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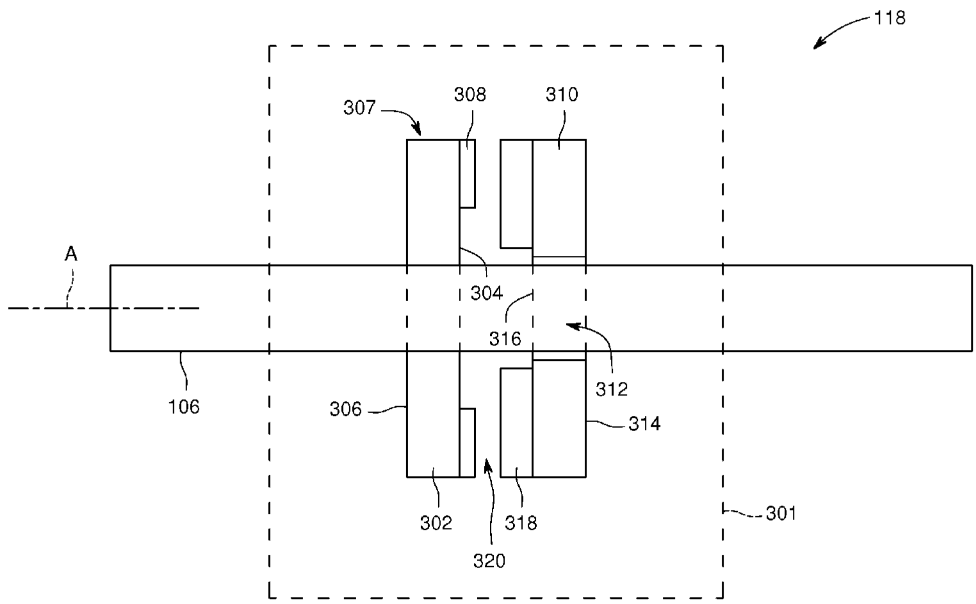

FIG. 3

(57) Abstract: An actuator for a turbomachinery system that includes a turbomachine and an electrical machine coupled to the turbomachine by a shaft extending therebetween. The actuator includes a rotor coupled to the shaft. The rotor includes a plurality of rotor magnetic field-generating elements. The actuator also includes a stator configured to receive at least a portion of the shaft proximate said rotor. The stator includes a plurality of stator magnetic field-generating elements proximate the plurality of rotor magnetic field-generating elements. The plurality of stator magnetic field-generating elements are configured to alternately energize and de-energize to alternately apply and remove, respectively, a corrective torque to the shaft to dampen torsional oscillations thereof.

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ELECTRICAL ACTUATOR DEVICES FOR REDUCTION OF TORSIONAL OSCILLATIONS IN TURBOMACHINERY SYSTEMS

BACKGROUND

The field of the disclosure relates generally to turbomachinery systems, and, more specifically, to electrical actuator devices for reduction of torsional oscillations in turbomachinery systems.

In known turbomachinery systems employing electrical machines which either drive turbomachines, e.g., electrical motors in pumping operations and compression plants, or are driven by turbomachines, e.g., electrical power generators, complex interactions of electrical networks with torsional dynamics of shafts in rotating equipment trains cause sub-synchronous torsional interactions (SSTIs). In such known turbomachinery systems, e.g., liquefied natural gas compression plants, SSTIs cause torsional oscillations resulting in increased maintenance costs, reduced operational efficiency, and equipment service life reduction.

In at least some known turbomachinery systems employing electrical machines, SSTIs experienced by shafts and rotating machinery coupled thereto are caused by torque imbalances arising in electrical machines including motors and generators. Such electrical machines, shafts, and associated rotating machinery often form long trains of equipment in which SSTIs arising in one portion of the train generate undesirable effects not only at that location, but at various other locations distant from the initial point of origin. Also, in such known turbomachinery systems, mitigation of SSTIs and resulting aberrant torques is expensive, requires substantial modification of existing systems and plant equipment, and is subject to design constraints from existing electrical and mechanical loads. Further, in such known turbomachinery systems, known SSTI and torque mitigation devices and systems are complex, require elaborate control systems, are cumbersome to integrate into existing plant operations, and require complete plant shutdown for their installation and maintenance.

BRIEF DESCRIPTION

In one aspect, an actuator for a turbomachinery system is provided. The turbomachinery system includes a turbomachine and an electrical machine coupled to the turbomachine by a shaft extending therebetween. The actuator includes a rotor coupled to the shaft. The rotor includes a plurality of rotor magnetic field-generating elements. The actuator also includes a stator configured to receive at least a portion of the shaft proximate the rotor. The stator includes a plurality of stator magnetic field-generating elements proximate the plurality of rotor magnetic field-generating elements. The plurality of stator magnetic field-generating elements are configured to alternately energize and de-energize to alternately apply and remove, respectively, a corrective torque to the shaft to dampen torsional oscillations thereof.

In another aspect, a turbomachinery system is provided. The turbomachinery system includes a turbomachine, an electrical machine, and a shaft coupled to the electrical machine and coupled to the turbomachine and extending therebetween. The turbomachinery system also includes an actuator including a rotor coupled to the shaft. The rotor includes a plurality of rotor magnetic field-generating elements. The actuator also includes a stator configured to receive at least a portion of the shaft proximate the rotor. The stator includes a plurality of stator magnetic field-generating elements proximate the plurality of rotor magnetic field-generating elements. The plurality of stator magnetic field-generating elements are configured to alternately energize and de-energize to alternately apply and remove, respectively, a corrective torque to the shaft to dampen torsional oscillations thereof.

In yet another aspect, a method of damping torsional oscillations of a shaft in a turbomachinery system is provided. The turbomachinery system includes an electrical machine coupled to a turbomachine by the shaft extending therebetween, and an actuator including a stator and a rotor coupled to the shaft proximate the stator. The method includes detecting, through a sensor coupled to the turbomachinery system, a physical characteristic of the turbomachinery system representative of torsional oscillations. The method also includes determining, through data transmitted by the sensor, a presence of torsional oscillations. The method further includes energizing the stator of the actuator to apply a corrective torque to the shaft to dampen torsional oscillations thereof.

