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[Continued on next page]

(54) Title: MODULAR ELECTRIC GENERATOR FOR VARIABLE SPEED TURBINES

(57) Abstract: An electric power generation system may be constructed of multiple similar generator modules arranged between a rotor and a stator. The rotor may be coupled to and/or integrated with a turbine that is configured to rotate in the presence of a fluid stream such as wind or water. Each generator module may have a rotor portion configured to generate a magnetic field having at least one characteristic that changes with respect to the rotational speed of the rotor. Each generator module may further have a stator portion configured to generate an alternating electric current responsive to the magnetic field. The generated electric current may be controlled by the stator portion of the generator module in order to magnetically control the rotational speed of the rotor and the turbine. Separation between the rotor and stator portions of the generator module may be magnetically maintained.

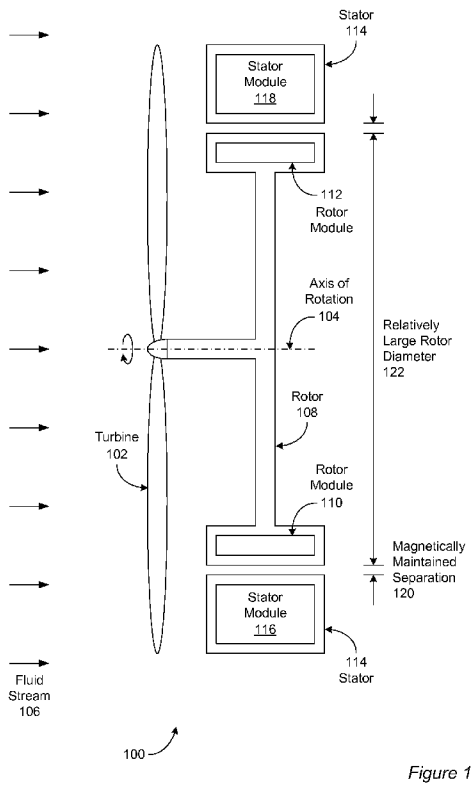


Figure 1

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Modular Electric Generator For Variable Speed Turbines

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims the benefit of US Provisional Application No. 61/310,234 (Attorney Docket No. 028442-000100US) filed on March 3, 2010, and US Provisional Application No. 61/414,732 Attorney Docket No. 028442-000200US) filed on November 17, 2010, the full disclosures of which are incorporated herein by reference.

BACKGROUND

[0002] From lighting and heating to electrolysis and electric motors, electric power is employed in an ever increasing number of applications in residential, commercial and industrial sectors. This demand for electric power is met by a wide variety of electric power generation systems ("generation systems") including coal and gas-fired power plants, nuclear power plants, hydroelectric power stations and wind turbines. However, conventional generation systems have disadvantages. For example, some conventional generation systems consume nonrenewable fuels and/or have adverse environmental impacts such as associated pollution and/or hazardous waste. Some conventional generation systems avoid these disadvantages, but have other shortcomings.

[0003] For example, some conventional generation systems generate electric power based on renewable fluid streams such as wind, renewable water flows including tidal and wave-associated water flows, and geothermally heated fluid streams. Such renewable fluid streams may be naturally occurring or naturally assisted, and may have characteristics such as flow rate and power density that vary significantly and/or depend on geographic location. Such variability of fluid stream characteristics can present a challenge to designers of conventional generation systems, and some conventional generation systems are designed to operate efficiently and/or effectively only within a relatively narrow range of characteristic values. For example, wind quality available at different geographical locations may be classified by average power density or wind

speed, and conventional wind turbines may require particular classes of wind to operate efficiently and/or effectively. Such limitations on conventional generation system designs may significantly constrain the geographical regions suitable for the generation systems and/or be associated with significant electric power transmission costs.

[0004] Some conventional generation systems attempt to expand the range of operationally suitable characteristic values by incorporating variable pitch turbines. However, variable pitch turbines can be significantly more expensive and/or less reliable than fixed pitch turbines. Some conventional generation systems attempt to expand the range of operationally suitable characteristic values by incorporating a mechanical gearbox. However, such gearboxes can be a significant portion of the purchase and/or maintenance cost of the system. Some conventional generation systems are custom manufactured to perform efficiently and/or effectively with respect to expected ranges of characteristic values at particular geographical locations. However, such custom manufacture can be significantly more expensive and/or require significantly longer to manufacture and/or maintain relative to designs amenable to mass production techniques.

SUMMARY

[0005] An electric power generation system may be constructed of multiple similar generator modules arranged between a rotor and a stator. The rotor may be coupled to and/or integrated with a turbine. The turbine may be configured to rotate in the presence of a fluid stream such as wind or water. A rotational speed of the turbine may vary depending on a flow rate of the fluid stream. A rotational speed of the rotor may correspond to the rotational speed of the turbine. The coupling of the turbine and rotor need not include a mechanical gearbox configured to mediate the rotational speed of the rotor with respect to the rotational speed of the turbine. Each generator module may have a rotor portion coupled to the rotor and configured to generate a magnetic field having at least one characteristic that changes with respect to the rotational speed of the rotor. Each generator module may further have a stator portion coupled to the stator and configured to generate an alternating electric current responsive to the magnetic field. The generated electric current may be controlled by the stator portion of

the generator module in order to magnetically control (e.g., decelerate) the rotational speed of the rotor and the turbine. Separation between the rotor and stator portions of the generator module may be magnetically maintained.

[0006] As part of magnetically controlling the rotational speed of the rotor and turbine, values of one or more characteristics of the rotor and/or generated electric current may be measured. Target values for those characteristics may be determined. For example, particular target values of the generated electric current may correspond to particular rotational speeds of the rotor and/or the turbine. An optimal value of the rotational speed of the turbine may exist with respect to a given flow rate of the fluid stream. Target values of the characteristics of the generated electric current may be selected to correspond to the optimal value of the rotation speed of the turbine. The generator modules of a generator may act individually and/or collectively to achieve the target values.

[0007] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter. Other objects and/or advantages of the present invention will be apparent to one of ordinary skill in the art upon review of the detailed description of the present invention and the included figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Various embodiments in accordance with the present disclosure will be described with reference to the drawings, in which:

[0009] Figure 1 is a cross-sectional diagram depicting aspects of an example electric generator in accordance with some embodiments of the present invention;

[0010] Figure 2 is a cross-sectional diagram depicting aspects of another example electric generator in accordance with some embodiments of the present invention;

[0011] Figure 3 is a cross-sectional diagram depicting aspects of still another example electric generator in accordance with some embodiments of the present invention;

[0012] Figure 4 is a cross-sectional diagram depicting aspects of yet another example electric generator in accordance with some embodiments of the present invention;

[0013] Figure 5 is a cross-sectional diagram depicting aspects of a further example electric generator in accordance with some embodiments of the present invention;

[0014] Figure 6 is a cross-sectional diagram depicting aspects of still another example electric generator in accordance with some embodiments of the present invention;

[0015] Figure 7 is a cross-sectional diagram depicting aspects of still yet another example electric generator in accordance with some embodiments of the present invention;

[0016] Figure 8 is a cross-sectional diagram depicting aspects of an example generator module in accordance with some embodiments of the present invention;

[0017] Figure 9 is a cross-sectional diagram depicting aspects of another example generator module in accordance with some embodiments of the present invention;

[0018] Figure 10 is a cross-sectional diagram depicting aspects of an example retrofitted electric generator in accordance with some embodiments of the present invention;

[0019] Figure 11 is a cross-sectional diagram depicting aspects of an example tower-mounted electric power generation system in accordance with some embodiments of the present invention;

[0020] Figure 12 is a schematic diagram depicting aspects of an example power electronics submodule in accordance with some embodiments of the present invention;

[0021] Figure 13 is a schematic diagram depicting aspects of an example generated AC management network in accordance with some embodiments of the present invention;

[0022] Figure 14 is a schematic diagram depicting aspects of an example generator module plate stack in accordance with some embodiments of the present invention;

[0023] Figure 15 is a flowchart depicting example steps for generating electric power in accordance with some embodiments of the present invention;

[0024] Figure 16 is a flowchart depicting example steps for configuring generator modules in accordance with some embodiments of the present invention; and

[0025] Figure 17 is a flowchart depicting further example steps for configuring generator modules in accordance with some embodiments of the present invention.

[0026] Note that the same numbers are used throughout the disclosure and figures to reference like components and features.

DETAILED DESCRIPTION

[0027] In an embodiment of the invention, mass produced generator modules may be arranged between a rotor and a stator to generate electric power. Electric generators of widely varying sizes and/or capacities (e.g., 100 kW to 20 MW) may be constructed with different numbers of the generator modules and, optionally, larger rotor and/or stator frames. The generator modules may be arranged in rings and/or layers, radially and/or axially. The rotor frame may be coupled to a turbine configured to rotate in a fluid stream. For example, the fluid stream may be a renewable fluid stream having variable characteristics such as wind, and the turbine may be a fixed pitch turbine. An electric generator incorporating the generator modules may adapt to changes in a rotational speed of the turbine and/or a corresponding torque resulting from the fluid stream with a magnetically-induced counter-torque and without use of a mechanical gearbox.

[0028] Each generator module may have a rotor portion ("rotor module") coupled to the rotor frame and a stator portion ("stator module") coupled to the stator frame. Separation of the rotor modules and the stator modules during rotation of the rotor may be maintained substantially with magnetic bearings. Each generator module may include a polyphase alternating current (AC) generator coil and a power electronics submodule configured at least to modify the generated electric voltage and/or current waveforms so as to maintain the rotational speed of the turbine at a desired and/or optimal value with respect to a flow rate of the fluid stream and the capabilities of the

generator. The generator may incorporate a central controller to coordinate the power electronics of the generator modules and/or the generator modules may act independently. The generator modules may be hot-swapped for maintenance purposes. For example, the generator modules of the generator may collectively adapt to an unexpected failure, hot-unplug and/or hot-plug of one or more of the generator modules.

[0029] An axis of rotation of the turbine may be horizontal or vertical. An axis of rotation of the coupled rotor frame and the rotor modules may correspond to the axis of rotation of the turbine or be arranged perpendicularly. Larger capacity generators (e.g., greater than 10 MW) may be possible when the rotor frame has a vertical axis of rotation. Conventional electric power generator structures may be retrofitted with generator modules to obtain one or more benefits in accordance with an embodiment of the invention. A retrofitted electric power generator structure may have an expanded dynamic range with respect to fluid stream flow rates at which the retrofitted system can operate efficiently and/or effectively. For example, a retrofitted wind turbine may operate effectively at lower wind power densities (e.g., less than 400 Watts per square meter) as well as at higher wind power densities (e.g., greater than 1000 Watts per square meter) and during wind bursts.

[0030] Figure 1 is a cross-section of an example electric generator 100 in accordance with an embodiment of the invention. Figure 1 is not to scale and omits structural elements for clarity. The electric generator 100 may incorporate a turbine 102 having a horizontal axis of rotation 104 that rotates in the presence of a fluid stream 106. For example, the fluid stream 106 may be air, and the turbine may incorporate one or more airfoil shaped blades. The cross-section of Figure 1 is from a point of view perpendicular to the axis of rotation 104. The rotational speed of the turbine 102 may vary depending a flow rate of the fluid stream 106. That is, the turbine 102 may be configured as a variable speed turbine. The turbine 102 may be coupled to a rotor 108 that incorporates multiple rotor modules 110-112. The rotor 108 may rotate within a stator 114 that incorporates multiple stator modules 116-118. Separation 120 between the rotor 108 and the stator 114 may be magnetically maintained, for example, with magnetic bearings. The magnetically maintained separation 120 can enable very low losses due to friction, as well as enabling generation of electric power when fluid stream

106 flow rates are relatively low including flow rates at which conventional electric power generation systems would perform sub-optimally or not at all (e.g., below conventional "cut-in" flow rates). The rotor diameter 122 may be relatively large with respect to diameters of rotors in conventional electric power generation systems.

[0031] For clarity, the example of a wind power generation system will be used throughout this description. However, each embodiment of the invention is not limited to this example. The fluid stream 106 may be a flow of any suitable fluid including suitable gases such as air and steam, as well as suitable liquids such as water. The term "fluid" is used herein in the technical sense of fluid dynamics, and is not limited to liquids. The mass of the rotor may be concentrated in the rotor modules 110-112, however, the rotor modules 110-112 need not have the proportions with respect to the rotor 108 depicted in Figure 1. As described below in more detail with reference to Figure 8 and Figure 9, the rotor modules 110-112 need not be embedded within the rotor 108, and the stator modules 116-118 need not be embedded within the stator 114.

[0032] Figure 2 is a cross-section of another example electric generator 200 in accordance with an embodiment of the invention from an illustrative perspective different from that of Figure 1. Figure 2 is not to scale and omits structural elements for clarity. The electric generator 200 includes a rotor 202 rotating about an axis of rotation 204 within a stator 206. The cross-section of Figure 2 is from a point of view parallel to the axis of rotation 204. The rotor 202 includes multiple rotor modules 208-218 arranged in a ring. The stator 206 includes multiple stator modules 220-230 arranged in a corresponding ring. The ellipses "..." between the rotor modules 208 and 218 and between the rotor modules 212 and 214 indicate that the rotor 202 may include any suitable number of rotor modules. Ellipses throughout the drawings have a similar meaning. The rotor modules 208-218 are examples of the rotor modules 110-112 of Figure 1. The stator modules 220-230 are examples of the stator modules 116-118 of Figure 1. In an embodiment of the invention, the ratio of rotor modules 208-218 to stator modules 220-230 is one-to-one (1:1), however, each embodiment of the invention is not so limited.

[0033] The electric generators 100 and 200 of Figure 1 and Figure 2 have rotors 108 and 202 nested within their respective stators 114 and 206. However, each

embodiment of the invention is not so limited. Figure 3 is a cross-section of still another example electric generator 300 in accordance with an embodiment of the invention. Figure 3 is not to scale and omits structural elements for clarity. The electric generator 300 includes components 302, 308, 310-312, 314 and 316-318 corresponding to the components 102, 108, 110-112, 114 and 116-118, respectively, of the electric generator 100 of Figure 1. However, the arrangement of the components 302, 308, 310-312, 314 and 316-318 is different. In the electric generator 300, the rotor 308 and rotor modules 310-312 may be coupled to and/or integrated with radial extremities of blades of the turbine 302. A hub 324 of the turbine 302 may be coupled with the stator 314, and may incorporate axial and/or radial bearings. Nevertheless, the separation 320 between the rotor 308 and the stator 314 may be substantially magnetically maintained, for example, with magnetic bearings incorporated into the rotor modules 310-312 and the stator modules 316-318.

