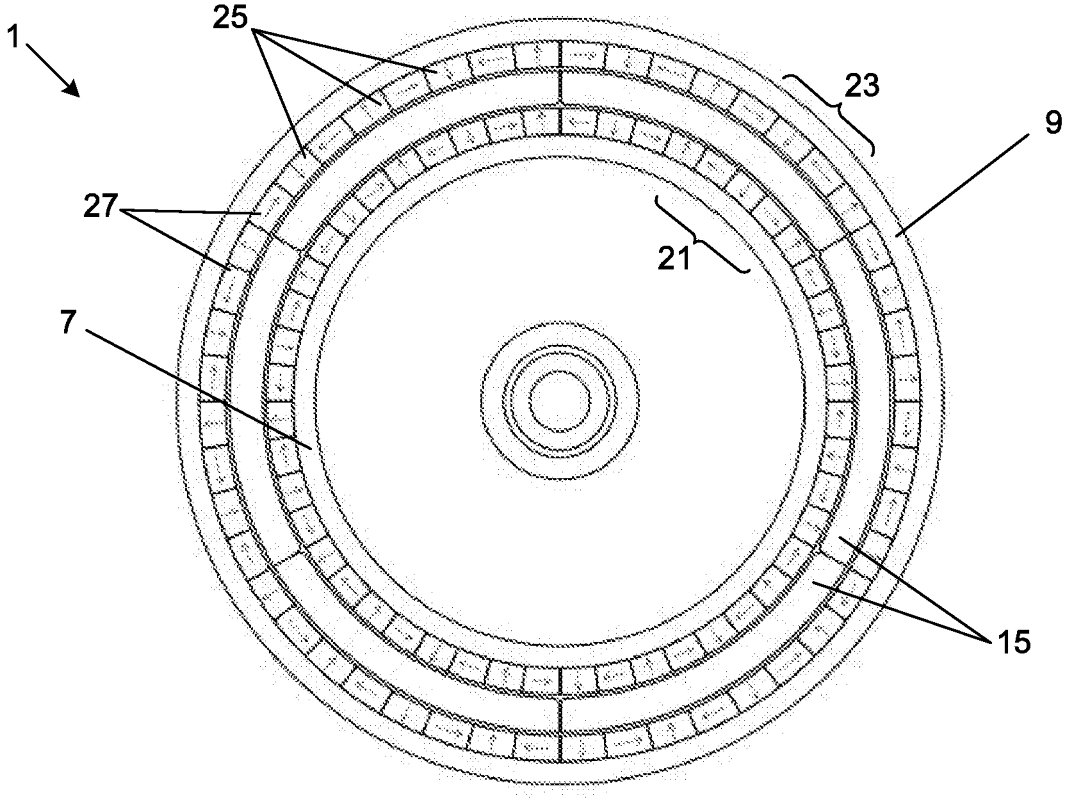

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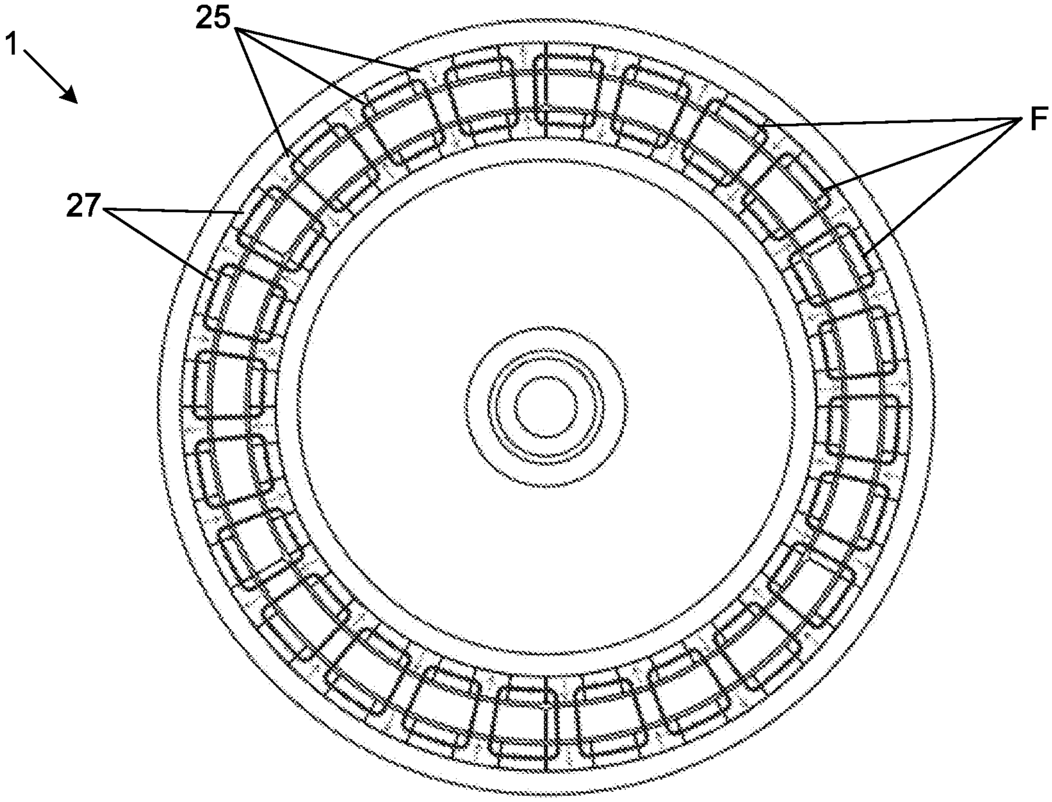