DRAWINGS

These and other features, aspects, and advantages of the present disclosure will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. 1 is a schematic diagram of an exemplary turbomachinery system;

FIG. 2 is a schematic diagram of an alternative turbomachinery system;

FIG. 3 is a cross-sectional view of an exemplary actuator that may be used in the turbomachinery systems shown in FIGs. 1 and 2;

FIG. 4 is a perspective view of an exemplary axial flux machine actuator that may be used in the turbomachinery systems shown in FIGs. 1 and 2;

FIG. 5 is a cross-sectional view of an alternative actuator that may be used in the turbomachinery systems shown in FIGs. 1 and 2;

FIG. 6 is a perspective view of an exemplary radial flux machine actuator that may be used in the turbomachinery systems shown in FIGs. 1 and 2;

FIG. 7 is a cross-sectional view of an alternative actuator that may be used in the turbomachinery systems shown in FIGs. 1 and 2;

FIG. 8 is a perspective view of an alternative radial flux machine actuator that may be used in the turbomachinery systems shown in FIGs. 1 and 2;

FIG. 9 is a cross-sectional view of an alternative actuator that may be used in the turbomachinery systems shown in FIGs. 1 and 2;

FIG. 10 is a perspective view of an alternative radial flux machine actuator that may be used in the turbomachinery systems shown in FIGs. 1 and 2; and

FIG. 11 is a flowchart diagram of an exemplary method of damping torsional oscillations of a shaft in a turbomachinery system that may be used with the turbomachinery systems shown in FIGs. 1 and 2.

Unless otherwise indicated, the drawings provided herein are meant to illustrate features of embodiments of this disclosure. These features are believed to be applicable in a wide variety of systems comprising one or more embodiments of this disclosure. As such, the drawings are not meant to include all conventional features known by those of ordinary skill in the art to be required for the practice of the embodiments disclosed herein.

DETAILED DESCRIPTION

In the following specification and the claims, reference will be made to a number of terms, which shall be defined to have the following meanings.

The singular forms “a”, “an”, and “the” include plural references unless the context clearly dictates otherwise.

“Optional” or “optionally” means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where the event occurs and instances where it does not.

Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about”, “approximately”, and “substantially”, are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Here and throughout the specification and claims, range limitations may be combined and/or interchanged, and such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise.

As used herein, the terms “processor” and “computer” and related terms, e.g., “processing device”, “computing device”, and “controller” are not limited to just those integrated circuits referred to in the art as a computer, but broadly refers to a microcontroller, a microcomputer, a programmable logic controller (PLC), an application specific integrated circuit (AISC), and other programmable circuits, and these terms are used interchangeably herein. In the embodiments described herein, memory may include, but is not limited to, a computer-readable medium, such as a random access memory (RAM), and a computer-readable non-volatile medium, such as flash memory. Alternatively, a floppy disk, a compact disc – read only memory (CD-ROM), a magneto-optical disk (MOD), and/or a digital versatile disc (DVD) may also be used. Also, in the embodiments described herein, additional input channels may be, but are not limited to, computer peripherals associated with an operator interface such as a mouse and a keyboard. Alternatively, other computer peripherals may also be used that may include, for example, but not be limited to, a scanner. Furthermore, in the exemplary embodiment, additional output channels may include, but not be limited to, an operator interface monitor.

Furthermore, as used herein, the term “real-time” refers to at least one of the time of occurrence of the associated events, the time of measurement and collection of predetermined data, the time to process the data, and the time of a system response to the events and the environment. In the embodiments described herein, these activities and events occur substantially instantaneously.

The electrical actuator devices for reduction of torsional oscillations in turbomachinery systems and associated control systems and methods described herein reduce sub-synchronous torsional interactions (SSTIs) of shafts and rotating machinery including electrical machines in rotating equipment trains. The embodiments described herein also mitigate undesirable effects of SSTIs and aberrant torques arising therefrom in turbomachinery systems. The embodiments described herein further reduce torque imbalances in electrical machines employed in turbomachinery systems. The electrical actuator devices for reduction of torsional oscillations in turbomachinery systems and associated control systems and methods described herein also reduce operating and maintenance costs and increase operational efficiency of turbomachinery systems. The embodiments described herein further provide less complex and less expensive SSTI mitigation devices, systems, and methods that are easier to operate and integrate into existing plant designs. The embodiments described herein also enable installation and maintenance of SSTI mitigation devices and systems without shutting down turbomachinery system operations.

FIG. 1 is a schematic diagram of an exemplary turbomachinery system 100. In the exemplary embodiment, turbomachinery system 100 is situated in a turbomachinery facility 101 and includes a turbomachine 102 including, without limitation, a gas turbine engine including a compressor and a turbine. Turbomachinery system 100 also includes an auxiliary machine 104 including, without limitation, a gear box. Auxiliary machine 104 is rotatably coupled to turbomachine 102 through a first shaft 106. Turbomachinery system 100 further includes an electrical machine 108 rotatably coupled to auxiliary machine 104 through a second shaft 110. In the exemplary embodiment, electrical machine 108 is a generator 112, turbomachine 102 is a prime mover for generator 112, and turbomachine facility 101 is an electrical power generation facility configured to supply electricity to a grid 114 through 3-phase power lines 116. In other embodiments, not shown, turbomachinery system 100 does not include auxiliary machine 104 and second shaft 110, and turbomachine 102 is rotatably coupled to generator 112 through first shaft 106.