[0034] When an axis of rotation 304 of the turbine 302 is horizontal (e.g., perpendicular to a local direction of gravitational force), gravitational loading can increase peak stress in particular portions of the generator 300. In an embodiment of the invention, peak stress can be reduced, and thus larger form factors and/or system capacities achieved with same cost materials, by utilizing a rotor with a vertical axis of rotation. Figure 4 is a cross-section of yet another example electric generator 400 in accordance with an embodiment of the invention. Figure 4 is not to scale and omits structural elements for clarity. The electric generator 400 includes components 402, 408, 410-412, 414 and 416-418 corresponding to the components 302, 308, 310-312, 314 and 316-318, respectively, of the electric generator 300 of Figure 3. In addition, the electric generator 400 includes a gearbox 424 suitable for transferring a torque generated by the turbine 402 rotating around a horizontal axis 426 to a vertical axis of rotation 428 of the rotor 408. The gearbox 424 need not adjust rotational speed, so that a rotational speed of the rotor 408 may correspond to a rotational speed of the turbine 402.

[0035] Alternatively, the gearbox 424 may be eliminated by incorporating a turbine that rotates around the vertical axis 428 in the presence of a fluid stream 406. Figure 5 is a cross-section of a further example electric generator 500 in accordance with an embodiment of the invention. Figure 5 is not to scale and omits structural elements for

clarity. The electric generator 500 includes components 508, 510-512, 514 and 516-518 corresponding to the components 408, 410-412, 414 and 416-418, respectively, of the electric generator 400 of Figure 4. However, the electric generator 500 incorporates turbine blades 524 oriented so as to cause rotation around a vertical axis 504 when in the presence of a fluid stream 506. In the example electric generator 500, the turbine blades 524 are fastened directly to the rotor 508, and so cause the rotor 508 to rotate around the vertical axis 504. However, each embodiment is not so limited, and the turbine blades 524 and/or a turbine frame (not shown in Figure 5) may be connectively coupled to the rotor 508 in any suitable manner. Furthermore, the turbine blades 524 need not have the number or arrangement depicted in Figure 5, but may include any suitable number of blades (including one) and may be arranged in any suitable configuration that causes rotation around the vertical axis 504 including configurations corresponding to those found in Darrieus wind turbines and Savonius wind turbines known to those of skill in the art.

[0036] In the example generators 100, 200, 300, 400, 500 of Figures 1-5, the separation between the rotors and the stators is depicted as being maintained with respect to a single rotor and/or stator surface. However, each embodiment of the invention is not so limited. Figure 6 is a cross-section of still another example electric generator 600 in accordance with an embodiment of the invention. Figure 6 is not to scale and omits structural elements for clarity. As in the electric generator 400 of Figure 4, the electric generator 600 includes a rotor 608 that incorporates multiple rotor modules 610-612. However, the electric generator 600 incorporates a stator 614 having a shape that requires separation between the stator 614 and the rotor 608 to be maintained with respect to multiple surfaces. The electric generator 600 further includes multiple sets of stator modules (e.g., a set of lower stator modules 624-626 and a set of upper stator modules 628-630) to maintain the separation. Such an arrangement may provide for greater separation stability, for example, in response to transient and/or stochastic perturbing forces and/or torques incident upon the rotor 608.

[0037] Referring back to Figure 1, the set of rotor modules 110-112 together with the set of stator modules 114-116 is collectively called a set, ring or plate of generator modules 110-116. In accordance with an embodiment of the invention, an electric generator may include multiple sets of generator modules. Figure 7 is a cross-section

of still yet another example electric generator 700 in accordance with an embodiment of the invention. Figure 7 is not to scale and omits structural elements for clarity. The electric generator 700 includes a rotor 708 that incorporates multiple sets of rotor modules 724-726, 728-730 and 732-734 rotating around a common axis 704. The rotor 708 rotates within a stator 714 that incorporates multiple sets of stator modules 736-738, 740-742 and 744-746. Each plate of generator modules may correspond to the plate of generator modules 110-116 of Figure 1. High capacity electric generators can be constructed from "stacks" of such plates, for example, as described below in more detail with reference to Figure 14.

[0038] The description now turns to generator module components in accordance with an embodiment of the invention. Figure 8 is a cross-section of an example generator module 800 in accordance with an embodiment of the invention. Figure 8 is not to scale and omits structural elements for clarity. The generator module 800 includes a rotor module 802 and a stator module 804 having a magnetically maintained separation 806.

[0039] The rotor module 802 may incorporate a set of magnetic bearings (e.g., magnetic bearing 808 and like shaded components in Figure 8) fastened to a rotor module frame 810 and configured at least in part to maintain the separation 806 between the rotor module 802 and the stator module 804. The rotor module 802 may further incorporate a field magnet 812 connectively coupled to the rotor module frame 810. A magnetic field keeper 814 may be inserted between the field magnet 812 and the rotor module frame 810 and configured at least in part to maintain the magnetic field generated by the field magnet 812.

[0040] The stator module 804 may also incorporate a set of magnetic bearings fastened to a stator module frame 816 and configured at least in part to maintain the separation 806 between the rotor module 802 and the stator module 804. The set of magnetic bearings fastened to the rotor module frame 810 and the set of magnetic bearings fastened to the stator module frame 816 may interact and cooperate to maintain the separation 806. The stator module 804 may further include a generation coil 818 configured at least to generate polyphase (e.g., 3 phase) alternating electric current (AC) responsive to a time-varying magnetic field generated at least in part by the field magnet 812. The field magnet 812 may incorporate a set of permanent

magnets arranged so as to generate the polyphase alternating electric current in the generation coil 818 as the rotor module 802 is rotated past the stator module 804. The field magnet 812 may incorporate any suitable type of permanent magnet. The stator module frame 816 may incorporate a magnetic core 820 configured at least to enhance a performance of the generation coil 818. For example, the magnetic core 820 may include laminated back-iron and/or ferrite.

[0041] The components of the generator module 800 may have manufacturing tolerances such that the separation 806 may be relatively small, for example, on the order of millimeters. This can be significant with respect to sizing and selecting generator module 800 components incorporating permanent magnets because of the strong dependence of magnetic force on distance, as will be apparent to one of skill in the art.

[0042] Figure 9 is a cross-section of another example generator module 900 in accordance with an embodiment of the invention. Figure 9 is not to scale and omits structural elements for clarity. The generator module 900 incorporates components 902, 904, 908, 910, 912, 916, 918 and 920 corresponding to components 802, 804, 808, 810, 812, 816, 818 and 820, respectively, of the generator module 800 of Figure 8, although differently arranged. Each generator module 900 may have small associated mass and be removed and serviced of other components of the generator 100 (Figure 1). In the generator module 900 of Figure 9, the magnetic bearings (e.g., components shaded like the magnetic bearing 908) may be sized and/or selected independently from a sizing and/or selection of the field magnet 912 and/or the generator coil 918. The field magnet 912 may be connectively coupled to the rotor module frame 910 with a flexible coupling 922 that provides the field magnet 912 with a freedom to move in a direction parallel with a main magnetic flux path, for example, in the axial direction and/or the radial direction with respect to the axis of rotation 104 (Figure 1). The flexible coupling 922 may further provide the field magnet 912 with a degree of isolation from vibrations in the rotor module frame 910.

[0043] A physical separation between the field magnet 912 and the generation coil 918 may be maintained and/or stabilized (collectively, “stabilized”) at least in part by a set of stabilization magnets (e.g., stabilization magnet 924 and like shaded components in

Figure 9). The separation stabilization may be assisted by a set of stabilization coils 926-928. Such separation stabilization may create a magnetic well that tightly controls a relative position of the field magnet 912 (e.g., with respect to the generation coil 918). In an embodiment of the invention, the configuration of the generator module 900 allows for the rotor module 902 to move past the stator module 904 at a wide variety of speeds.

[0044] The polyphase alternating electric current (the "AC waveform") generated in the generation coil 918 by the passage of the rotor module 902 may be managed by a power electronics submodule 930. In an embodiment of the invention, the relative speed of the rotor module 902 with respect to the stator module 904, and thus the generated AC waveform, depends directly on a rotational speed of the turbine 102 (Figure 1) to which the rotor module 902 is coupled. The power electronics submodule 930 may convert the generated AC waveform into an AC waveform in accordance with local power grid specifications. By managing the AC waveform in the generation coil 918 (e.g., with respect to amplitude, frequency and/or phase), the power electronics submodule 930 may influence a motion of the rotor module 902 and the structures to which the rotor module 902 is connectively coupled such as the turbine 102. For example, the power electronics submodule 930 may act to adjust (e.g., decelerate or accelerate) a rotational speed of the turbine 102 to perform optimally with respect to one or more characteristics (e.g., flow rate, fluid density) of the fluid stream 106. An example power electronics submodule 930 in accordance with an embodiment of the invention is described below in more detail with reference to Figure 12.

[0045] Each generator module 900 may have small associated mass and be removed and serviced independent of other components of the generator 100 (Figure 1). The generator module 900 may further include one or more active or passive thermal regulation components (not shown in Figure 9). The generator module 900 may utilize any suitable thermal regulation technology including air or liquid cooling. Each generator module 900 may include sufficient thermal regulation capacity to regulate itself independent of other components of the generator 100.

[0046] In an embodiment of the invention, conventional electric power generation system structures may be retrofitted with generator modules 900. Figure 10 is a cross-

section of an example retrofitted electric power generator 1000 in accordance with an embodiment of the invention. Figure 10 is not to scale and omits structural elements for clarity. The retrofitted electric power generator 1000 may incorporate multiple sets of generator modules arranged between a rotor frame 1002 and a stator frame 1004. In Figure 10, generator module arrangement and/or configuration is depicted with generator module symbol 1006. For example, each such generator module symbol may correspond to the generator module 900 of Figure 9. As depicted in Figure 10, sets of generator modules may be layered axially and nested radially to fit a desired form factor. Although the magnetic bearings of the generator modules may act as the main bearings of the generator 1000, the generator 1000 may incorporate a thrust bearing 1008 to facilitate rotation of the rotor frame 1002. Salvaged turbine blades (not shown in Figure 10) may be reused, recycled and/or retrofitted to the generator 1000 at least in part by connectively coupling the salvaged turbine blades to the rotor frame 1002 with a retrofit hub 1010 and/or retrofit hub adapter 1012.

[0047] Each of the rotor frame 1002, the stator frame 1004, the retrofit hub 1010 and the retrofit hub adapter 1012 may be composed of segments capable of being transported through constrained areas and assembled in the field. For example, these components may each have segments determined according to a 3-fold rotational symmetry of the generator 1000. If the generator 1000 incorporates a shroud such as a nacelle shroud (not shown in Figure 10), the shroud may be similarly segmented. As an alternative to the retrofit hub 1010 and the retrofit hub adapter 1012, corresponding original equipment may be connectively coupled to the rotor frame 1002.

[0048] In an embodiment of the invention, the power electronics submodule 930 of the generator module 900 (Figure 9) may be configured to allow the generator submodule 900 to act both as an electric generator and an electric motor. As well as influencing motion of the turbine 102 (Figure 1), sets of generator modules may be arranged to provide for yaw control of the turbine 102 and thus adapt to changes in direction of the fluid stream 106. Figure 11 is a cross-section of an example tower-mounted electric power generation system 1100 in accordance with an embodiment of the invention. Figure 11 is not to scale and omits structural elements for clarity.

[0049] A generator 1102 (e.g., corresponding to the generator 1000 of Figure 10) may be connectively coupled to a tower 1104 with a tower adapter 1106. In an embodiment of the invention, the tower adapter 1106 may be a simple fixed coupling, and yaw control of the turbine 1108 with respect to the fluid stream 1110 may be enabled by a set of generator modules 1112 arranged between a swiveling base 1114 of the tower 1104 and a fixed base 1116 of the tower 1104. The fixed based 1116 may be attached to a suitable foundation embedded in a suitable geologic surface including hill tops, hill sides, river beds and ocean beds. The generator modules 1112 may act as main bearings for the tower 1104 and be configured as motors to rotate the tower 1104 about an axis 1118 responsive to changes in a direction of the fluid stream 1110. In this case, and when larger rotational diameters are available to achieve higher tangential velocities (e.g., in other cases where there is a vertical axis of rotation), the magnetic bearings of the generator module 900 (Figure 9) may be replaced and/or supplemented with passive magnetic levitation ("passive maglev"). The tower 1104 may be airfoil-shaped to reduce shock experienced by turbine 1108 blades as they rotate past the tower 1104.

[0050] The power electronics submodule 930 (Figure 9) of the generator module 900 plays a significant role in the performance of the generator module 900. Figure 12 is a schematic diagram of an example power electronics submodule 1202 in accordance with an embodiment of the invention. A polyphase alternating electric current generation coil 1204 (e.g., the generation coil 918 of Figure 9) may be tapped at multiple points 1206-1208 enabling the coil 1204 to adapt to significant variation in rotor module 902 speed. In an embodiment of the invention, this enables electric power generation system design flexibility with respect to location of the rotor module 902 at different distances from the axis of rotation (e.g., as in the generator 1000 of Figure 10). The power electronics submodule 1202 may include corresponding electronically controlled sets of coil tap selection switches 1210-1212 that enable the power electronics submodule 1202 to select an appropriate coil tap point.

[0051] The AC waveform generated in the polyphase coil 1204 may be presented to an active rectifier 1214. The active rectifier 1214 may be a standardized and easily replaceable component of the power electronics submodule 1202. In an embodiment of the invention, the coil tap selection switches 1210-1212 may be incorporated into the

active rectifier 1214 and/or the active rectifier 1214 may incorporate corresponding power routing to distinct sets of subcomponents designed to manage AC waveforms with different characteristics (e.g., with respect to amplitude and frequency). The active rectifier 1214 may rectify the AC waveform into a direct electric current (DC). The active rectifier 1214 may have multiple DC outputs 1216-1218, for example, corresponding to different voltage and/or current levels. The power electronics submodule 1202 may incorporate corresponding electronically controlled sets of DC power bus selection switches 1220-1222 that enable the electronics submodule 1202 to select an appropriate DC power routing.