Figure 4

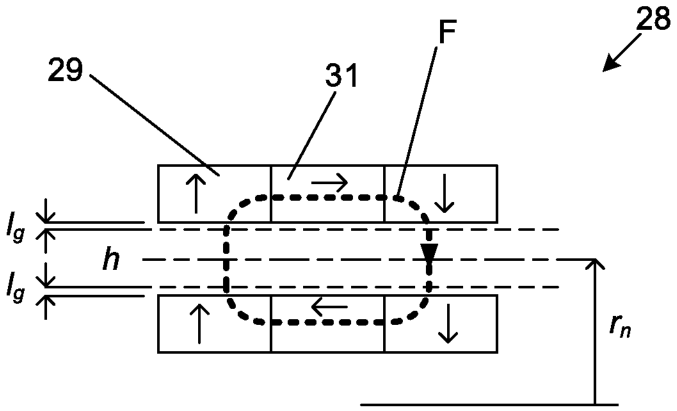


Figure 5A

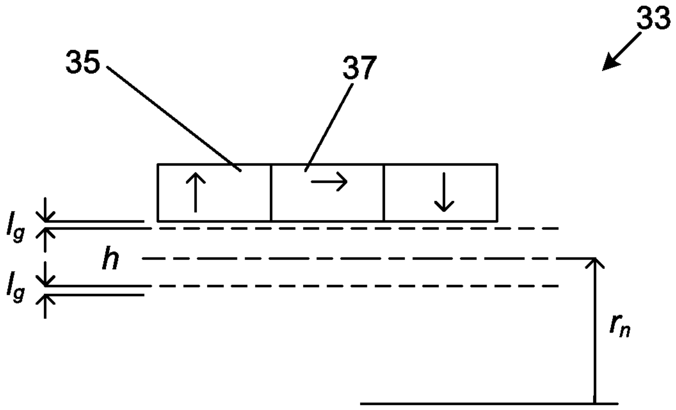


Figure 5B

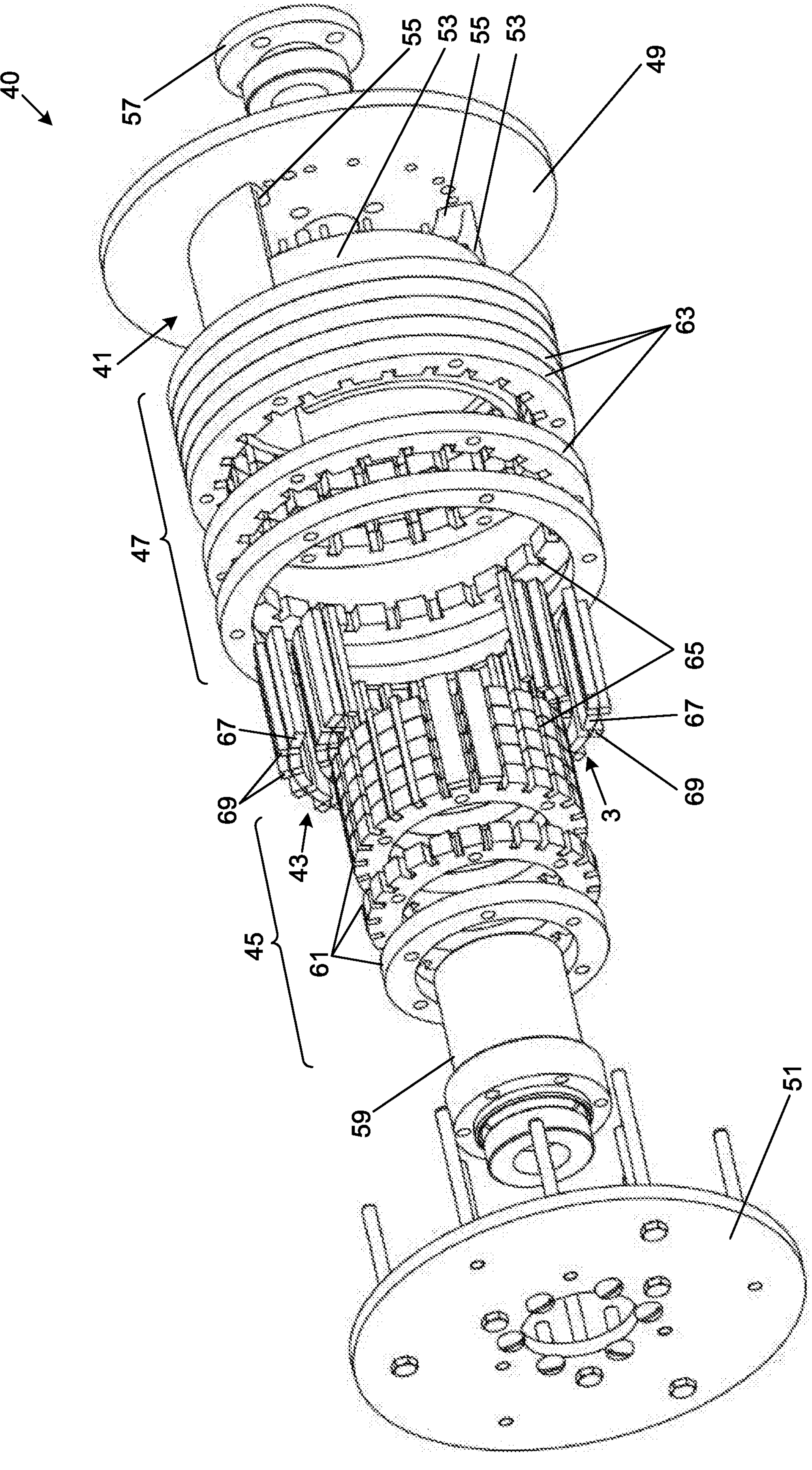
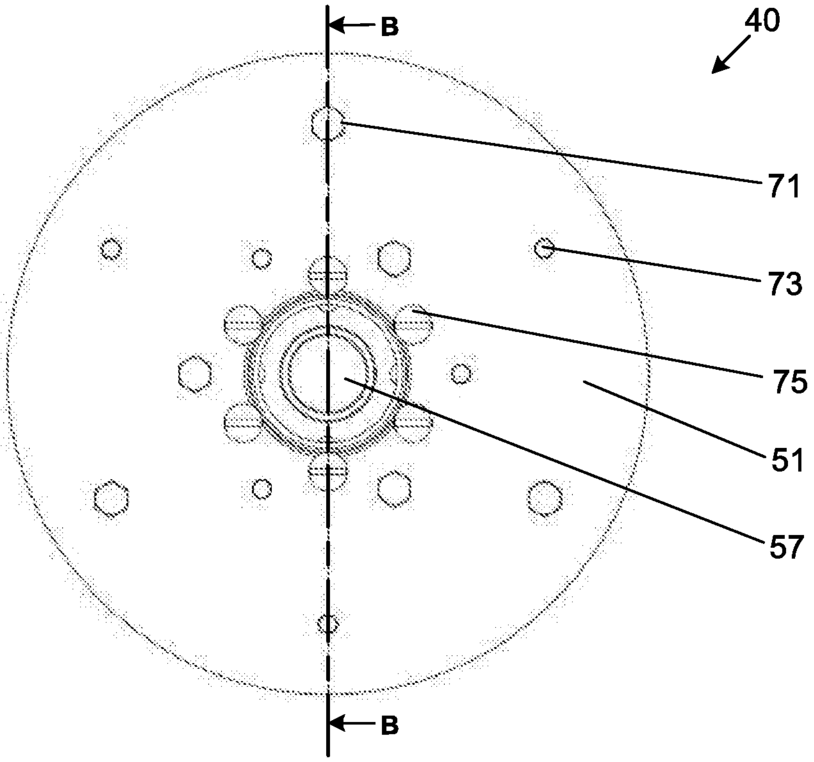