Turbomachinery system 100, in the exemplary embodiment, includes an actuator 118 coupled to second shaft 110 proximate generator 112. In other embodiments, not shown, actuator 118 is coupled to second shaft 110 distal generator 112 including, without limitation, proximate auxiliary machine 104. In still other embodiments, not shown, at least one additional actuator 118 is coupled to at least one of first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Turbomachinery system 100, in the exemplary embodiment, includes an actuator power converter 120 coupled to actuator 118 through at least one actuator electrical line 122. Actuator power converter 120 is an alternating current (AC) power converter including, without limitation, at least one of a direct current (DC)-to-AC power converter and an AC-to-AC power converter, and actuator 118 is an AC actuator. A power supply 124 including, without limitation, at least one of a DC power supply and an AC power supply, is coupled to actuator power converter 120 through at least one actuator electrical line 122. Furthermore, an actuator controller 126 is coupled to actuator 118. Actuator controller 126 is further coupled to at least one of actuator power converter 120 and power supply 124. In other embodiments, not shown, one actuator 118 of a plurality of actuators 118 is coupled to one respective actuator controller 126 of a plurality of actuator controllers 126. In still other embodiments, not shown, one sensor 128 of a plurality of sensors 128 is coupled to more than one actuator controller 126 of a plurality of actuator controllers 126.

Turbomachinery system 100, in the exemplary embodiment, includes at least one sensor 128 coupled to actuator controller 126. Sensor 128 is further coupled to at least one of first shaft 106 and second shaft 110 and at least one sensor 128 is further coupled to at least one of generator 112 and 3-phase power lines 116. In other embodiments, not shown, at least one sensor 128 is further coupled to other locations within turbomachinery system 100 other than at least one of first shaft 106, second shaft 110, generator 112, and 3-phase power lines 116.

In operation, in the exemplary embodiment, shafts including, without limitation, first shaft 106 and second shaft 110, of turbomachinery system 100 are susceptible to torsional oscillations during operation of turbomachinery system 100. Sensor 128 is configured to detect a physical characteristic of turbomachinery system 100 representative of torsional oscillations and transmit a control signal 130 to actuator controller 126.

Physical characteristics representative of torsional oscillations of turbomachinery system 100 include, without limitation, at least one of a magnitude, a direction, and a frequency of an axial deflection of at least one of first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Physical characteristics representative of torsional oscillations of turbomachinery system 100 also include, without limitation, at least one of a direction and an angular velocity of a rotation of at least one of first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Physical characteristics representative of torsional oscillations of turbomachinery system 100 also include, without limitation, at least one of a magnitude, a direction, and a frequency of a torque associated with torsional oscillations of at least one of first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Physical characteristics representative of torsional oscillations of turbomachinery system 100 further include, without limitation, at least one of a magnitude, a direction, and a frequency of a current feeding at least one of a rotor winding of electrical machine 108 and a stator winding of electrical machine 108. Physical characteristics representative of torsional oscillations of turbomachinery system 100 also include, without limitation, at least one of a magnitude, a direction, and a frequency of a voltage across electrical terminals of at least one of a rotor winding of electrical machine 108 and a stator winding of electrical machine 108. Physical characteristics representative of torsional oscillations of turbomachinery system 100 further include, without limitation, at least one of a magnitude, a direction, and a frequency of at least one of a vibration and an acceleration associated with at least one of electrical machine 108, turbomachine 102, auxiliary machine 104, actuator 118, first shaft 106, second shaft 110, additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104, and any other component of turbomachinery system 100 whereupon an occurrence of at least one of vibrations and accelerations is representative of torsional oscillations in turbomachinery system 100. In the exemplary embodiment, sensor 128 includes sensor types configured to detect and measure the aforementioned physical characteristics including, without limitation, deflection sensors, angular velocity sensors, torque sensors, electrical current sensors, voltage potential sensors, electrical frequency sensors, vibration sensors, and acceleration sensors.

In operation of the exemplary embodiment, actuator 118 is configured to alternately apply and remove a corrective torque to turbomachinery system 100 shafts including, without limitation, first shaft 106 and second shaft 110, as further shown and described below with reference to FIGs. 3-7. Receipt of control signal 130 including, without limitation, receipt of control signal 130 in real-time, by actuator controller 126 is indicative of a presence of torsional oscillations within turbomachinery system 100. In the exemplary embodiment, control signal 130 contains data having a first value when torsional oscillations are present in turbomachinery system 100, and control signal 130 contains data having a second value different from the first value when torsional oscillations are not present in turbomachinery system 100.

In operation of the exemplary embodiment, receipt of control signal 130 having the first value by actuator controller 126 enables a flow of electrical current from power supply 124 to actuator 118 and thereby enables application of corrective torque by actuator 118 by energizing actuator 118. Further, receipt of control signal 130 having the second value by actuator controller 126 disables the flow of electrical current from power supply 124 to actuator 118 and thereby removes corrective torque by actuator 118 by de-energizing actuator 118, as further described below with reference to FIGs. 3-7. In other embodiments, not shown, control signal 130 contains only the first value of data indicative of torsional oscillations in turbomachinery system 100, and control signal 130 is absent and contains no data when torsional oscillations are absent in turbomachinery system 100. In still other embodiments, control signal 130 contains a range of varying data values which not only indicate presence of torsional oscillations in turbomachinery system 100, but also quantify properties of torsional oscillations, e.g., for operational trending purposes. In yet other embodiments, not shown, actuator controller 126 is configured to adjust flow of electrical current from at least one of power supply 124 and actuator power converter 120 to actuator 118 between a range of values including 0 (zero) amps to enable application of an amount of corrective torque by actuator 118 between a range of values including 0 newton·meters depending on an intensity of torsional oscillations requiring corrective torque.

FIG. 2 is a schematic diagram of an alternative turbomachinery system 200. In this alternative embodiment, turbomachinery system 200 is situated in a turbomachinery facility 201. Turbomachinery system 200 includes electrical machine 108, i.e., a motor 202 including, without limitation, a 3-phase motor. Turbomachinery system 200 also includes a motor power converter 204 coupled to grid 114 through 3-phase power lines 116. Motor power converter 204 is further coupled to motor 202 through 3-phase power lines 116. Further, turbomachinery system 200 includes auxiliary machine 104 including, without limitation, a compressor for process fluid. Auxiliary machine 104 is rotatably coupled to motor 202 through first shaft 106 which extends through auxiliary machine 104 and is rotatably coupled to turbomachine 102. In other embodiments, not shown, first shaft 106 does not extend through auxiliary machine 104 and at least one other shaft besides first shaft 106 is rotatably coupled to and between auxiliary machine 104 and turbomachine 102 in turbomachinery system 200. In this alternative embodiment, second shaft 110 is rotatably coupled to and between turbomachine 102 and additional rotating machines (not shown) downstream of turbomachine 102 in turbomachinery system 200. As such, turbomachine facility 201 is a compression train.