[0052] The DC power output by the active rectifier 1214 may be routed to an inverter 1224. The inverter 1224 may be a standardized and easily replaceable component of the power electronics submodule 1202. In an embodiment of the invention, the DC power bus selection switches 1220-1222 may be incorporated into the inverter 1224 and/or the inverter 1224 may incorporate corresponding power routing to distinct sets of subcomponents designed to manage DC power with different characteristics (e.g., with respect to voltage and/or current levels). The inverter 1224 may transform the routed DC power into a polyphase AC waveform 1226 in accordance with local power grid specifications ("grid-quality AC").

[0053] The active rectifier 1214 and/or the inverter 1224 may be configured and/or controlled by a submodule controller 1228 capable of acting in accordance with command messages and/or signals sent over a data bus 1230 to the power electronics submodule 1202. For example, the data bus may be optical fiber or shielded twisted pair (STP). The submodule controller 1228 may include a communication component 1232 capable of participating in sophisticated communication protocols such as internet protocols. The communication component 1232 may route command messages and/or signals to a rectifier controller 1234 and/or an inverter controller 1236 as appropriate. Alternatively, the communication component 1232 may translate received command messages and/or signals to forms (e.g., simpler forms) suitable for the rectifier controller 1234 and/or the inverter controller 1236. The rectifier controller 1234 and the inverter controller 1236 may translate received command messages and/or signals into command messages and/or signals suitable for controlling the active rectifier 1214 and

the inverter 1224, respectively, and/or generate suitable such command messages and/or signals.

[0054] For example, the communication component 1232 may receive an internet protocol (IP) message or datagram specifying a current flow rate of the fluid stream 106 (Figure 1) using Unicode characters. In response, the communication component 1232 may generate a signal voltage over a controller signaling path 1238 to the rectifier controller 1234 that has a level corresponding to the received current flow rate. In response to the signal voltage, the rectifier controller 1234 may generate a pulse-width modulation (PWM) signal 1240 suitable for controlling the active rectifier 1214.

[0055] As another example, the communication component 1232 may receive one or more signals corresponding to a rotational speed, and/or other characteristic, of the rotor 108 (Figure 1) and/or the turbine 102. In response, the communication component 1232 may relay the one or more signals over a controller signaling path 1238 to the rectifier control 1234. Alternatively, the stator module 904 (Figure 9) may include one or more sensors (not shown in Figure 9) configured to generate suitable such signals, freeing the communication component 1232 for other tasks.

[0056] In an embodiment of the invention, the power electronics submodule 1202 integrated into the generator module 900 (Figure 9) includes the active rectifier 1214 and the inverter 1224 and outputs grid-quality AC. However, in alternative embodiments, components of the power electronics submodule 1202 may be differently distributed throughout the electric power generation system (e.g., the electric power generation system 1100). For example, in one alternative, the components above the dashed line 1242 may be incorporated in each generator module 900, and then multiple DC power buses 1216-1218 and a data bus 1230 and/or signaling bus 1238 routed to an inverter 1224 and submodule controller 1228 assigned to multiple generator modules. In another alternative, the components below the dashed line 1244 may be located remotely from the generator modules with the appropriate power and signaling routing.

[0057] In an embodiment of the invention, single power electronics submodules may be configured to manage an AC waveform generated by multiple generation coils such as the polyphase coil 1204. Figure 13 is a schematic diagram of an example generated

AC management network 1300 in accordance with an embodiment of the invention. Multiple polyphase generation coils 1302-1306 (such as polyphase generation coil 918 of Figure 9) may be connected to an inter-coil AC bus 1308. The inter-coil AC bus 1308 may incorporate coil selection switches 1310-1316 enabling selection, isolation, partition and/or grouping of particular sets of generation coils 1302-1306. Similarly, multiple power electronics modules 1318-1320 (such as power electronics submodule 930) may be connected to an inter-module AC bus 1322. The inter-module AC bus 1322 may incorporate module selection switches 1324-1332 enabling selection, isolation, partition and/or grouping of particular sets of power electronics modules 1318-1320. The inter-coil AC bus 1308 and the inter-module AC bus 1322 may be connected by a suitable set of coil-module interconnect pathways and switches 1334-1338. The network 1300 switches 1310-1316 and 1324-1338 may be controlled by the power electronics modules 1318-1320 and/or a system controller 1340 communicatively linked to the power electronics modules 1318-1320 by a data bus 1342. Different groupings of coils 1302-1306 and/or power electronics modules 1318-1320, and different assignments of such groups, can further expand the dynamic range of the electric power generation system 100 (Figure 1), for example, with respect to the range of fluid stream 106 flow rates (and thus turbine 102 and rotor 108 rotation speeds) at which the system 100 can generate grid-quality AC.

[0058] Each power electronics module 1318-1320, and/or a stator module that incorporates the power electronics module, may be associated with a data network address (e.g., an internet protocol address), and the system controller 1340 may be located remotely in the data network and/or at a remote physical distance from the power electronics modules 1318-1320. The system controller 1340 may set any suitable parameters of the power electronics modules 1318-1320, both individually and collectively. Alternatively, or in addition, functionality of the system controller 1340 may be partially or fully distributed among the power electronics modules 1318-1320, for example, in accordance with distributed computing techniques well known to those of skill in the art. The power electronics modules 1318-1320 may share status data with each other. Individual power electronics modules 1318-1320 may adjust their settings based on status data received from a particular set of neighboring power electronics modules 1318-1320. The set of neighbors may be fixed or automatically determined

and/or re-determined, for example, in accordance with a network peer discovery protocol and/or overlay network protocol.

[0059] As described above with reference to Figure 7, high capacity generators may be constructed from stacks of plates of generator modules. Figure 14 is a schematic diagram of an example generator module plate stack 1400 in accordance with an embodiment of the invention. The stack 1400 includes multiple generator plates 1402-1406 having a common rotor 1408. In the illustrated example, the stator modules 1410-1432 all output grid-quality AC 1434, which may be simply routed to the local power grid. Alternatively, as described above with reference to Figure 12, DC power may be routed to a collective inverter or set of inverters to produce the grid-quality AC 1434.

[0060] The description now turns to steps that may be performed in accordance with an embodiment of the invention. Such steps may be implemented with any suitable number and type of electronic components. Examples of suitable electronics components include resistors, capacitors, inductive devices, semiconductor switching devices such as diodes, thyristors and transistors, integrated circuits (ICs) including analog ICs and digital ICs such as processors, volatile memory, non-volatile memory, and programmable logic devices, switches, excessive current and/or voltage protection devices, transducers, and optoelectronic devices. Processors and programmable logic devices may be programmed with any suitable programming language and/or computer-executable instructions.

[0061] Figure 15 depicts example steps for generating electric power in accordance with an embodiment of the invention. At step 1502, one or more generated power characteristics may be measured. For example, the power electronics submodule 930 (Figure 9) may measure one or more characteristics of the AC waveform generated in the coil 918 and/or the DC power output from the active rectifier 1214 (Figure 12). Such characteristics may include amplitude (e.g., amplitude current), frequency and phase of the voltage and/or current waveforms. Alternatively, or in addition, individual power electronics modules 1318-1320 (Figure 13) may provide measurement data to the system controller 1340, and the system controller 1340 may process the measurement data to take system-level measurements of the generated electric power.

[0062] At step 1504, one or more desired power characteristics may be determined. For example, the power electronics submodule controller 1228 (Figure 12) may determine a desired set of characteristics for the AC waveform in the coil 918 (Figure 9) and/or the DC power output from the active rectifier 1214 based at least in part on the characteristic(s) measured at step 1502, as well as the configuration of the generator 100 of Figure 1 (e.g., coil groupings) and factors such as fluid stream 106 flow rate and operating temperature. Again, such characteristics may include amplitude, frequency and phase of the voltage and/or current waveforms. At a system level, the system controller 1340 (Figure 13) may monitor a ratio of commanded to actually generated current and determine the ratio of a highest performing generator module to be used as a target.

[0063] One or more intermediate factors may be explicitly determined as part of determined the desired power characteristic(s) of step 1504. For example, rotation speeds (e.g., RPM) of the rotor 108 (Figure 1) and/or the turbine 102 may be derived from other measurements if not measured directly. At step 1506, current turbine rotational speed may be determined. For example, the power electronics submodule controller 1228 (Figure 12) may determine the current turbine rotational speed based at least in part on the generated power characteristic(s) measured at step 1502 (e.g., waveform frequency).

[0064] At step 1508, a desired turbine rotational speed may be determined. The power electronics submodule controller 1228 (Figure 12) may determine an optimal turbine rotational speed with respect to a fixed pitch of the turbine 102 and/or a current flow rate of the fluid stream 106 (Figure 1). For example, the optimal rotational speed of the turbine may be the rotational speed that maximizes power capture for the current flow rate and/or effective flow rate of the fluid stream 106. The turbine 102 and/or rotor 108 may operate with respect to a torque curve (e.g., torque generated responsive to changing rotational speed) having a local slope near a current operating point, and the local slope may be adjusted with a counter-torque induced by managing the generated AC waveform so as to optimize an angle of attack of the turbine 102 blades with respect to the fluid stream 106. In an embodiment of the invention, managing turbine rotational speed may have the effect of flattening the torque and/or power curve and extending the dynamic range of the electric power generation system 100. There may also be

maximum rotational speeds that can be reliably and/or safely sustained in the short-term and over longer periods, and the desired turbine rotational speed may be selected in accordance with these limits and enforced by the torque control system (i.e., management of the generated AC waveform).

[0065] At step 1510, one or more targets for one or more generated power characteristics may be determined. The power electronics submodule controller 1228 (Figure 12) and/or the system controller 1340 (Figure 13) may determine one or more targets for one or more characteristics of the generated AC waveform in the polyphase coil 1204 and/or coil group 1302-1306 based at least in part on the desired turbine rotational speed determined at step 1508. For example, a phase shift in the generated AC waveform may magnetically induce a deceleration with respect to the rotational speed of the rotor 108 (Figure 1) and/or turbine 102.

[0066] At step 1512, one or more generator modules may be configured to achieve the desired power characteristic(s) determined at step 1504. For example, the power electronics submodule controller 1228 may configure the power electronics submodule 1202 to seek the target(s) determined at step 1510. In addition, the system controller 1340 may command and/or signal the power electronics submodule controllers of multiple generator modules to seek system-level targets. In an embodiment of the invention, coil groups may be configured to achieve the desired power characteristic(s). As part of measuring the generated power characteristic(s) at step 1502, it may be detected that one or more generator modules, or components thereof, have failed, become inactive (e.g., due to hot-unplugging) and/or are performing sub-optimally. The configuration of step 1512 may compensate appropriately, for example, by rerouting AC and/or DC power and/or adjusting individual generator module settings to redistribute and/or decrease the generated power load.

[0067] Figure 16 depicts example steps for configuring generator modules in accordance with an embodiment of the invention. At step 1602, coil groups may be determined for a generator. For example, the system controller 1340 (Figure 13) may partition the generator coils 1302-1306 of the stator modules 220-230 (Figure 2) of the generator 200 into equally sized sets based at least in part on a rotational speed of the rotor 202 (e.g., as determined at step 1506 of Figure 15). At step 1604, power

electronics modules may be assigned to coil groups. For example, the system controller 1340 may assign the power electronics modules 1318-1320 to the coil groups determined at step 1602 based at least in part on expected generated AC waveform characteristics of the determined coil groups.

[0068] At step 1606, the generation coils 1302-1306 (Figure 13) may be disconnected from the power electronics modules 1318-1320, for example, with the coil-module interconnect switches 1334-1338. At step 1608, the coil selection switches 1310-1316 may be signaled to create the coil groups determined at step 1602, for example, responsive to commands and/or signals generated by the system controller 1340. At step 1610, the power module selection switches 1324-1332 may be signaled to change state in accordance with the power electronics module assignments determined at step 1604. For example, the power module selection switches 1324-1332 may change state responsive to commands and/or signals generated by the system controller 1340. At step 1612, the generation coils 1302-1306 may be reconnected to the power electronics modules 1318-1320 in accordance with the power electronics module assignments determined at step 1604. For example, the coil-module interconnect switches 1334-1338 may change state responsive to commands and/or signals generated by the system controller 1340.

[0069] Figure 17 depicts further example steps for configuring generator modules in accordance with an embodiment of the invention. At step 1702, desired system level generator module settings may be determined, for example, by the system controller 1340 (Figure 13) as described above with reference to Figure 15 and Figure 16. At step 1704, one or more commands may be sent to one or more generator modules. For example, the system controller 1340 may send the command(s) to configure the generator module(s) in accordance with the desired generator module settings determined at step 1702.

[0070] Dashed line 1706 indicates that steps 1708-1716 may be performed by each of the generator module(s) to which commands were sent at step 1704. At step 1708, a command may be received. For example, the communication component 1232 (Figure 12) of the power electronics submodule 1202 may receive the command specifying desired generator module settings sent by the system controller 1340 (Figure 13). At

step 1710, desired rectifier settings may be determined. For example, the submodule controller 1228 may determine settings for the active rectifier 1214 corresponding to the desired generator module settings specified in the command received at step 1708. At step 1712, desired inverter settings may be determined. For example, the submodule controller 1228 may determine settings for the inverter 1224 corresponding to the desired generator module settings specified in the command received at step 1708. At step 1714, one or more rectifier controllers may be configured. For example, the communication component 1232 may configure the rectifier controller 1234 in accordance with the desired rectifier settings determined at step 1710. At step 1716, one or more inverter controllers may be configured. For example, the communication component 1232 may configure the inverter controller 1236 in accordance with the desired inverter settings determined at step 1712.

[0071] All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and/or were set forth in its entirety herein.

[0072] The use of the terms "a" and "an" and "the" and similar referents in the specification and in the following claims are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms "having," "including," "containing" and similar referents in the specification and in the following claims are to be construed as open-ended terms (e.g., meaning "including, but not limited to,") unless otherwise noted. Recitation of ranges of values herein are merely indented to serve as a shorthand method of referring individually to each separate value inclusively falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate embodiments of the invention and does not pose a limitation to the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to each embodiment of the present invention.

[0073] Preferred embodiments of the invention are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the specification. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than as explicitly described herein. Accordingly, embodiments of the invention include all modifications and equivalents of the subject matter recited in the following claims as permitted by applicable law.