Figure 6



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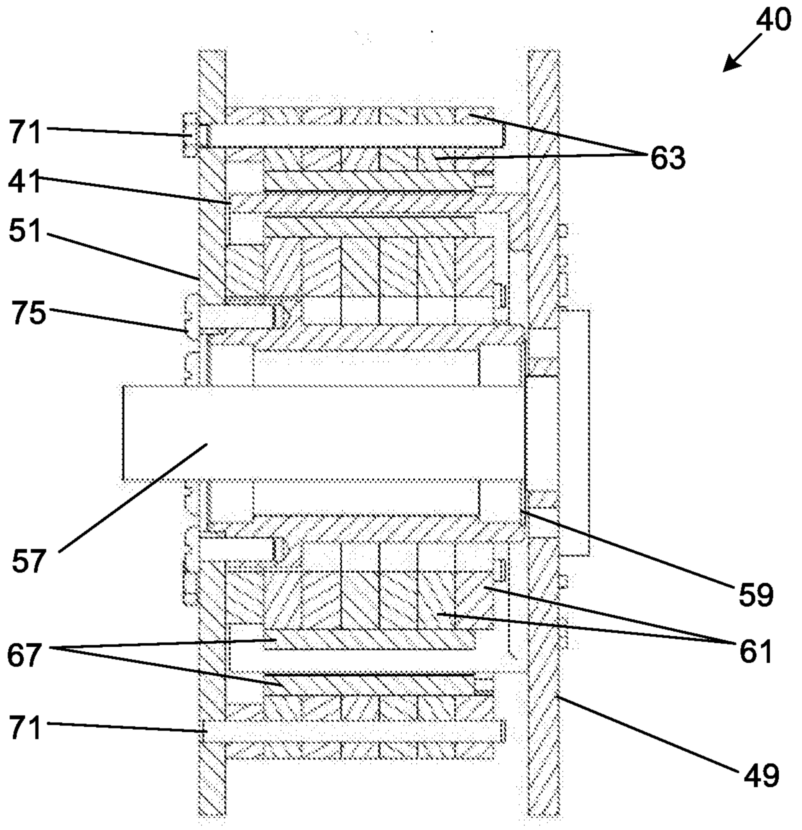