Turbomachinery system 200 includes actuator 118 coupled to first shaft 106 proximate motor 202. In other embodiments, not shown, actuator 118 is coupled to first shaft 106 distal motor 202 including, without limitation, proximate auxiliary machine 104. In still other embodiments, not shown, at least one additional actuator 118 is coupled to at least one of first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Further, turbomachinery system 200 includes, in this alternative embodiment, actuator power converter 120 coupled to actuator 118 through at least one actuator electrical line 122. Actuator power converter 120 is an AC power converter including, without limitation, at least one of a DC-to-AC power converter and an AC-to-AC power converter, and actuator 118 is an AC actuator. Power supply 124, including, without limitation, at least one of a DC power supply and an AC power supply, is coupled to actuator power converter 120 through actuator electrical line 122. Actuator controller 126 is coupled to actuator 118 and to at least one of actuator power converter 120 and power supply 124. In other embodiments, not shown, one actuator 118 of a plurality of actuators 118 is coupled to one respective actuator controller 126 of a plurality of actuator controllers 126. In still other embodiments, not shown, one sensor 128 of a plurality of sensors 128 is coupled to more than one actuator controller 126 of a plurality of actuator controllers 126.

Turbomachinery system 200 further includes at least one sensor 128 coupled to actuator controller 126. Sensor 128 is further coupled to at least one of first shaft 106 and second shaft 110 and at least one sensor 128 is further coupled to at least one of motor 202 and 3-phase power lines 116. In other embodiments, not shown, at least one sensor 128 is further coupled to other locations within turbomachinery system 200 other than at least one of first shaft 106, second shaft 110, motor 202, and 3-phase power lines 116.

Shafts including, without limitation, first shaft 106 and second shaft 110, of turbomachinery system 200 are susceptible to torsional oscillations during operation of turbomachinery system 200. Sensor 128 is configured to detect a physical characteristic of turbomachinery system 200 representative of torsional oscillations and transmit control signal 130 to actuator controller 126. These physical characteristics representative of torsional oscillations of turbomachinery system 200 include, without limitation, at least one of a magnitude, a direction, and a frequency of an axial deflection of at least one of first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104.

Physical characteristics representative of torsional oscillations of turbomachinery system 200 also include, without limitation, at least one of a direction and an angular velocity of a rotation of at least one of first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Physical characteristics representative of torsional oscillations of turbomachinery system 200 also include, without limitation, at least one of a magnitude, a direction, and a frequency of a torque associated with torsional oscillations of at least one of first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Physical characteristics representative of torsional oscillations of turbomachinery system 200 further include, without limitation, at least one of a magnitude, a direction, and a frequency of a current feeding at least one of a rotor winding of electrical machine 108 and a stator winding of electrical machine 108. Physical characteristics representative of torsional oscillations of turbomachinery system 200 also include, without limitation, at least one of a magnitude, a direction, and a frequency of a voltage across electrical terminals of at least one of a rotor winding of electrical machine 108 and a stator winding of electrical machine 108. Physical characteristics representative of torsional oscillations of turbomachinery system 200 further include, without limitation, at least one of a magnitude, a direction, and a frequency of at least one of a vibration and an acceleration associated with at least one of electrical machine 108, turbomachine 102, auxiliary machine 104, actuator 118, first shaft 106, second shaft 110, additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104, and any other component of turbomachinery system 200 whereupon an occurrence of at least one of vibrations and accelerations is representative of torsional oscillations in turbomachinery system 200. Sensor 128 includes sensor types configured to detect and measure the aforementioned physical characteristics including, without limitation, deflection sensors, angular velocity sensors, torque sensors, electrical current sensors, voltage potential sensors, electrical frequency sensors, vibration sensors, and acceleration sensors.

In operation of this alternative embodiment, actuator 118 is configured to alternately apply and remove a corrective torque to turbomachinery system 200 shafts including, without limitation, first shaft 106 and second shaft 110, as further shown and described below with reference to FIGs. 3-7. Receipt of control signal 130 including, without limitation, receipt of control signal 130 in real-time, by actuator controller 126 is indicative of a presence of torsional oscillations within turbomachinery system 200. In this alternative embodiment, control signal 130 contains data having a first value when torsional oscillations are present in turbomachinery system 200, and control signal 130 contains data having a second value different from the first value when torsional oscillations are not present in turbomachinery system 200.

In operation of this alternative embodiment, receipt of control signal 130 having the first value by actuator controller 126 enables a flow of electrical current from power supply 124 to actuator 118 and thereby enables application of corrective torque by actuator 118 by energizing actuator 118. Further, receipt of control signal 130 having the second value by actuator controller 126 disables the flow of electrical current from power supply 124 to actuator 118 and thereby removes corrective torque by actuator 118 by de-energizing actuator 118, as further described below with reference to FIGs. 3-7. In other embodiments, not shown, control signal 130 contains only the first value of data indicative of torsional oscillations in turbomachinery system 200, and control signal 130 is absent and contains no data when torsional oscillations are absent in turbomachinery system 200. In still other embodiments, control signal 130 contains a range of varying data values which not only indicate presence of torsional oscillations in turbomachinery system 200, but also quantify properties of torsional oscillations, e.g., for operational trending purposes. In yet other embodiments, not shown, actuator controller 126 is configured to adjust flow of electrical current from at least one of power supply 124 and actuator power converter 120 to actuator 118 between a range of values including 0 amps to enable application of an amount of corrective torque by actuator 118 between a range of values including 0 newton·meters depending on intensity of torsional oscillations requiring corrective torque.