WHAT IS CLAIMED IS:

1. An electric power generation system, comprising:

a turbine configured at least to rotate in a fluid flow, the fluid flow having a varying flow rate, a rotational speed of the turbine based at least in part on the flow rate of the fluid flow;

a rotor frame connectively coupled at least to the turbine such that the rotor frame rotates around an axis of rotation with a rotational speed corresponding to the rotational speed of the turbine;

a plurality of rotor modules connectively coupled at least to the rotor frame and arranged in one or more rings of rotor modules distributed axially or radially with respect to the axis of rotation, the plurality of rotor modules collectively configured at least to generate a magnetic field having at least one characteristic based at least in part on the rotational speed of the rotor frame; and

a plurality of stator modules magnetically coupled to the plurality of rotor modules and arranged in one or more rings of stator modules corresponding to the one or more rings of rotor modules, each stator module incorporating at least one generating coil configured at least to generate an alternating electric current responsive to the magnetic field and managed to produce a desired magnetically-induced torque that at least partially controls rotation of the rotor frame.

2. An electric power generation system in accordance with claim 1, wherein the fluid flow is wind.

3. An electric power generation system in accordance with claim 1, wherein a number of the plurality of rotor modules corresponds to a number of the plurality of stator modules and each pair of rotor and stator modules is incorporated in a corresponding generator module.

4. An electric power generation system in accordance with claim 3, wherein each of the rotor modules is paired with a corresponding stator module and the pair is manufactured, assembled and tested as a unit prior to installation in the electric power generation system.

5. An electric power generation system in accordance with claim 1, wherein a separation between the plurality of rotor modules and the plurality of stator modules is maintained substantially with magnetic bearings.

6. An electric power generation system in accordance with claim 1, wherein the turbine is a fixed pitch turbine and the rotational speed of the turbine is controlled independently of a mechanical gearbox.

7. An electric power generation system in accordance with claim 6, wherein a magnitude of the magnetically-induced torque is determined based at least in part on a target rotational speed that is optimal with respect to performance of the fixed pitch turbine.

8. An electric power generation system in accordance with claim 1, wherein the plurality of stator modules act collectively to cause the magnetically-induced torque and the plurality of stator modules are configured at least to collectively compensate for a temporary inactivity of one or more of the plurality of stator modules.

9. An electric power generation system, comprising:

a turbine configured at least to rotate in a fluid flow, the fluid flow having a varying flow rate, a rotational speed of the turbine based at least in part on the flow rate of the fluid flow;

a plurality of rotor modules connectively coupled at least to the turbine, the plurality of rotor modules collectively configured at least to generate a magnetic field having at least one characteristic based at least in part on the rotational speed of the turbine; and

a plurality of stator modules configured to collectively, at least:

generate at least one alternating electric current responsive at least in part to the magnetic field generated by the plurality of rotor modules;

maintain a relative position of the plurality of rotor modules with respect to the plurality of stator modules with magnetic force; and

control a rotational speed of the turbine with magnetic force.

10. An electric power generation system in accordance with claim 9, wherein controlling the rotational speed of the turbine comprises controlling at least one characteristic of said at least one alternating electric current generated by the plurality of stator modules.

11. An electric power generation system in accordance with claim 10, wherein each of the plurality of stator modules comprises an active rectifier and controlling said at least one characteristic of said at least one alternating electric current comprises modifying said at least one characteristic with at least one active rectifier.

12. An electric power generation system in accordance with claim 9, further comprising a system control module configured at least to coordinate individual stator module participation with respect to control of the rotational speed of the turbine.

13. An electric power generation system in accordance with claim 9, wherein each of the plurality of stator modules comprises a generator coil with a plurality of tap points that are dynamically selectable with switches.

14. An electric power generation system in accordance with claim 9, wherein each of the plurality of rotor modules comprises a permanent magnet fastened to a frame of the rotor module with a flexible coupling that allows movement of the permanent magnet with respect to the frame in a direction parallel to a main magnetic flux path.

15. An electric power generation system in accordance with claim 9, wherein each rotor module comprises at least one stabilization magnet, each stator module comprises at least one corresponding stabilization magnet, and the stabilization magnets act collectively to keep stable a separation between the plurality of rotor modules and the plurality of stator modules.

16. A method of generating electric power, comprising:

measuring at least one value of at least one characteristic of a plurality of rotor modules rotating around an axis, the rotating rotor modules generating an alternating electric current in at least one generating coil of at least one stator module;

determining at least one value of at least one characteristic of at least one signal controlling the alternating electric current based at least in part on said at least one value of said at least one characteristic of the plurality of rotor modules and a target speed of rotation of the plurality of rotor modules around the axis; and

configuring said at least one stator module at least to control the alternating electric current in accordance with said at least one signal, said at least one stator module arranged with respect to the plurality of rotor modules such that modifying the alternating electric current modifies a speed of rotation of the plurality of rotor modules around the axis.

17. A method in accordance with claim 16, wherein the plurality of rotor modules are connectively coupled to a turbine that causes the plurality of rotor modules to rotate around the axis with the speed of rotation and said at least one value of said at least one characteristic of the plurality of rotor modules corresponds to a speed of rotation of the turbine.

18. A method in accordance with claim 16, wherein configuring said at least one stator module comprises configuring a plurality of groups of generating coils among a plurality of stator modules based at least in part on said at least one measured value of said at least one characteristic of the plurality of rotor modules.

19. A method in accordance with claim 16, wherein measuring said at least one value of said at least one characteristic of the plurality of rotor modules comprises measuring a plurality of values corresponding to characteristics of alternating electric currents in generating coils of a plurality of stator modules, and configuring said at least one stator module comprises configuring each of the plurality of stator modules to modify the alternating electric current in a generating coil of the stator module based at least in part on the corresponding characteristic value.

20. A method in accordance with claim 19, wherein the modification of the alternating electric current in each of the generating coils of the plurality of stator modules is further based at least in part on the plurality of measured characteristic values.

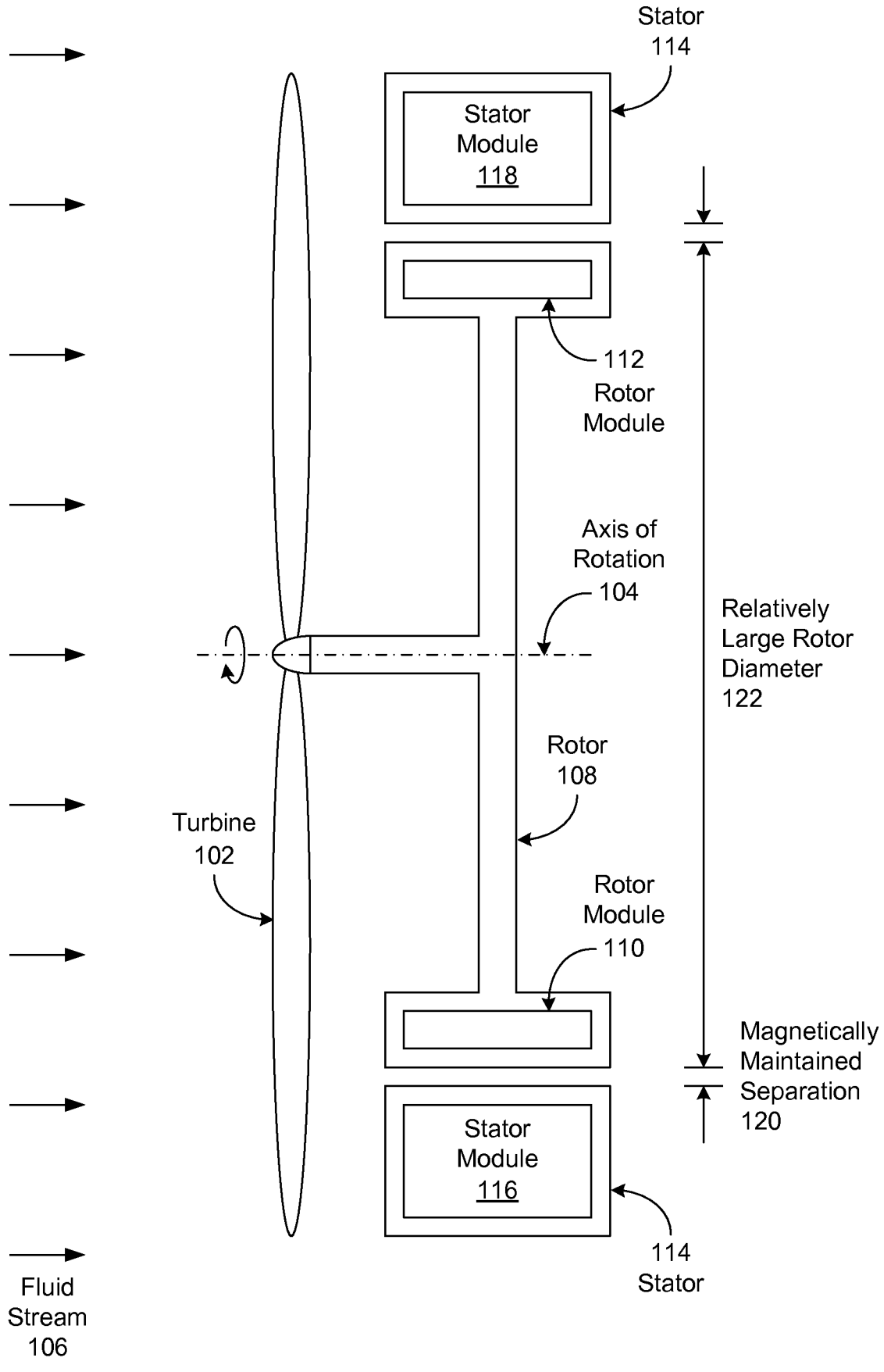

Stator
114
Stator
Module
118
112
Rotor
Module
Axis of
Rotation
104
Relatively
Large Rotor
Diameter
122
Rotor
108
Turbine
102
Rotor
Module
110
Magnetically
Maintained
Separation
120
Stator
Module
116
114
Stator
Fluid
Stream
106
100

Figure 1

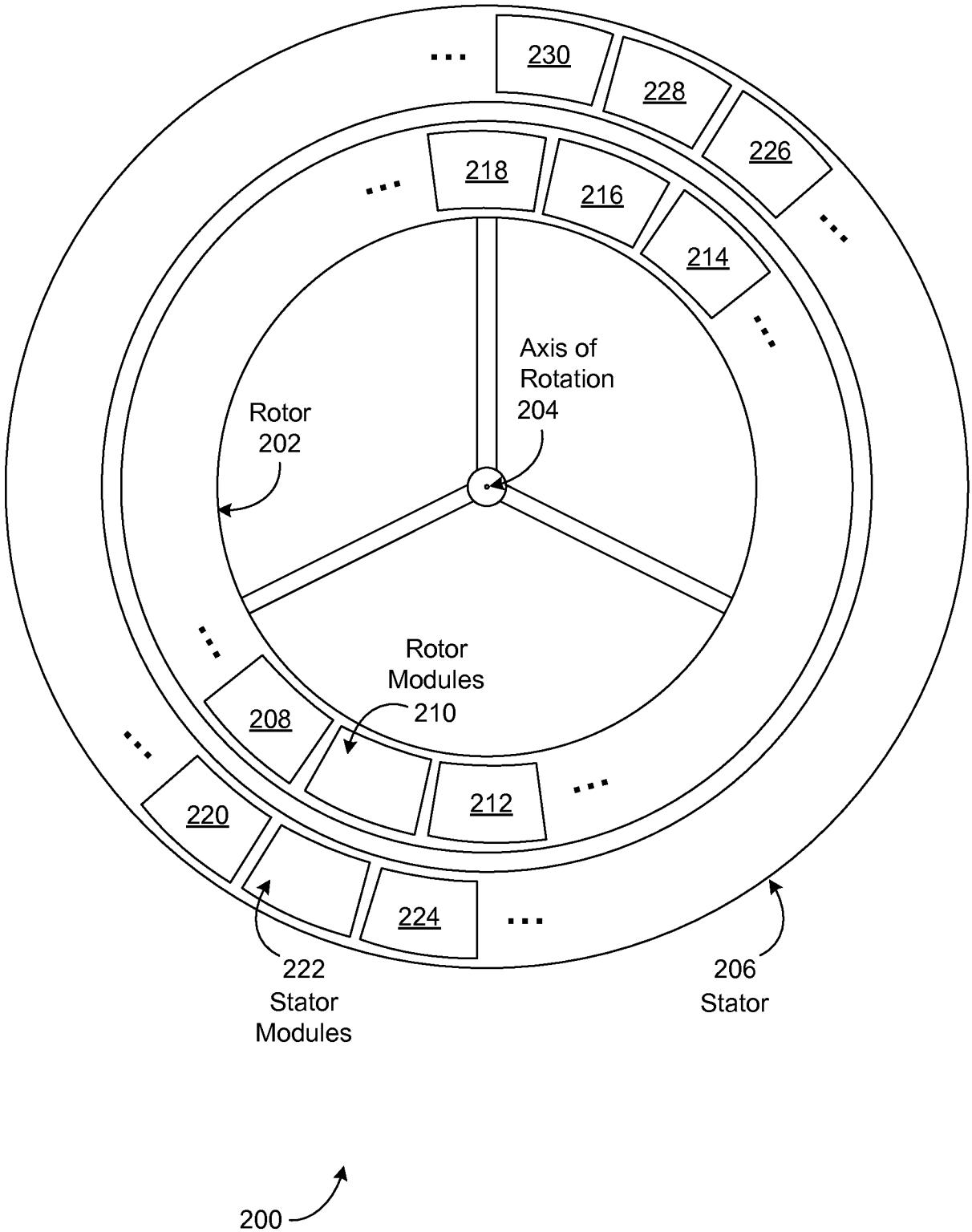

230
228
226
218
216
214
Axis of
Rotation
204
Rotor
202
Rotor
Modules
210
208
212
220
224
222
Stator
Modules
206
Stator
200