Figure 8

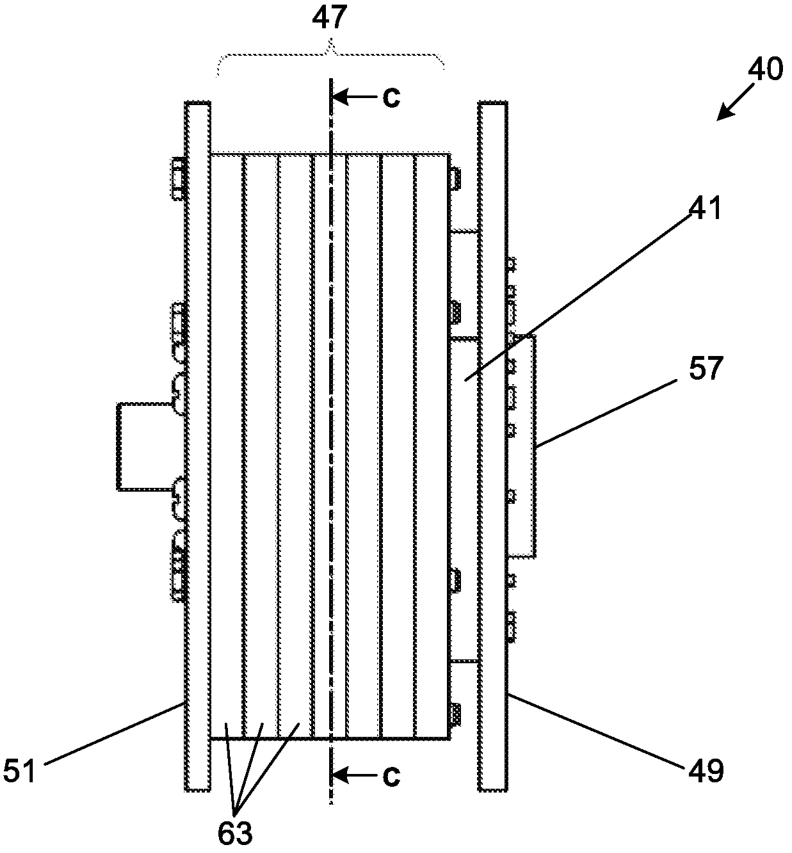
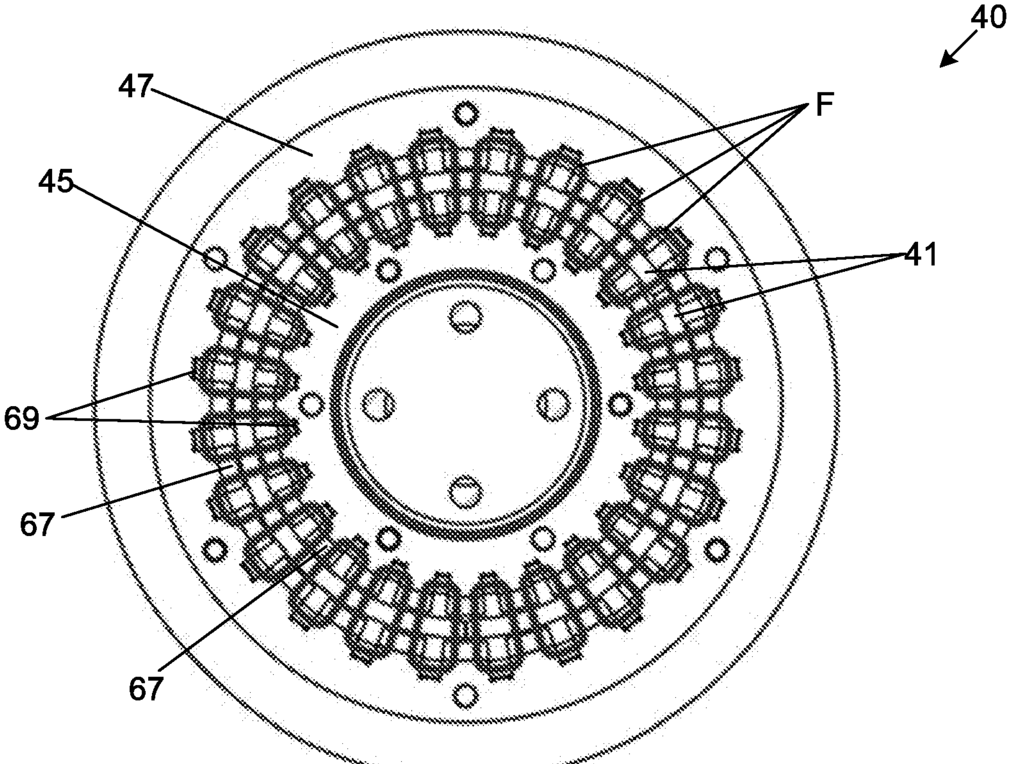


Figure 9



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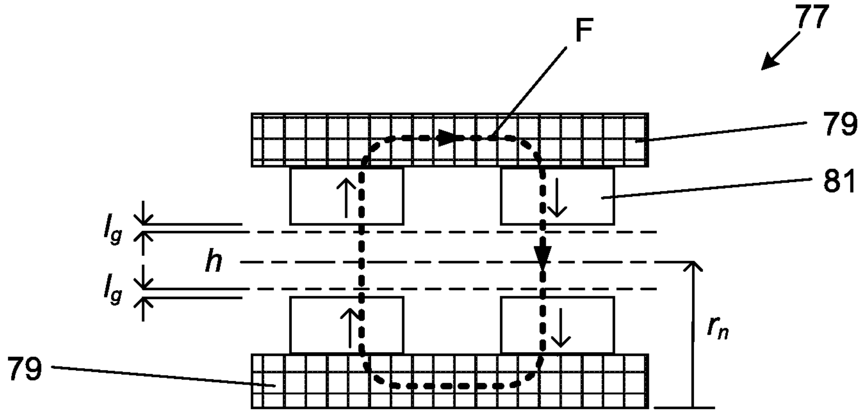