FIG. 3 is a cross-sectional view of an exemplary actuator 118 that may be used in turbomachinery system 100 and turbomachinery system 200 shown in FIGs. 1 and 2, respectively. In the exemplary embodiment, actuator 118 is configured as an axial flux machine 301 and includes a rotor 302 coupled to first shaft 106. Rotor 302 includes a first rotor side 304 and a second rotor side 306 opposite first rotor side 304. First rotor side 304 and second rotor side 306 extend radially outward from an axis A of first shaft 106 to a rotor circumference 307 of rotor 302. Rotor 302 also includes a plurality of rotor magnetic field-generating elements 308 coupled to first rotor side 304. The plurality of rotor magnetic field-generating elements 308, in the exemplary embodiment, includes a plurality of permanent magnets, e.g., formed of a ferromagnetic material. In other embodiments, not shown, the plurality of rotor magnetic field-generating elements 308 include a type of magnetic field-generating elements other than permanent magnets including, without limitation, a plurality of rotor electromagnetic elements coupled to an electrical power source coupled and configured to energize the plurality of rotor electromagnetic elements. In the exemplary embodiment, the plurality of rotor magnetic field-generating elements 308 are coupled to first rotor side 304 in a substantially radial arrangement and with a predetermined spacing including, without limitation, an equidistant spacing, between each rotor magnetic field-generating element 308 of the plurality of rotor magnetic field-generating elements 308.

Axial flux machine 301, in the exemplary embodiment, includes a stator 310 extending circumferentially around first shaft 106 proximate rotor 302. Stator 310 also includes a cavity 312 defined therethrough. Stator 310 is not coupled to first shaft 106, but rather cavity 312 of stator 310 is configured to receive first shaft 106 and facilitate rotation of first shaft 106 within cavity 312. Stator 310, in the exemplary embodiment, is a stator disk having a stator circumference 313, and cavity 312 is defined in the center thereof with a cavity circumference defined substantially equidistant from axis A of first shaft 106. Stator 310 also includes a first stator side 314 and a second stator side 316 opposite first stator side 314. Second stator side 316 is positioned proximate first rotor side 314, and first stator side 314 and second stator side 316 extend radially inward from stator circumference 313 to cavity 312.

Stator 310 further includes a plurality of stator magnetic field-generating elements 318 coupled to second stator side 316. In the exemplary embodiment, the plurality of stator magnetic field-generating elements 318 are coupled to second stator side 316 in a substantially radial arrangement and with a predetermined spacing including, without limitation, an equidistant spacing, between each stator magnetic field-generating element 318 of the plurality of stator magnetic field-generating elements 318. Stator magnetic field-generating elements 318 are positioned proximate rotor magnetic field-generating 308 elements to define an air gap 320 therebetween.

In operation, stator magnetic field-generating elements 318 are coupled to at least one of actuator power converter 120, actuator controller 126, and power supply 124 (not shown). Stator 310 is an AC stator configured to induce a rotating magnetic field through the plurality of stator magnetic field-generating elements 318. Stator magnetic field-generating elements 318 are configured to alternately energize and de-energize to alternately apply and remove, respectively, corrective torque to shafts of at least one of turbomachinery system 100 and turbomachinery system 200 including, without limitation, first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Rotating magnetic field through the plurality of stator magnetic field-generating elements 318 is induced when energized by the flow of electrical current thereto from at least one of power supply 124 and actuator power converter 120. Stator 310 is also configured to apply corrective torque to first shaft 106 in both a clockwise direction and a counterclockwise direction, depending on an alignment of phases of AC power transmitted to stator 310 on actuator electrical line 122 (not shown). In other embodiments, not shown, stator 310 is configured to apply corrective torque to first shaft 106 in only one of a clockwise and a counterclockwise direction. Also, in operation, disabling the flow of electrical current to stator 310 de-energizes the plurality of stator magnetic field-generating elements 318 and removes corrective torque from first shaft 106.

In operation of the exemplary embodiment, rotating magnetic field through plurality of stator magnetic field-generating elements 318 interacts electromechanically through air gap 320 with plurality of rotor magnetic field generating elements 308 on rotor 302. Depending on the direction at which stator 310 rotating magnetic field rotates, at least one of a clockwise and a counterclockwise corrective torque is applied to first shaft 106 to dampen torsional oscillations thereof. An amount of corrective torque applied by axial flux machine 301 to first shaft 106 by energizing stator 310 is dictated by user-determined parameters of turbomachinery system 100. User-determined parameters include, without limitation, parameters that depend on data contained in control signal 130. User-determined parameters also include, without limitation, design parameters of at least one of turbomachinery system 100, electrical machine 108, actuator power converter 120, and actuator controller 126. User-predetermined parameters further include, without limitation, a time, a magnetic flux intensity, and a magnetic field strength of an induced magnetic field including, without limitation, rotating magnetic field through the plurality of stator magnetic field-generating elements 318.

FIG. 4 is a perspective view of an exemplary axial flux machine 301 actuator 118 that may be used in turbomachinery system 100 and turbomachinery system 200 shown in FIGs. 1 and 2. In the exemplary embodiment, stator 310 of axial flux machine 301 includes at least one detachment link 402 and stator 310 is coupled to at least one of turbomachinery system 100 and turbomachinery system 200. Detachment link 402 defines at least one section of stator 310 including, without limitation, an arcuate portion of stator disk. Detachment link 402 is configured to facilitate removal of stator 310 from first shaft 106 without necessitating at least one of disassembling and decoupling axial flux machine 301 from at least one of turbomachinery system 100 and turbomachinery system 200. Detachment link 402 is also configured to facilitate at least one of reassembling and recoupling stator 310 to first shaft 106 of at least one of turbomachinery system 100 and turbomachinery system 200 following user-initiated activities including, without limitation, maintenance of at least one of first shaft 106, rotor 302, stator 310, electrical machine 108, auxiliary machine 104, and turbomachine 102.