Figure 2

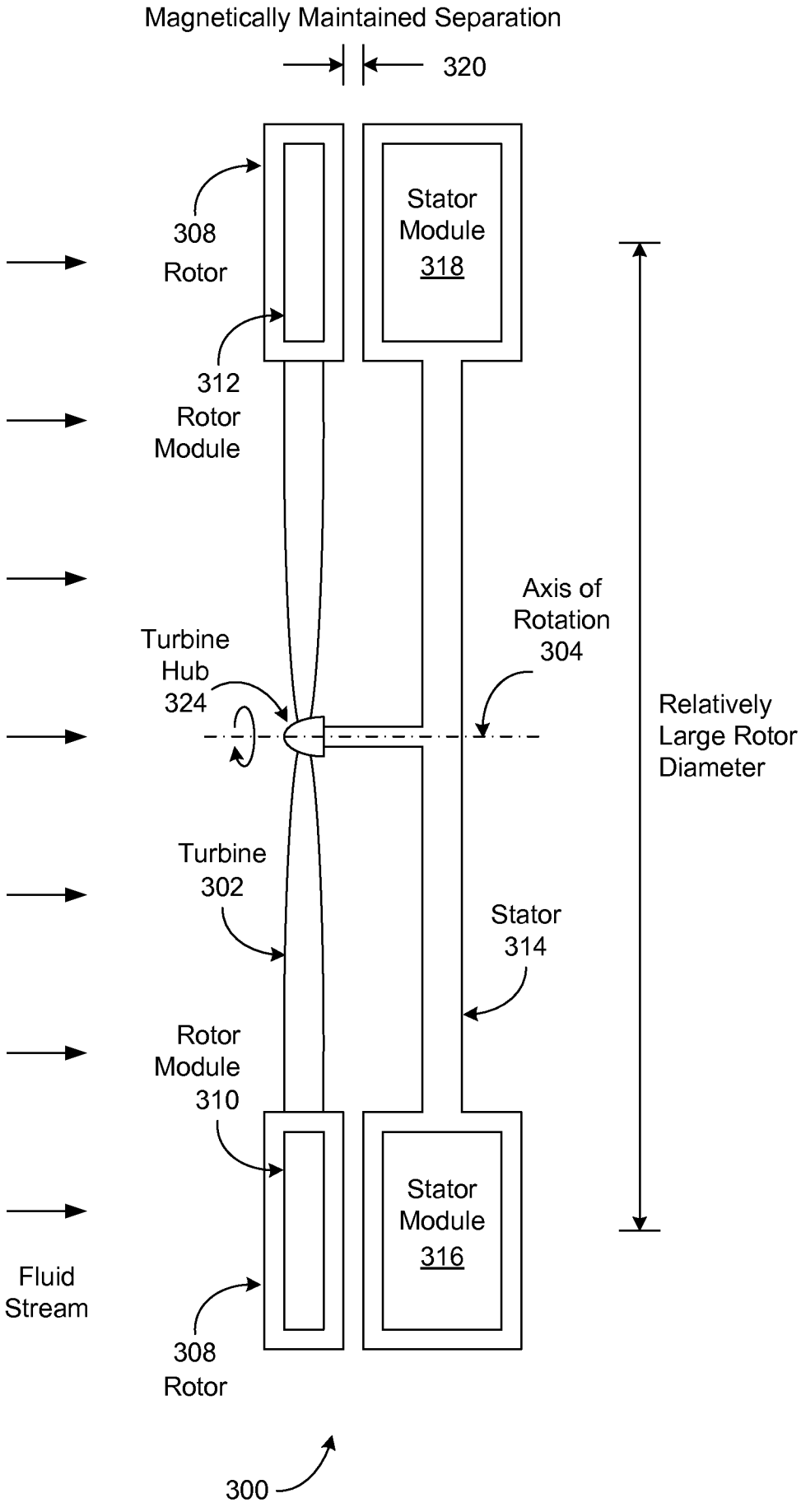

Magnetically Maintained Separation
320
308
Rotor
312
Rotor
Module
Stator
Module
318
Axis of
Rotation
304
Turbine
Hub
324
Relatively
Large Rotor
Diameter
Turbine
302
Stator
314
Rotor
Module
310
Stator
Module
316
Fluid
Stream
308
Rotor
300

Figure 3

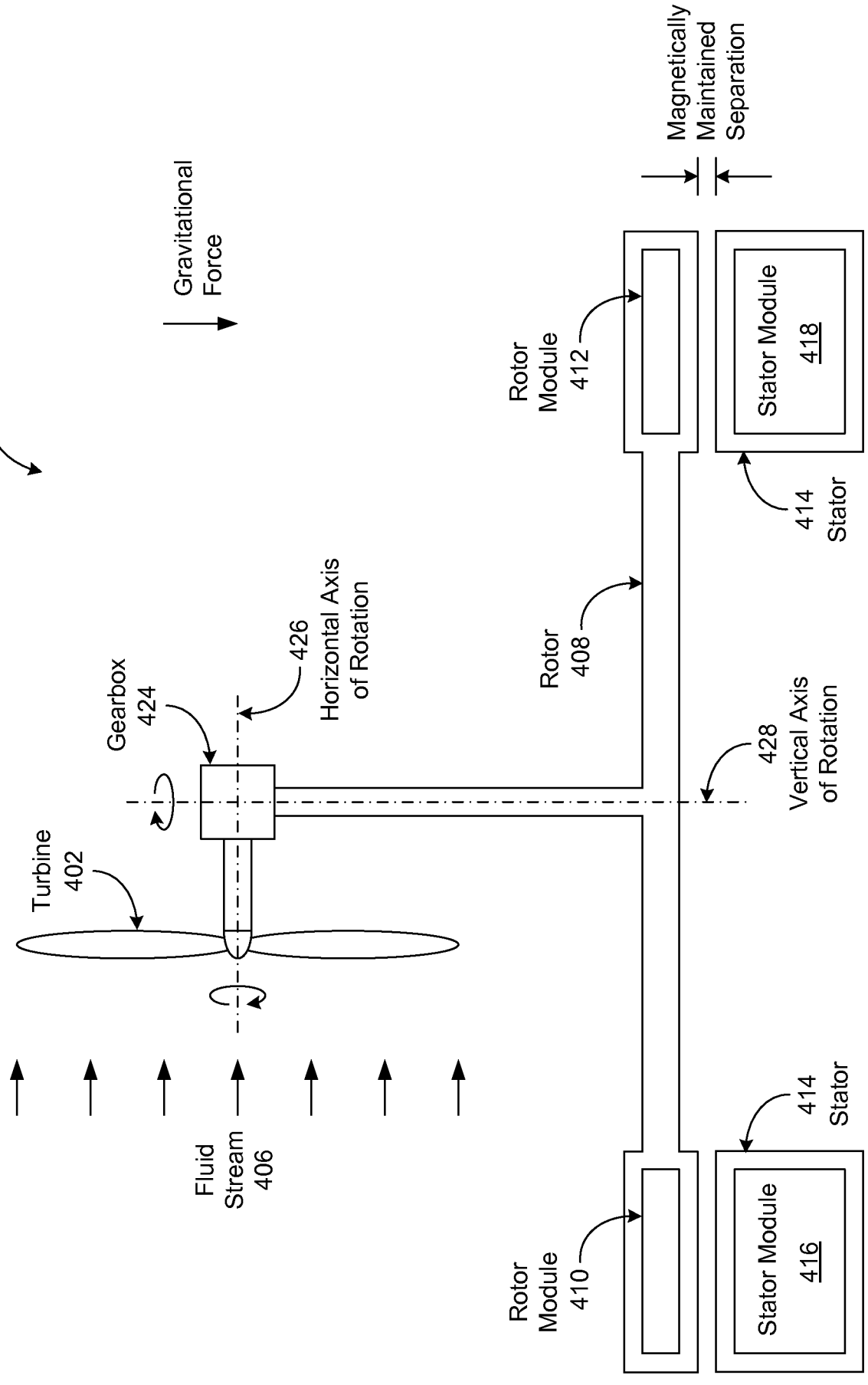

400
Gravitational Force
Magnetically Maintained Separation
Rotor Module 412
Stator Module 418
414 Stator
Rotor 408
426 Horizontal Axis of Rotation
Gearbox 424
Turbine 402
428 Vertical Axis of Rotation
Fluid Stream 406
Rotor Module 410
Stator Module 416
414 Stator

Figure 4

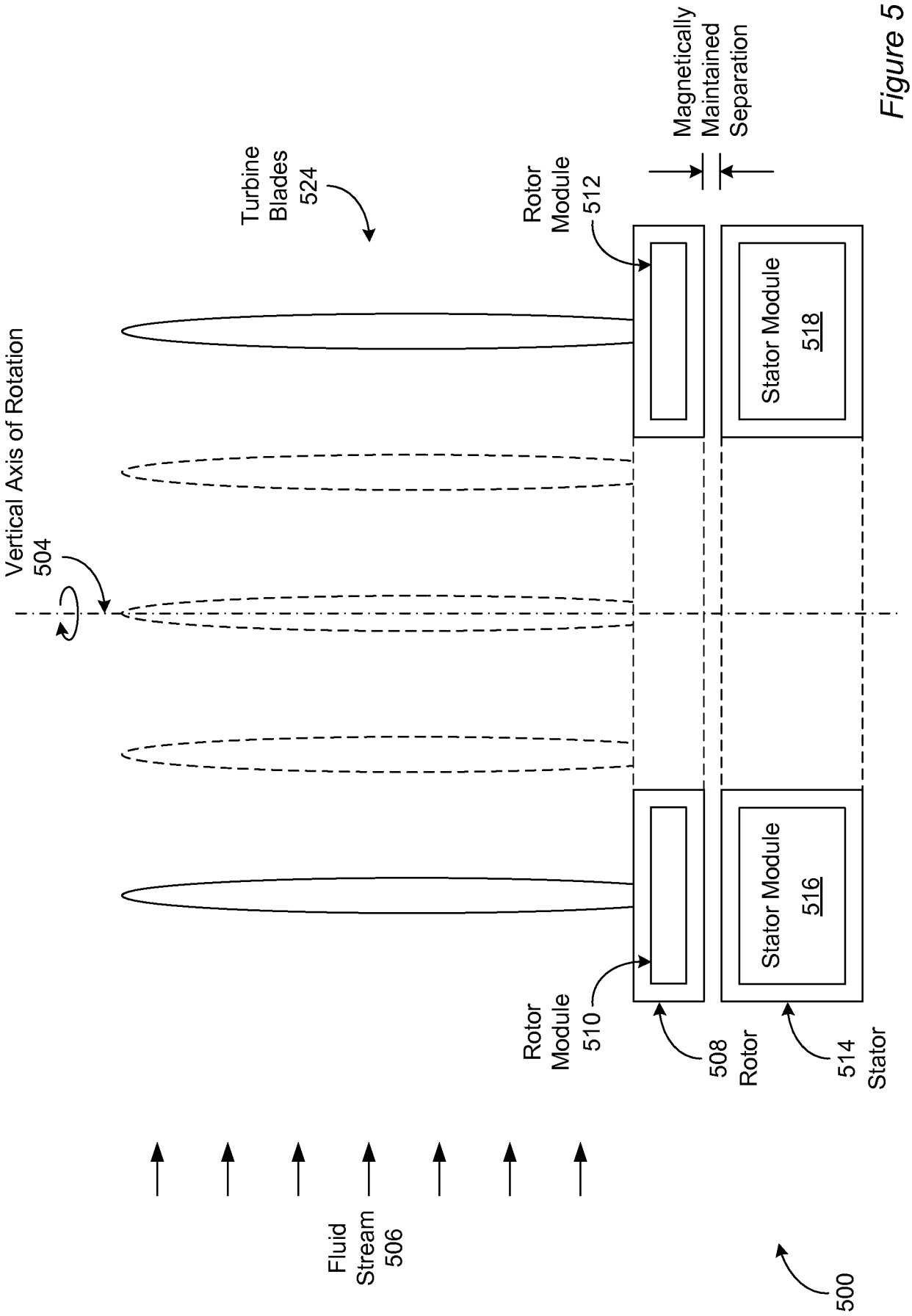

Vertical Axis of Rotation
504
Turbine Blades
524
Rotor Module
512
Magnetically Maintained Separation
Stator Module
518
Stator Module
516
Rotor Module
510
508 Rotor
514 Stator
Fluid Stream
506
500

Figure 5

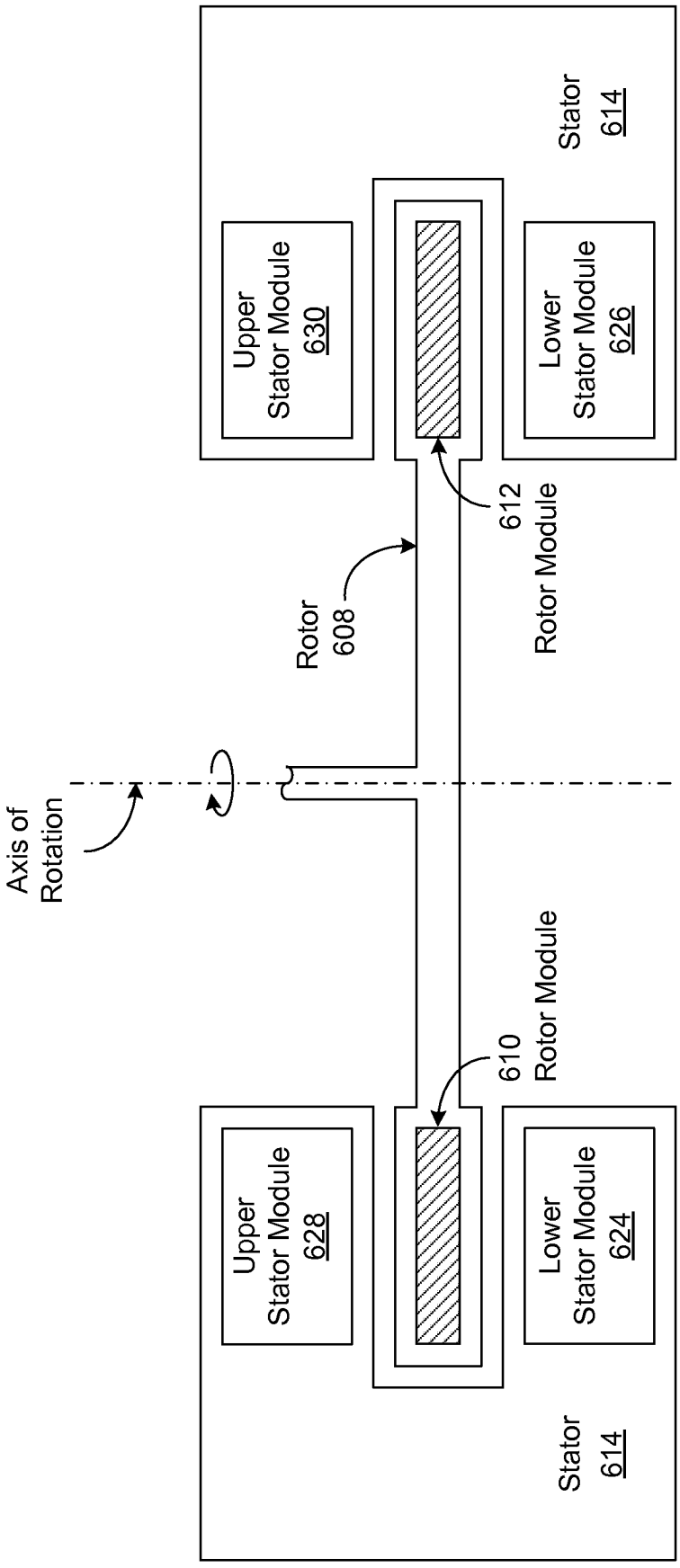

Stator
614
Upper
Stator Module
630
Lower
Stator Module
626
612
Rotor Module
Rotor
608
Axis of
Rotation
610
Rotor Module
Upper
Stator Module
628
Lower
Stator Module
624
Stator
614
600