Figure 11A

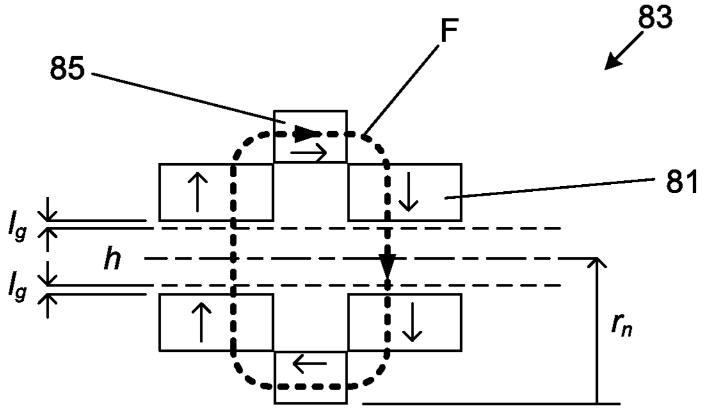

Figure 11B

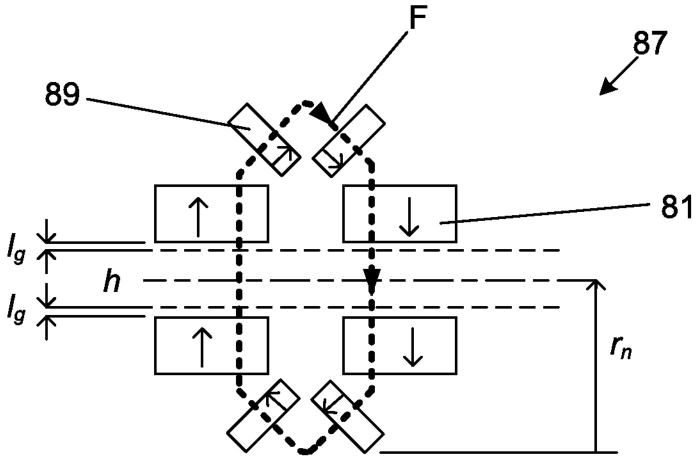

Figure 11C

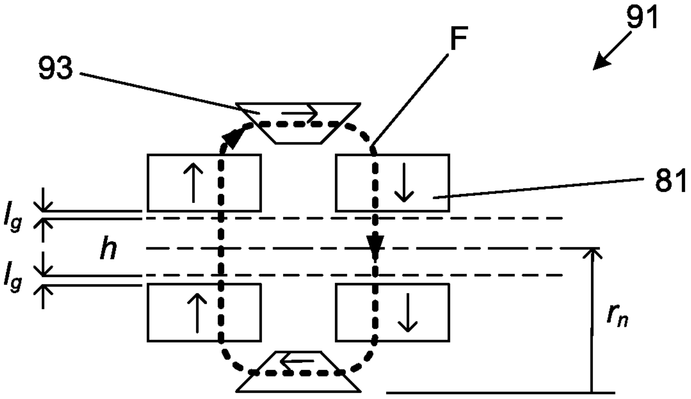

Figure 11D

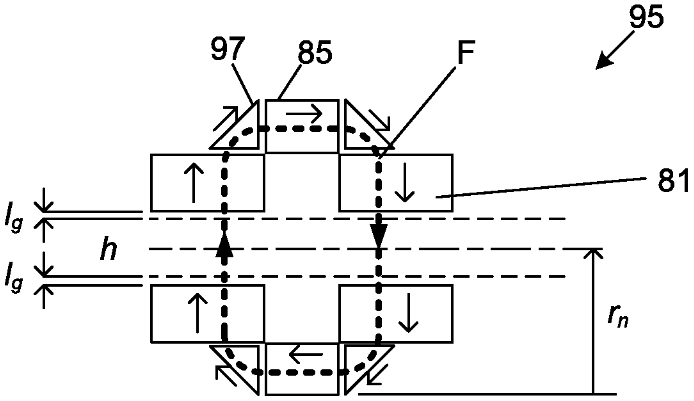

Figure 11E

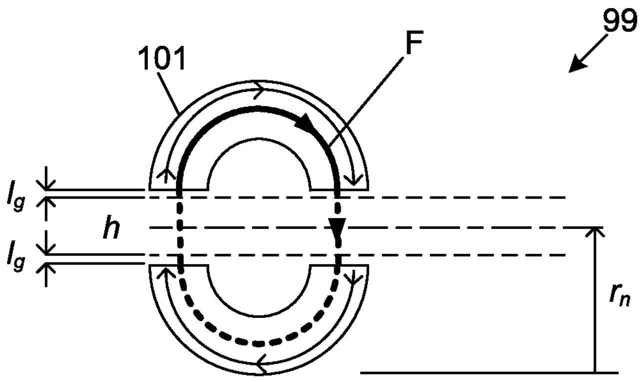

Figure 11F

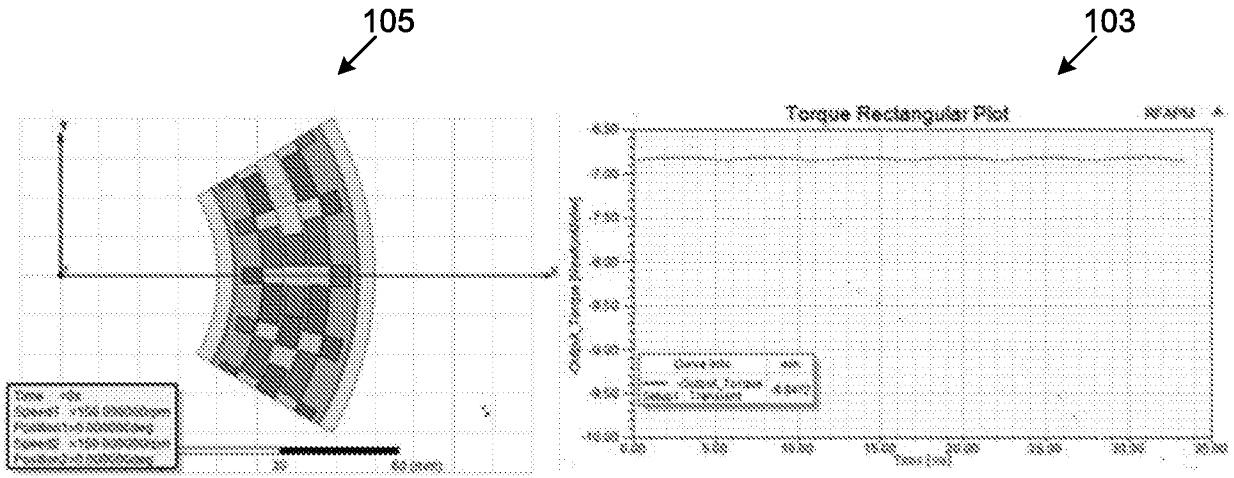

Figure 12A

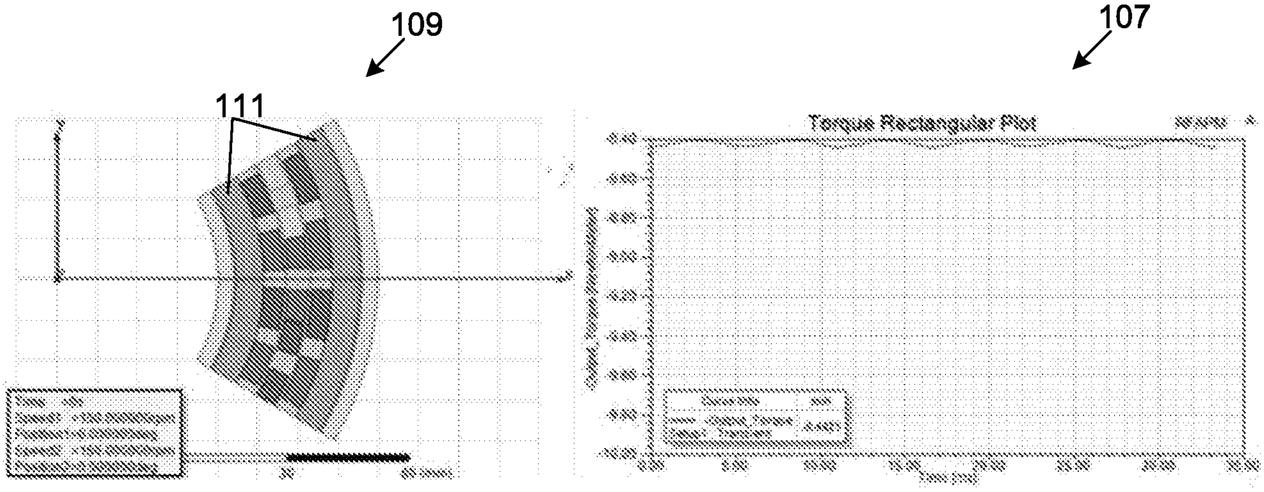

Figure 12B

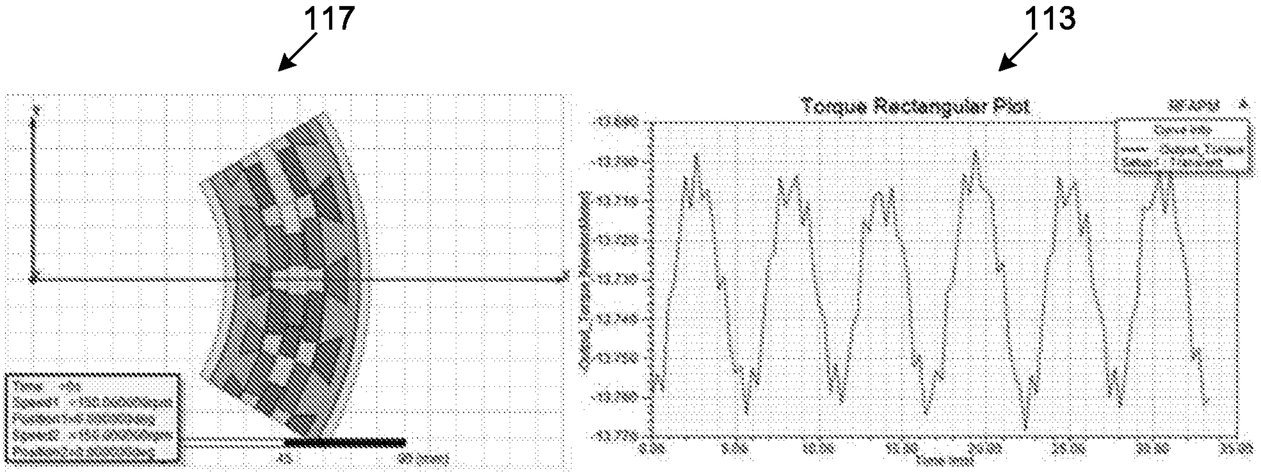

Figure 13A

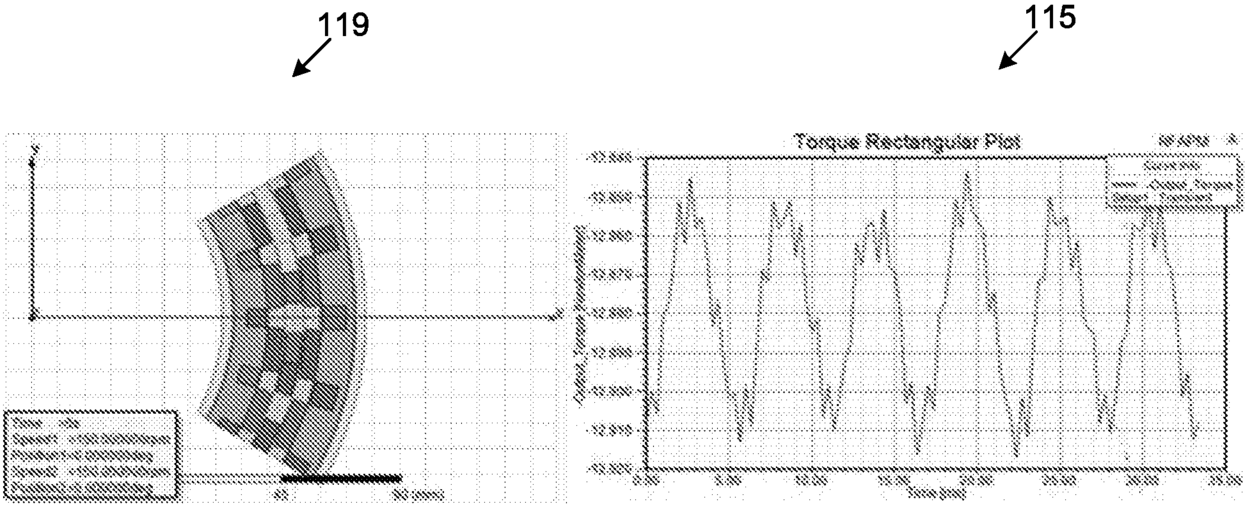

Figure 13B

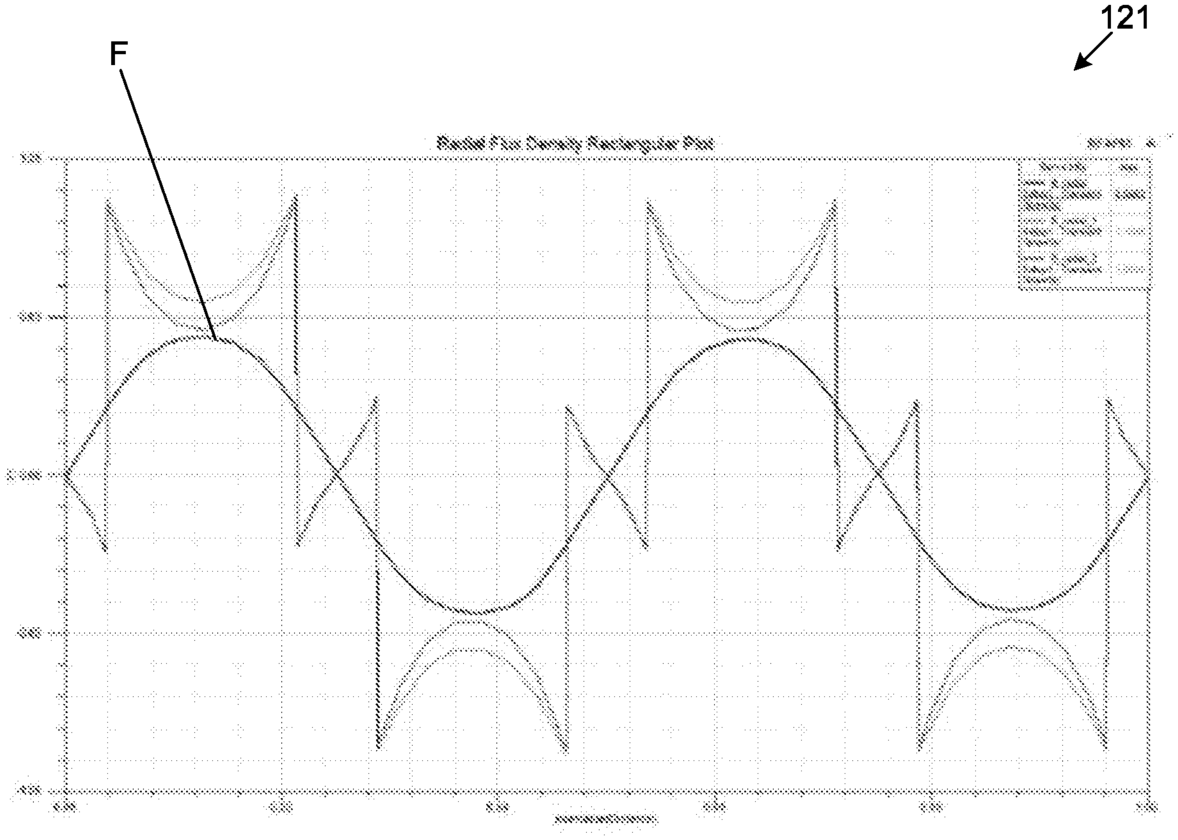

Figure 14

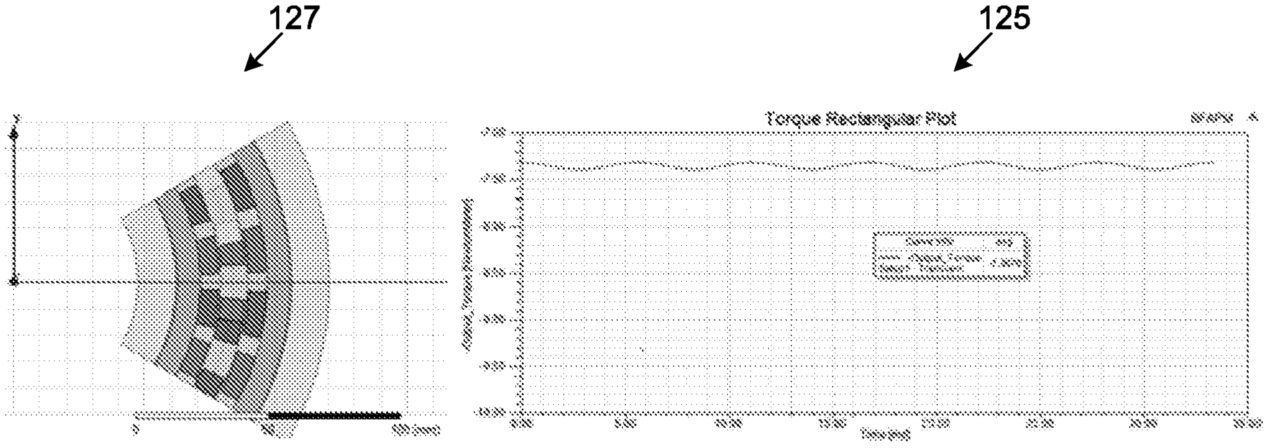