FIG. 5 is a cross-sectional view of an alternative actuator 118 that may be used in turbomachinery system 100 and turbomachinery system 200 shown in FIGs. 1 and 2. In this alternative embodiment, actuator 118 is configured as a radial flux machine 501. Radial flux machine 501 includes a rotor 502 coupled to first shaft 106. Rotor 502 extends as a rotor disk radially outward from axis A of first shaft 106 to a rotor circumference 503 of rotor 502. Rotor 502 also includes a plurality of rotor magnetic field-generating elements 504 coupled to rotor circumference 503. In other embodiments, not shown, the plurality of rotor magnetic field-generating elements 504 are coupled to first shaft 106, radial flux machine 501 does not include rotor 502, and first shaft 106 functions as a shaft-integrated rotor. The plurality of rotor magnetic field-generating elements 504, in this alternative embodiment, includes a plurality of permanent magnets, e.g., formed of ferromagnetic material. In other embodiments, not shown, the plurality of rotor magnetic field-generating elements 504 include type of magnetic field-generating elements other than permanent magnets including, without limitation, a plurality of rotor electromagnetic elements coupled to an electrical power source coupled thereto and configured to energize the plurality of rotor electromagnetic elements. The plurality of rotor magnetic field-generating elements 504, in this alternative embodiment, are coupled to rotor circumference 503 in a substantially axial arrangement and with a predetermined spacing including, without limitation, an equidistant spacing, between each rotor magnetic field-generating element 504 of the plurality of rotor magnetic field-generating elements 504.

Radial flux machine 501 includes a stator 506 embodied in an annular ring extending substantially circumferentially around first shaft 106 proximate rotor 502. Stator 506 defines a cavity 508. Stator 506 is not coupled to first shaft 106, but rather stator 506 is configured to receive first shaft 106 and rotor 502 and facilitate rotation of rotor 502 and first shaft 106 within cavity 508. Stator 506 also includes a stator circumference 509. Stator 506 annular ring also includes an inner radius 510 defined between axis A and a radially inward surface of stator 506 annular ring. Inner radius 510 also defines a radially outward boundary of cavity 508 and, in this alternative embodiment, cavity 508 is embodied in an annular cavity through stator 506. Stator 506 also includes an outer radius 512 defined between axis A and stator circumference 509.

Stator 506 further includes a plurality of stator magnetic field-generating elements 514 positioned, including coupled to, a radially inward side of stator 506 annular ring along inner radius 510. The plurality of stator magnetic field-generating elements 514 are coupled to stator 506 annular ring along inner radius 510 in a substantially axial arrangement and with a predetermined spacing including, without limitation, an equidistant spacing, between each stator magnetic field-generating element 514 of the plurality of stator magnetic field-generating elements 514. Stator magnetic field-generating elements 514 are positioned proximate rotor magnetic field-generating elements 504 to facilitate defining an air gap 516 therebetween.

In operation, stator magnetic field-generating elements 514 are coupled to at least one of actuator power converter 120, actuator controller 126, and power supply 124 (not shown). Stator 506 is an AC stator configured to induce a rotating magnetic field through the plurality of stator magnetic field-generating elements 514. Stator magnetic field-generating elements 514 are configured to alternately energize and de-energize to alternately apply and remove, respectively, corrective torque to shafts of at least one of turbomachinery system 100 and turbomachinery system 200 including, without limitation, first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104.

Rotating magnetic field through the plurality of stator magnetic field-generating elements 514 is induced when energized by the flow of electrical current thereto from at least one of power supply 124 and actuator power converter 120. Stator 506 is also configured to apply corrective torque to first shaft 106 in both a clockwise direction and a counterclockwise direction, depending on an alignment of phases of AC power transmitted to stator 506 on actuator electrical line 122 (not shown). In other embodiments, not shown, stator 506 is further configured to apply corrective torque to first shaft 106 in only one of a clockwise and a counterclockwise direction. Also, in operation, disabling the flow of electrical current to stator 506 de-energizes the plurality of stator magnetic field-generating elements 514 and removes corrective torque from first shaft 106.

In operation of this alternative embodiment, rotating magnetic field through plurality of stator magnetic field-generating elements 514 interacts electromechanically through air gap 516 with plurality of rotor magnetic field generating elements 504 on rotor 502. Depending on the direction at which stator 506 rotating magnetic field rotates, at least one of a clockwise and a counterclockwise corrective torque is applied to first shaft 106 to dampen torsional oscillations thereof. An amount of corrective torque applied by radial flux machine 501 to first shaft 106 by energizing stator 506 is dictated by user-determined parameters of at least one of turbomachinery system 100 and turbomachinery system 200. User-determined parameters include, without limitation, parameters that depend on data contained in control signal 130. User-determined parameters also include, without limitation, design parameters of at least one of turbomachinery system 200, electrical machine 108, actuator power converter 120, and actuator controller 126. User-predetermined parameters further include, without limitation, a time, a magnetic flux intensity, and a magnetic field strength of an induced magnetic field including, without limitation, rotating magnetic field through the plurality of stator magnetic field-generating elements 514.

FIG. 6 is a perspective view of an exemplary radial flux machine 501 actuator 118 that may be used in turbomachinery system 100 and turbomachinery system 200 shown in FIGs. 1 and 2. In the exemplary embodiment, stator 506 of radial flux machine 501 includes at least one detachment link 402 and stator 506 is coupled to at least one of turbomachinery system 100 and turbomachinery system 200. Detachment link 402 defines at least one section of stator 506 including, without limitation, an arc segment of stator 506 annular ring. Detachment link 402 is configured to facilitate removal of stator 506 from first shaft 106 without necessitating at least one of disassembling and decoupling radial flux machine 501 from at least one of turbomachinery system 100 and turbomachinery system 200. Detachment link 402 is also configured to facilitate at least one of reassembling and recoupling stator 506 to first shaft 106 of at least one of turbomachinery system 100 and turbomachinery system 200 following user-initiated activities including, without limitation, maintenance of at least one of first shaft 106, rotor 502, stator 506, electrical machine 108, auxiliary machine 104, and turbomachine 102.