Figure 6

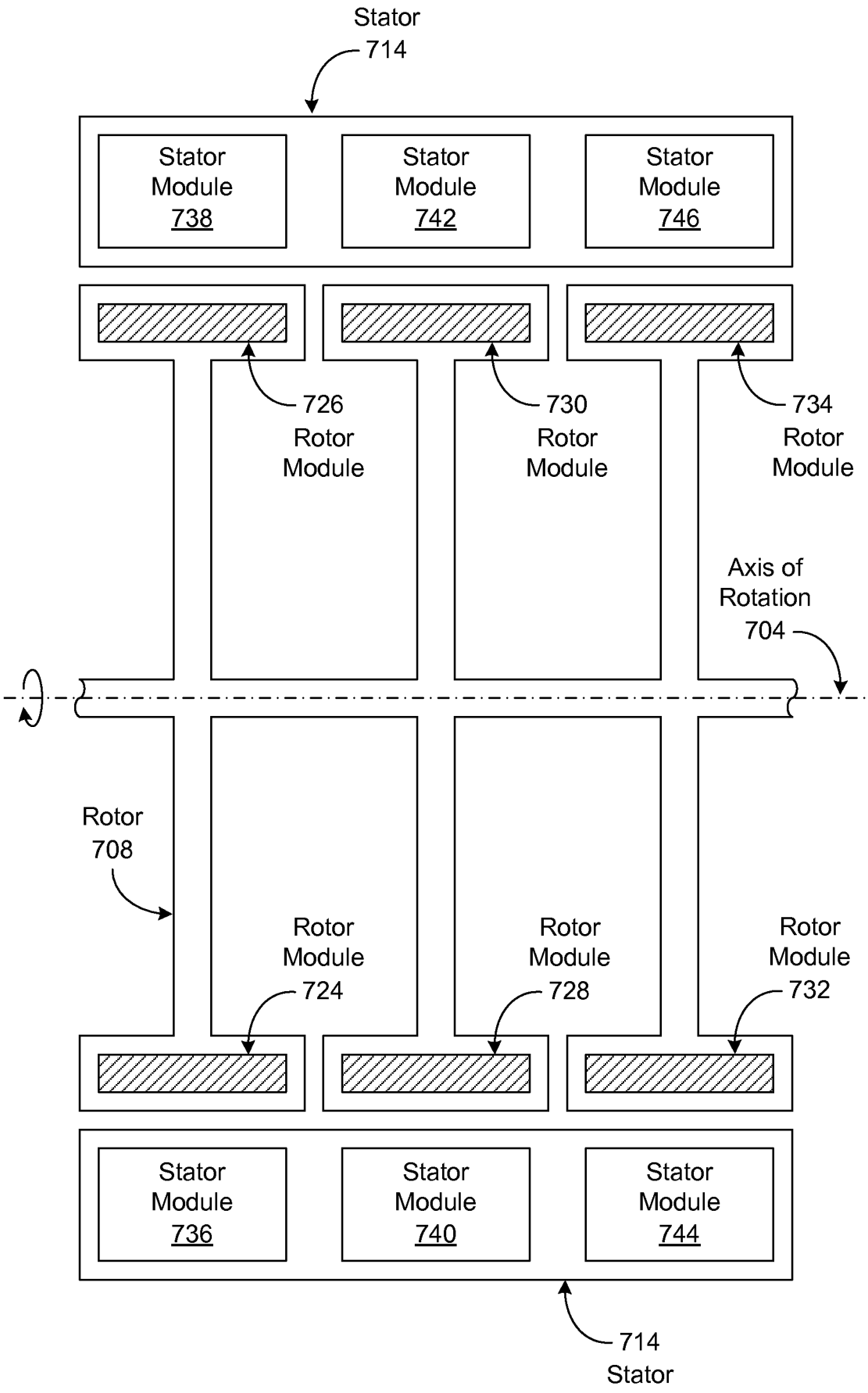

Stator
714
Stator Module 738
Stator Module 742
Stator Module 746
726 Rotor Module
730 Rotor Module
734 Rotor Module
Axis of Rotation
704
Rotor
708
Rotor Module
724
Rotor Module
728
Rotor Module
732
Stator Module 736
Stator Module 740
Stator Module 744
714
Stator
700

Figure 7

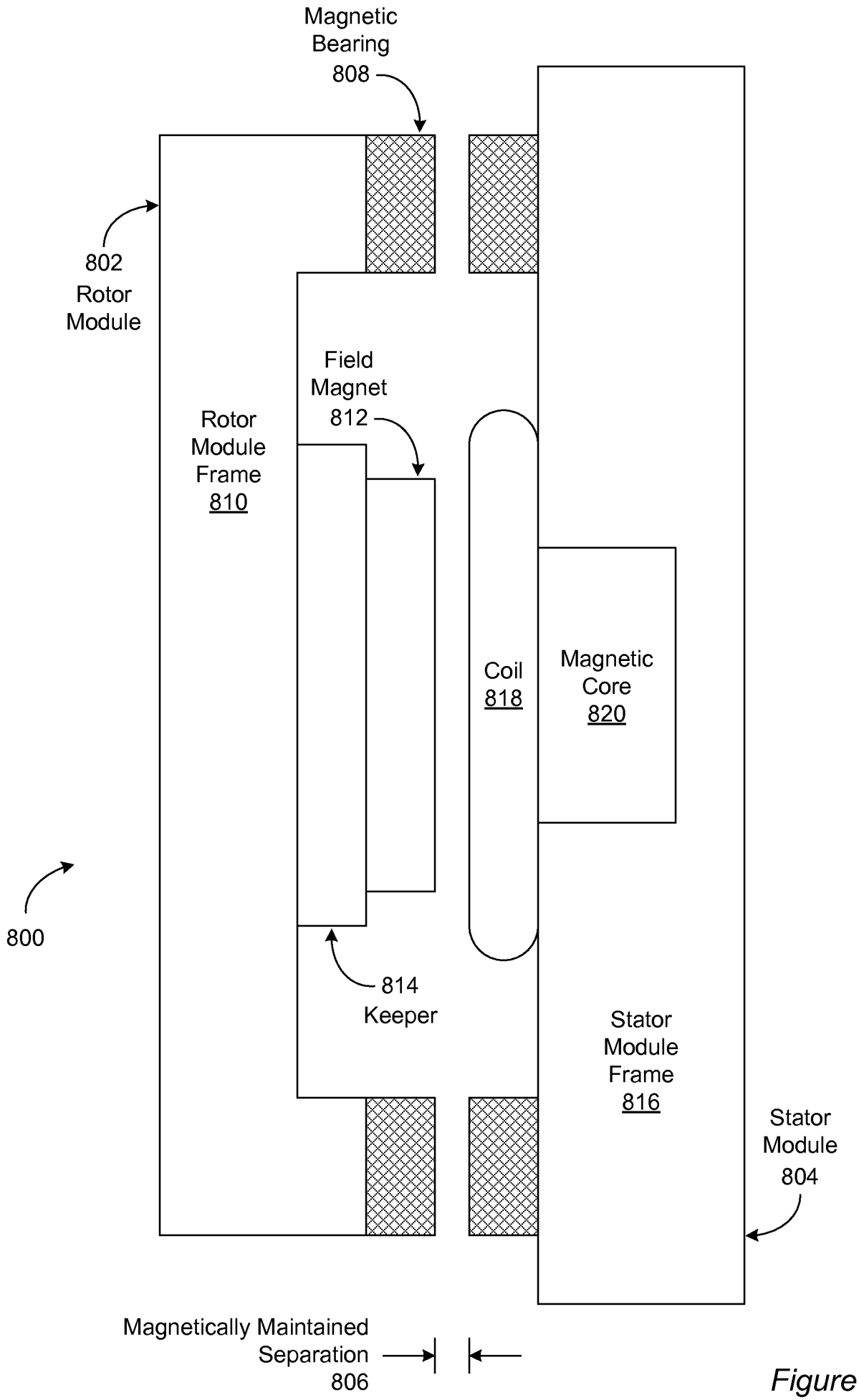

Magnetic Bearing 808
802 Rotor Module
Field Magnet 812
Rotor Module Frame 810
Coil 818
Magnetic Core 820
800
814 Keeper
Stator Module Frame 816
Stator Module 804
Magnetically Maintained Separation 806

Figure 8

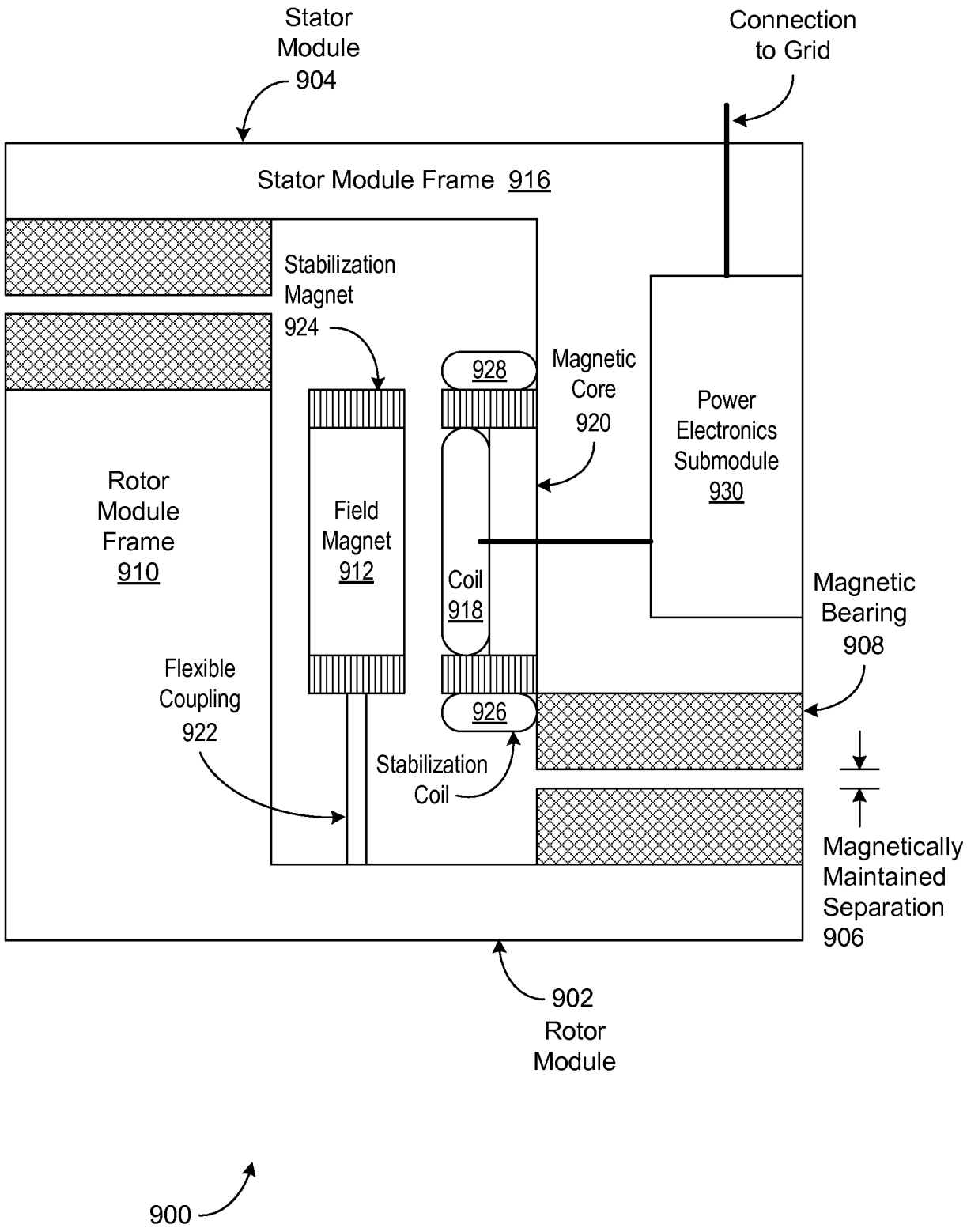

Stator Module 904
Connection to Grid
Stator Module Frame 916
Stabilization Magnet 924
928
Magnetic Core 920
Power Electronics Submodule 930
Rotor Module Frame 910
Field Magnet 912
Coil 918
Magnetic Bearing 908
Flexible Coupling 922
926
Stabilization Coil
Magnetically Maintained Separation 906
902 Rotor Module
900