Figure 15A

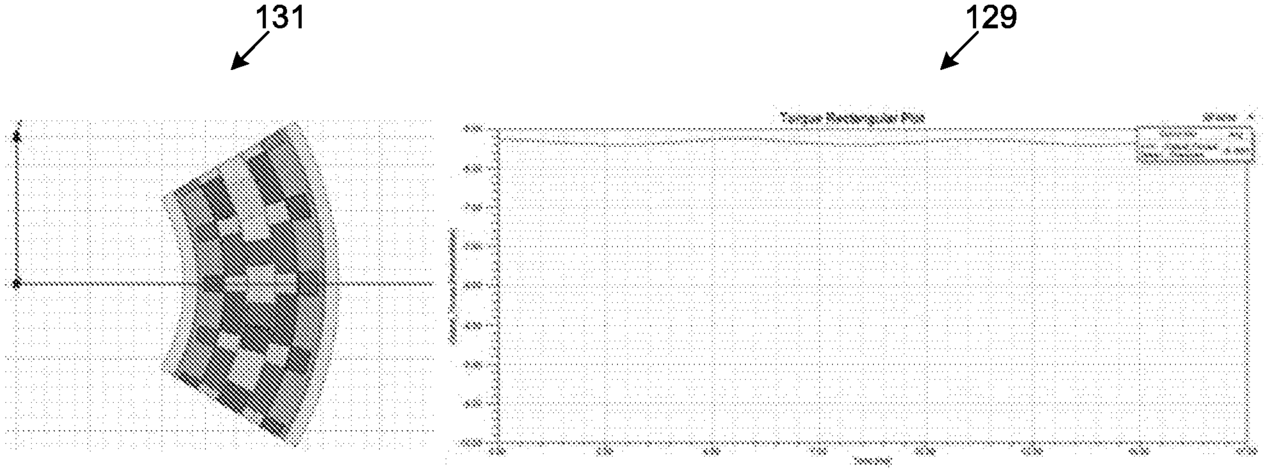

Figure 15B

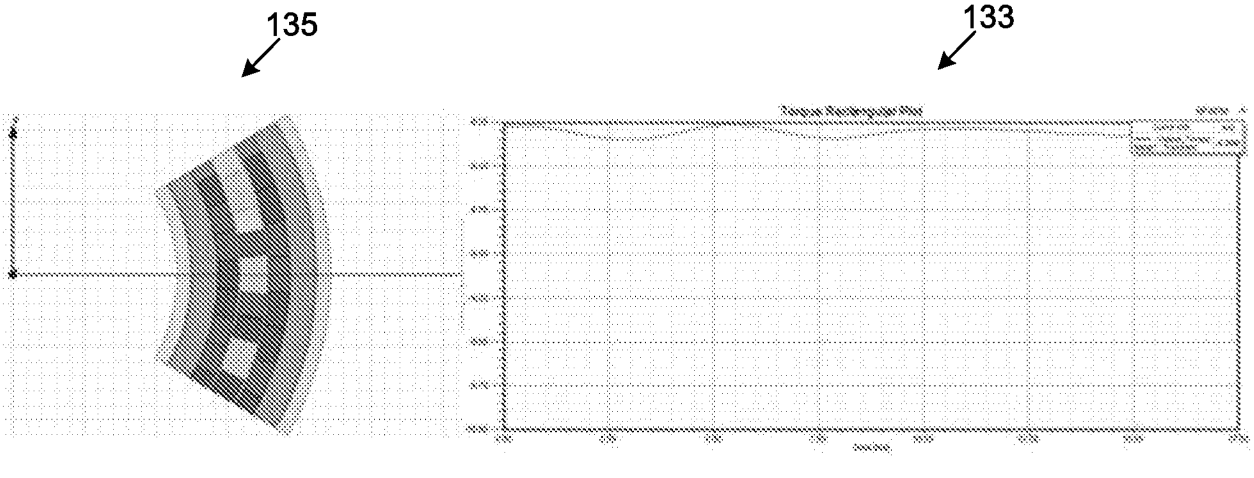

Figure 15C

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2015/053489

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02K16/02
ADD. H02K1/27

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)
H02K

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2006/033393 A1 (RITCHEY JONATHAN G [CA]) 16 February 2006 (2006-02-16) paragraphs [0044], [0046], [0048], [0049], [0050]; figures 8-9a, 10 -----	1-5, 8-13,15, 16,18-20
X	JP 2009 201343 A (TOSHIBA CORP) 3 September 2009 (2009-09-03) paragraphs [0008], [0024], [0025], [0026]; figures 1, 7, 16 -----	1-5, 8-12,14, 16-20
X	WO 2010/036747 A2 (AEROVIRONMENT INC [US]; RIPPEL WALLEY [US]; HIBBS BART [US]; PHAN BANG) 1 April 2010 (2010-04-01) paragraphs [0015], [0016], [0021]; figure 3 ----- -/--	1-12, 16-20

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

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"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 16 July 2015	Date of mailing of the international search report 23/07/2015
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Czogalla, Thomas

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INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2015/053489

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US 2005/225192 A1 (KLOEPZIG MARKUS [DE] ET AL) 13 October 2005 (2005-10-13) paragraphs [0027] - [0032]; figures 4-7 -----	6-9
A	DE 10 2011 005713 A1 (SIEMENS AG [DE]) 20 September 2012 (2012-09-20) paragraphs [0038], [0042], [0043]; figures 6-8 -----	6-11

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Information on patent family members

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