FIG. 7 is a cross-sectional view of an alternative actuator 118 that may be used in turbomachinery system 100 and turbomachinery system 200 shown in FIGs. 1 and 2. In this alternative embodiment, actuator 118 is embodied in a squirrel cage induction motor, and actuator 118 is configured as a radial flux machine 701 including an annular squirrel cage rotor 702 coupled to first shaft 106. Squirrel cage rotor 702 extends as a rotor cage radially outward from axis A of first shaft 106 to a rotor circumference 703 of squirrel cage rotor 702. Squirrel cage rotor 702 is coupled to a shaft circumference 704 through a coupling layer 705 including, without limitation, a thermoplastic-based adhesive layer having a lower thermal conductivity than both of first shaft 106 and squirrel cage rotor 702. In other embodiments, not shown, squirrel cage rotor 702 is coupled to shaft circumference 704 as a caged sleeve structure that is coupled to shaft circumference 704 not through coupling layer 705, but rather through coupling processes including, without limitation, welding, thermal expansion, thermal contraction, molding, and extrusion. Squirrel cage rotor 702 also includes a plurality of cross bars 706 formed of a conductive material. The plurality of cross bars 706 are coupled to and extend between at least two annular rotor rings 708. In other embodiments, not shown, squirrel cage rotor 702 is instead embodied in a plurality of cross bars 706 formed of a ferromagnetic material, e.g., permanent magnets, coupled to shaft circumference 704 without rotor ring 708.

In operation, stator magnetic field-generating elements 514 are coupled to at least one of actuator power converter 120, actuator controller 126, and power supply 124 (not shown). Stator 506 is an AC stator configured to induce a rotating magnetic field through the plurality of stator magnetic field-generating elements 514. Stator magnetic field-generating elements 514 are configured to alternately energize and de-energize to alternately apply and remove, respectively, corrective torque to shafts of at least one of turbomachinery system 100 and turbomachinery system 200 including, without limitation, first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Rotating magnetic field through the plurality of stator magnetic field-generating elements 514 is induced when energized by the flow of electrical current thereto from at least one of power supply 124 and actuator power converter 120. Stator 506 is also configured to apply corrective torque to first shaft 106 in both a clockwise direction and a counterclockwise direction, depending on an alignment of phases of AC power transmitted to stator 506 on actuator electrical line 122 (not shown). In other embodiments, not shown, stator 506 is further configured to apply corrective torque to first shaft 106 in only one of a clockwise and a counterclockwise direction. Also, in operation, disabling the flow of electrical current to stator 506 de-energizes the plurality of stator magnetic field-generating elements 514 and removes corrective torque from first shaft 106.

In operation of this alternative embodiment, rotating magnetic field through plurality of stator magnetic field-generating elements 514 interacts electromechanically through air gap 516 with squirrel cage rotor 702 to induce a flow of electrical current through cross bars 706 and rotor rings 708, thereby inducing a magnetic field and an electromagnetic torque therein. Depending on the direction at which stator 506 rotating magnetic field rotates, at least one of a clockwise and a counterclockwise corrective torque is applied to first shaft 106 to dampen torsional oscillations thereof. An amount of corrective torque applied by radial flux machine 701 to first shaft 106 by energizing stator 506 is dictated by user-determined parameters of at least one of turbomachinery system 100 and turbomachinery system 200. User-determined parameters include, without limitation, parameters that depend on data contained in control signal 130. User-determined parameters also include, without limitation, design parameters of at least one of turbomachinery system 200, electrical machine 108, actuator power converter 120, and actuator controller 126. User-predetermined parameters further include, without limitation, a time, a magnetic flux intensity, and a magnetic field strength of an induced magnetic field including, without limitation, rotating magnetic field through the plurality of stator magnetic field-generating elements 514.

FIG. 8 is a perspective view of an alternative radial flux machine 701 actuator 118 that may be used in turbomachinery system 100 and turbomachinery system 200 shown in FIGs. 1 and 2. In this alternative exemplary embodiment, stator 506 (shown in a partial section view) of radial flux machine 701 includes at least one detachment link 402 and stator 506 is coupled to at least one of turbomachinery system 100 and turbomachinery system 200. Detachment link 402 defines at least one section of stator 506 including, without limitation, an arc segment of stator 506 annular ring. Detachment link 402 is configured to facilitate removal of stator 506 from first shaft 106 without necessitating at least one of disassembling and decoupling radial flux machine 701 from at least one of turbomachinery system 100 and turbomachinery system 200. Detachment link 402 is also configured to facilitate at least one of reassembling and recoupling stator 506 to first shaft 106 of at least one of turbomachinery system 100 and turbomachinery system 200 following user-initiated activities including, without limitation, maintenance of at least one of first shaft 106, squirrel cage rotor 702, stator 506, electrical machine 108, auxiliary machine 104, and turbomachine 102.

FIG. 9 is a cross-sectional view of an alternative actuator 118 that may be used in turbomachinery system 100 and turbomachinery system 200 shown in FIGs. 1 and 2. In this alternative embodiment, actuator 118 is embodied in squirrel cage induction motor, and actuator 118 is configured as a radial flux machine 901 including squirrel cage rotor 702 coupled to first shaft 106. Squirrel cage rotor 702 extends as a rotor cage radially outward from axis A of first shaft 106 to rotor circumference 703 of squirrel cage rotor 702. Rotor circumference 703, in this alternative embodiment, is substantially flush with shaft circumference 704, and first shaft 106 includes a slot 902 defined circumferentially therein. Squirrel cage rotor 702 is positioned in slot 902 and coupled to first shaft 106 through coupling layer 705 including, without limitation, a thermoplastic-based adhesive layer having a lower thermal conductivity than both of first shaft 106 and squirrel cage rotor 702. In other embodiments, not shown, squirrel cage rotor 702 is positioned in slot 902 and coupled to first shaft 106 by construction of squirrel cage rotor 702 piece-wise within slot 902, with slot 902 defined in first shaft 106 one of before or after installation of first shaft 106 in at least one of turbomachinery system 100 and turbomachinery system 200. In still other embodiments, not shown, squirrel cage rotor 702 is positioned in slot 902 and coupled to first shaft 106 not through coupling layer 705, but rather through coupling processes including, without limitation, welding, thermal expansion, thermal contraction, molding, and extrusion. Squirrel cage rotor 702 also includes the plurality of cross bars 706 formed of a conductive material and coupled to and extend between at least two annular rotor rings 708, as shown and described above with reference to FIGs. 7 and 8. In other embodiments, not shown, squirrel cage rotor 702 is instead embodied in the plurality of cross bars 706 formed of a ferromagnetic material, e.g., permanent magnets, positioned in slot 902 and coupled to first shaft 106 without rotor ring 708.