Figure 9

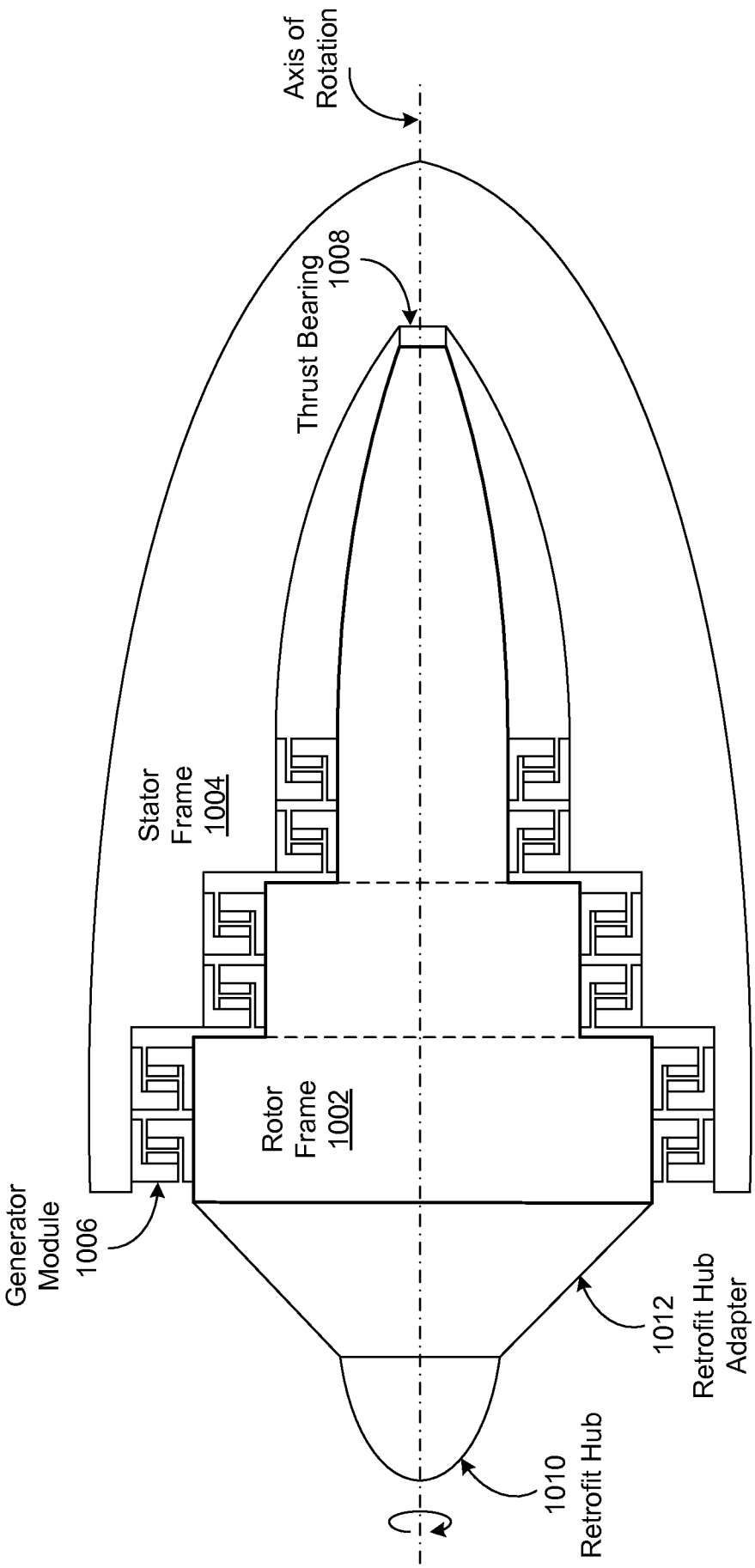

Axis of Rotation
Thrust Bearing 1008
Stator Frame 1004
Rotor Frame 1002
Generator Module 1006
1012 Retrofit Hub Adapter
1010 Retrofit Hub
1000

Figure 10

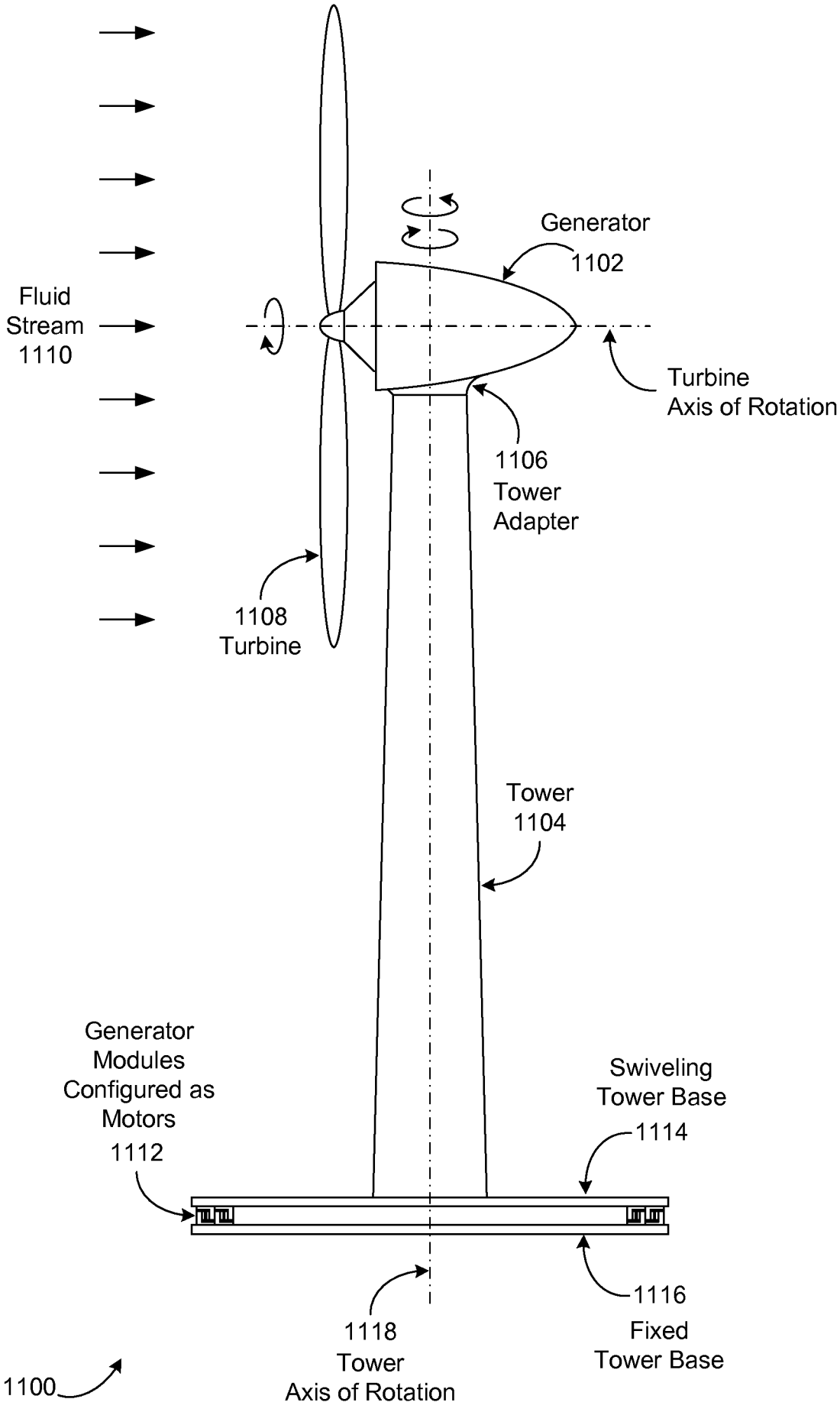

Fluid
Stream
1110
Generator
1102
Turbine
Axis of Rotation
1106
Tower
Adapter
1108
Turbine
Tower
1104
Generator
Modules
Configured as
Motors
1112
Swiveling
Tower Base
1114
1116
Fixed
Tower Base
1118
Tower
Axis of Rotation
1100

Figure 11

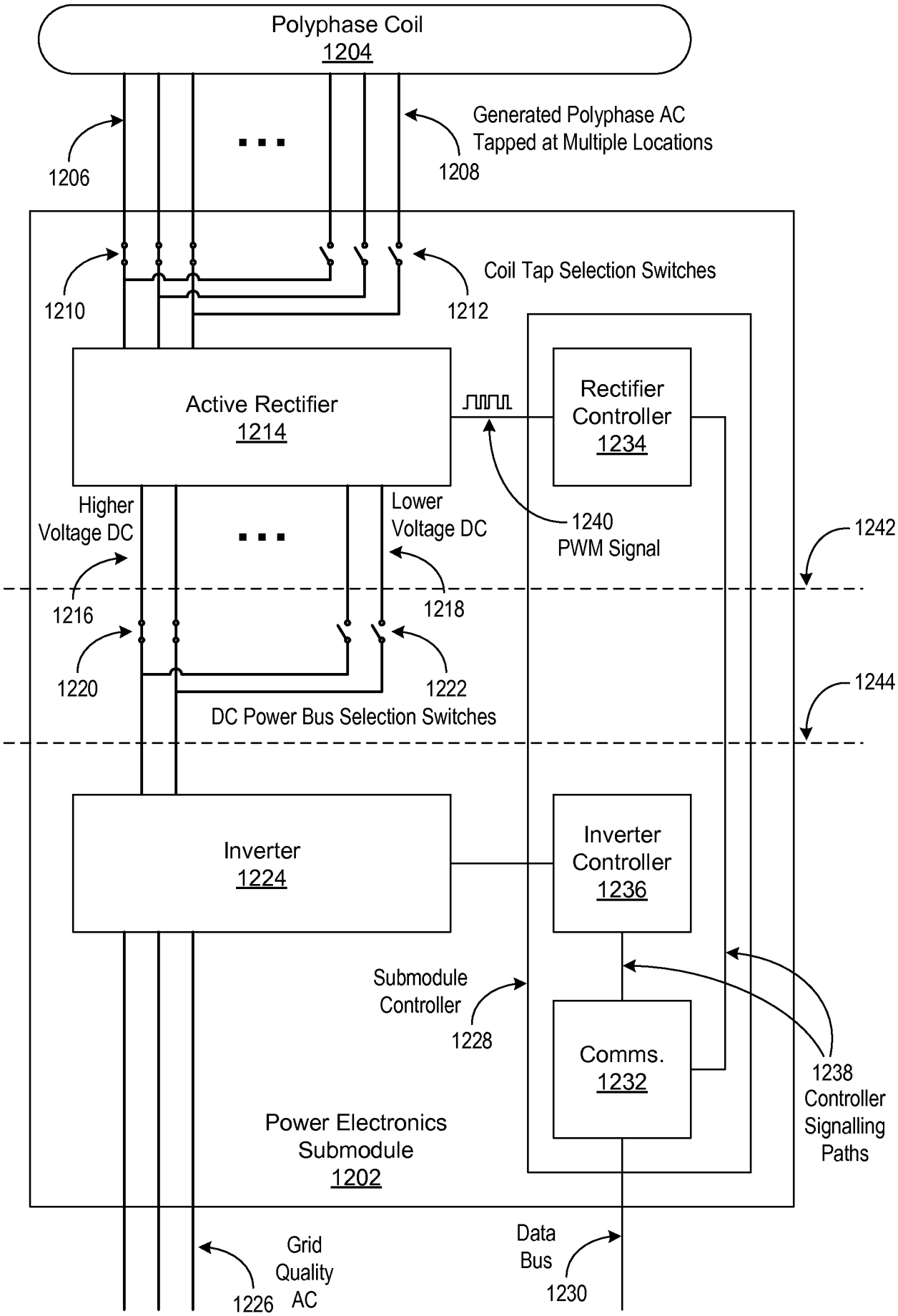

Polyphase Coil
1204
Generated Polyphase AC
Tapped at Multiple Locations
1206
1208
Coil Tap Selection Switches
1210
1212
Active Rectifier
1214
Rectifier
Controller
1234
Higher
Voltage DC
Lower
Voltage DC
1240
PWM Signal
1242
1216
1218
1220
1222
1244
DC Power Bus Selection Switches
Inverter
1224
Inverter
Controller
1236
Submodule
Controller
1228
Comms.
1232
1238
Controller
Signalling
Paths
Power Electronics
Submodule
1202
Grid
Quality
AC
1226
Data
Bus
1230

Figure 12

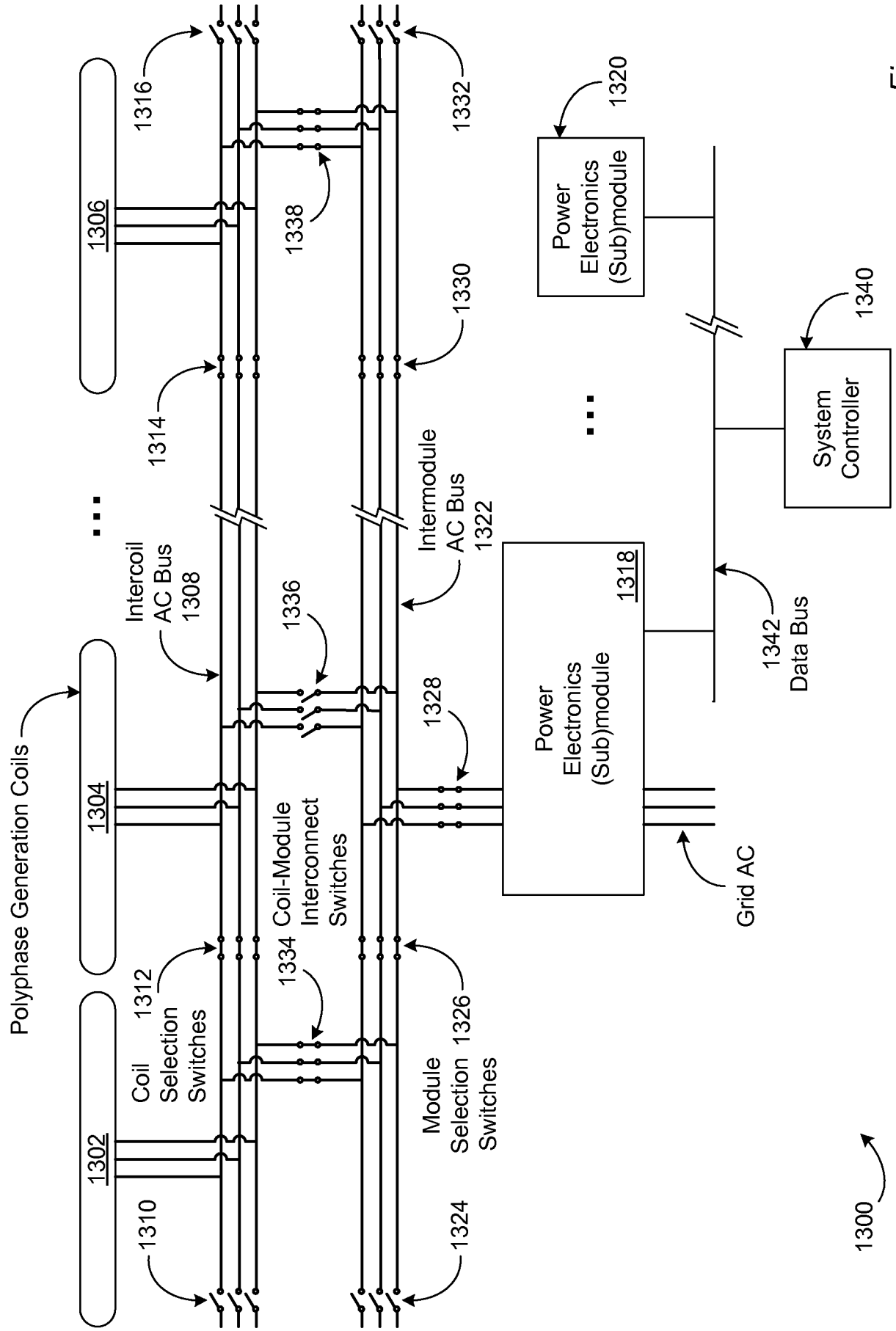

Polyphase Generation Coils
1302
1304
1306
Coil Selection Switches 1312
Intercoil AC Bus 1308
Coil-Module Interconnect Switches
1334
1336
Module Selection Switches 1326
Intermodule AC Bus 1322
1310
1314
1316
1324
1328
1330
1332
1338
Power Electronics (Sub)module 1318
Power Electronics (Sub)module 1320
System Controller 1340
1342 Data Bus
Grid AC
1300

Figure 13

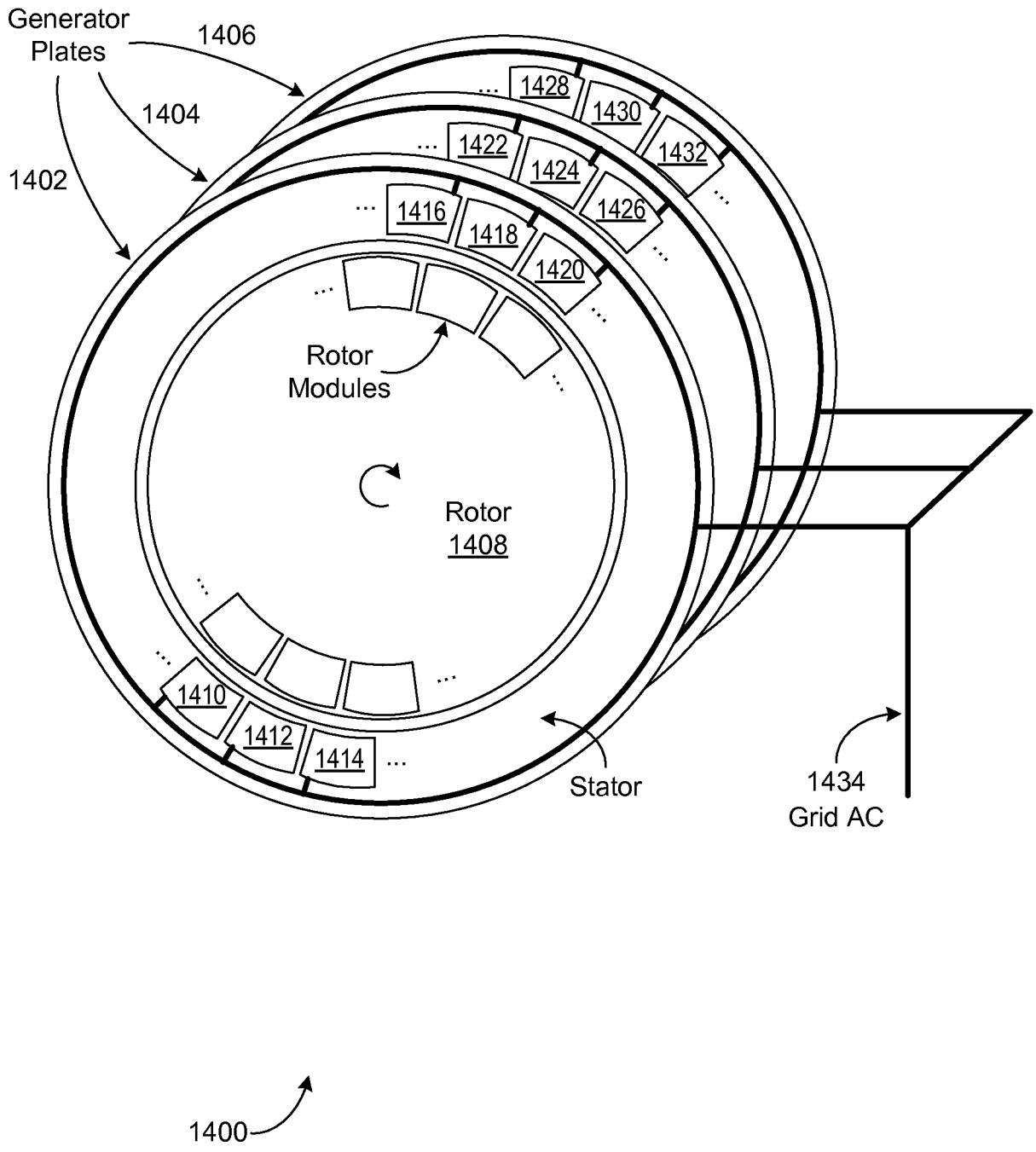

Generator Plates
1406
1404
1402
1428
1430
1432
1422
1424
1426
1416
1418
1420
Rotor Modules
Rotor 1408
1410
1412
1414
Stator
1434 Grid AC
1400

Figure 14

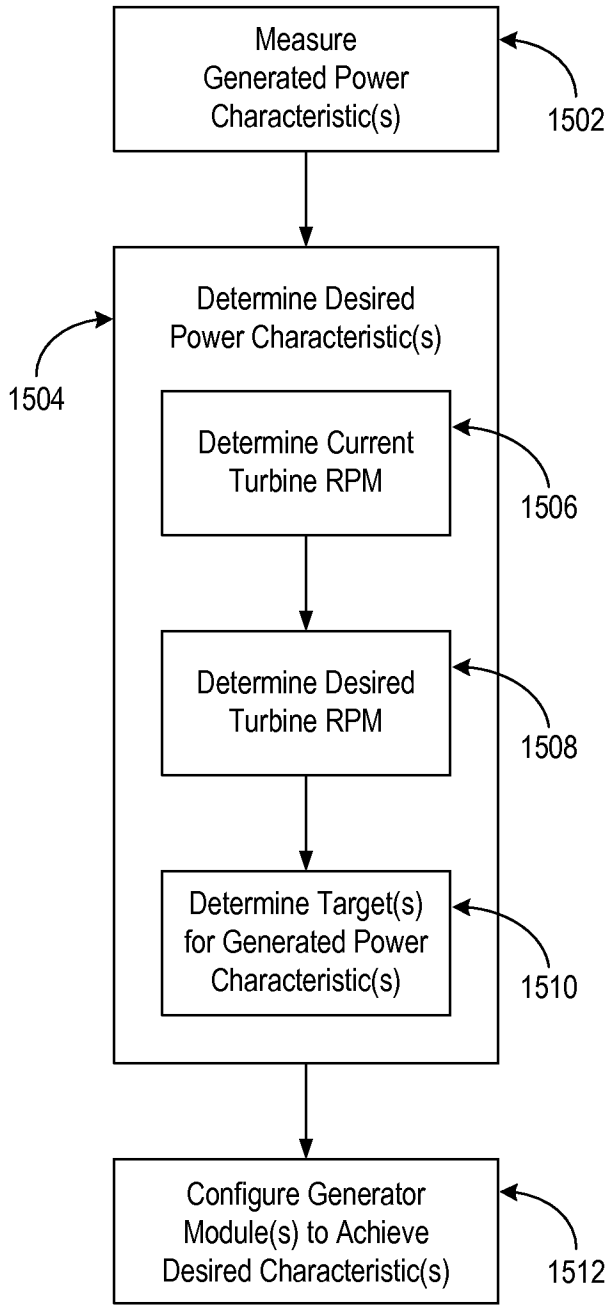

Measure Generated Power Characteristic(s)
1502
Determine Desired Power Characteristic(s)
1504
Determine Current Turbine RPM
1506
Determine Desired Turbine RPM
1508
Determine Target(s) for Generated Power Characteristic(s)
1510
Configure Generator Module(s) to Achieve Desired Characteristic(s)
1512

Figure 15

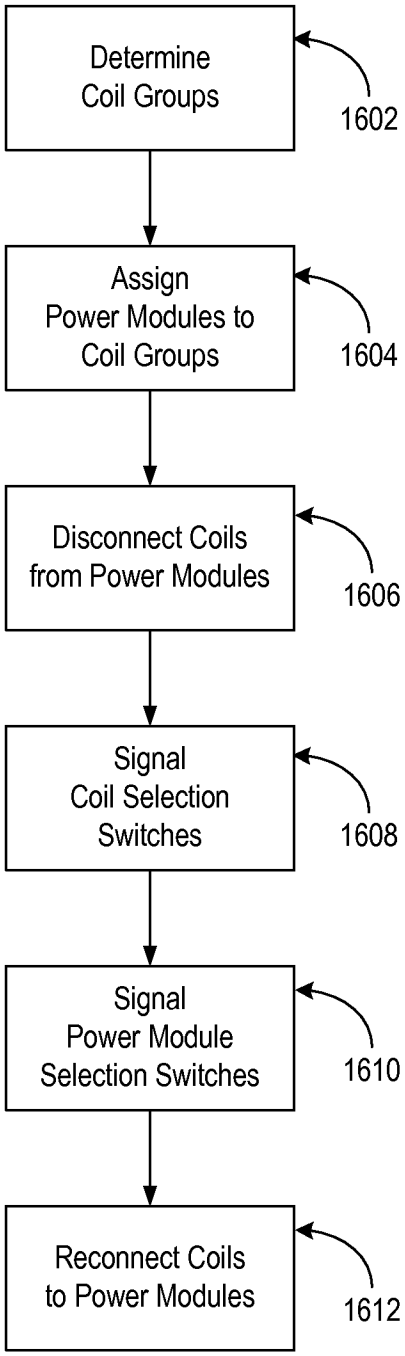

Determine Coil Groups
1602
Assign Power Modules to Coil Groups
1604
Disconnect Coils from Power Modules
1606
Signal Coil Selection Switches
1608
Signal Power Module Selection Switches
1610
Reconnect Coils to Power Modules
1612

Figure 16

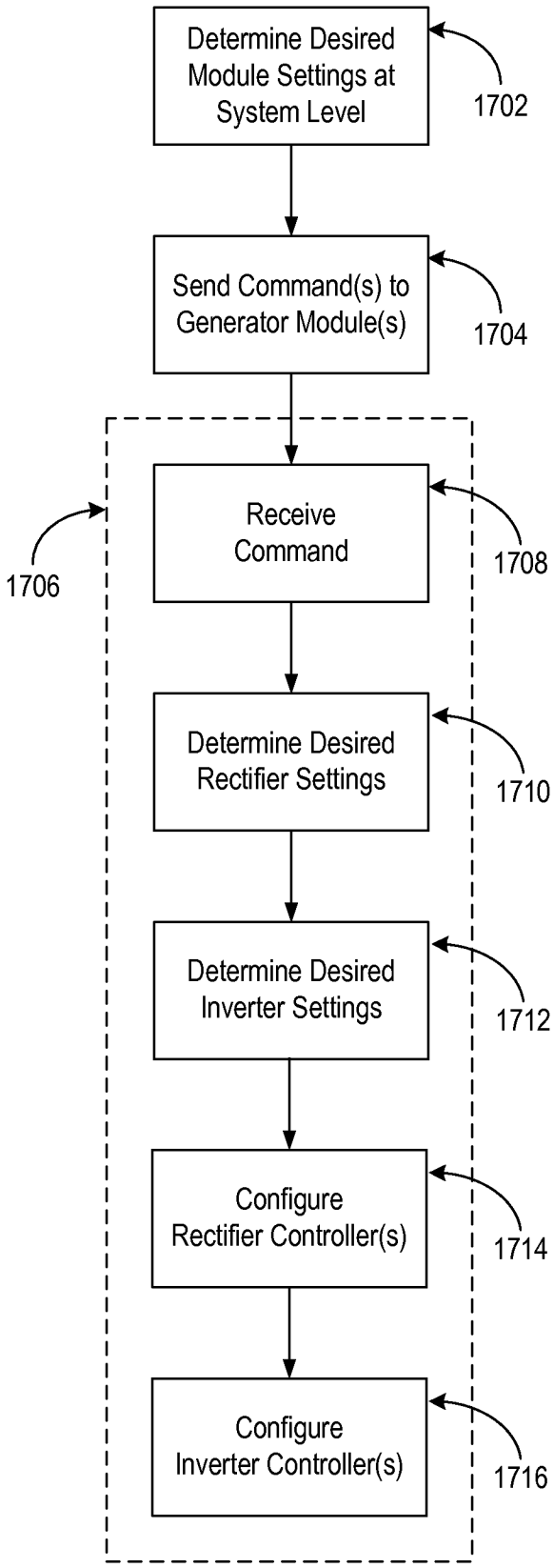

Determine Desired Module Settings at System Level
1702
Send Command(s) to Generator Module(s)
1704
1706
Receive Command
1708
Determine Desired Rectifier Settings
1710
Determine Desired Inverter Settings
1712
Configure Rectifier Controller(s)
1714
Configure Inverter Controller(s)
1716

Figure 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 11/27086

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H02K 21/12 (2011.01)
USPC - 310/156.36
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)
USPC: 310/156.36

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 290/54, 55; 310/156.36, 156.32, 156.08, 156.01, 152, 114, 40R, 10 (keyword limited; terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST (USPT, PGPB, EPAB, JPAB); Google Web; Google Patents
Keywords: turbine; wind; rotor; stator; modules; generator; separation; torque

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2008/0315709 A1 (UCHIYAMA) 25 December 2008 (25.12.2008), entire document, especially; para [0005], [0006], [0008]-[0010], [0015], [0021]-[0025], [0030], [0039], [0045], [0047], [0048], [0143], [0148], [0149], [0152], [0165], [0176], [0179], [0182], [0183], [0211], [0225], [0226], [0251], [0328]	1-10, 12-20 ---------- 11
Y	US 2007/0024147 A1 (HIRZEL) 01 February 2007 (01.02.2007), entire document, especially; para [0026], [0104], [0139]-[0142]	11
A	US 2005/0184689 A1 (MASLOV et al.) 25 August 2005 (25.08.2005), entire document	1-20
A	US 2009/0126369 A1 (WALITZKI et al.) 21 May 2009 (21.05.2009), entire document	1-20

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"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
23 April 2011 (23.04.2011)	06 MAY 2011
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)