In operation, stator magnetic field-generating elements 514 (not shown) are coupled to at least one of actuator power converter 120, actuator controller 126, and power supply 124 (not shown). Stator 506 is an AC stator configured to induce a rotating magnetic field through the plurality of stator magnetic field-generating elements 514. Stator magnetic field-generating elements 514 are configured to alternately energize and de-energize to alternately apply and remove, respectively, corrective torque to shafts of at least one of turbomachinery system 100 and turbomachinery system 200 including, without limitation, first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104. Rotating magnetic field through the plurality of stator magnetic field-generating elements 514 is induced when energized by the flow of electrical current thereto from at least one of power supply 124 and actuator power converter 120. Stator 506 is also configured to apply corrective torque to first shaft 106 in both a clockwise direction and a counterclockwise direction, depending on an alignment of phases of AC power transmitted to stator 506 on actuator electrical line 122 (not shown). In other embodiments, not shown, stator 506 is further configured to apply corrective torque to first shaft 106 in only one of a clockwise and a counterclockwise direction. Also, in operation, disabling the flow of electrical current to stator 506 de-energizes the plurality of stator magnetic field-generating elements 514 and removes corrective torque from first shaft 106.

In operation of this alternative embodiment, rotating magnetic field through plurality of stator magnetic field-generating elements 514 interacts electromechanically through air gap 516 with squirrel cage rotor 702 to induce a flow of electrical current through cross bars 706 and rotor rings 708, thereby inducing a magnetic field and an electromagnetic torque therein. Depending on the direction at which stator 506 rotating magnetic field rotates, at least one of a clockwise and a counterclockwise corrective torque is applied to first shaft 106 to dampen torsional oscillations thereof. An amount of corrective torque applied by radial flux machine 901 to first shaft 106 by energizing stator 506 is dictated by user-determined parameters of at least one of turbomachinery system 100 and turbomachinery system 200. User-determined parameters include, without limitation, parameters that depend on data contained in control signal 130. User-determined parameters also include, without limitation, design parameters of at least one of turbomachinery system 200, electrical machine 108, actuator power converter 120, and actuator controller 126. User-predetermined parameters further include, without limitation, a time, a magnetic flux intensity, and a magnetic field strength of an induced magnetic field including, without limitation, rotating magnetic field through the plurality of stator magnetic field-generating elements 514.

FIG. 10 is a perspective view of an alternative radial flux machine 901 actuator 118 that may be used in turbomachinery system 100 and turbomachinery system 200 shown in FIGs. 1 and 2. In this alternative embodiment, stator 506 (shown in a partial section view) is coupled to at least one of turbomachinery system 100 and turbomachinery system 200. Detachment link 402 defines at least one section of stator 506 including, without limitation, an arc segment of stator 506 annular ring. Detachment link 402 is configured to facilitate removal of stator 506 from first shaft 106 without necessitating at least one of disassembling and decoupling radial flux machine 901 from at least one of turbomachinery system 100 and turbomachinery system 200. Detachment link 402 is also configured to facilitate at least one of reassembling and recoupling stator 506 to first shaft 106 of at least one of turbomachinery system 100 and turbomachinery system 200 following user-initiated activities including, without limitation, maintenance of at least one of first shaft 106, squirrel cage rotor 702, stator 506, electrical machine 108, auxiliary machine 104, and turbomachine 102.

FIG. 11 is a flowchart diagram of an exemplary method 1100 of damping torsional oscillations of a shaft in a turbomachinery system that may be used with turbomachinery system 100 and turbomachinery system 200 shown in FIGs. 1 and 2. Referring to FIGs. 1-10, method 1100 includes detecting 1102, through sensor 128 coupled to at least one of turbomachinery system 100 and turbomachinery system 200, a physical characteristic of at least one of turbomachinery system 100 and turbomachinery system 200 representative of torsional oscillations. Method 1100 also includes determining 1104, through data transmitted by sensor 128, a presence of torsional oscillations. Method 1100 further includes energizing 1106 at least one of stator 310 and stator 506 of actuator 118 to apply a corrective torque to at least one of first shaft 106, second shaft 110, and additional shafts rotatably coupled to at least one of turbomachine 102, electrical machine 108, and auxiliary machine 104, to dampen torsional oscillations thereof.

The above-described electrical actuator devices for reduction of torsional oscillations in turbomachinery systems and associated systems and methods reduce SSTIs of shafts and rotating machinery including electrical machines in rotating equipment trains. The above-described embodiments also mitigate undesirable effects of SSTIs and aberrant torques arising therefrom in turbomachinery systems. The above-described embodiments further reduce torque imbalances in electrical machines employed in turbomachinery systems. The above-described electrical actuator devices for reduction of torsional oscillations in turbomachinery systems and associated control systems and methods also reduce operating and maintenance costs and increase operational efficiency of turbomachinery systems. The above-described embodiments further provide less complex and less expensive SSTI mitigation devices, systems, and methods that are easier to operate and integrate into existing plant designs. The above-described embodiments also enable installation and maintenance of SSTI mitigation devices and systems without shutting down turbomachinery system operations.

An exemplary technical effect of the above-described electrical actuator devices for reduction of torsional oscillations in turbomachinery systems and associated systems and methods includes at least one of the following: (a) reducing SSTIs of shafts and rotating machinery including electrical machines in rotating equipment trains; (b) mitigating undesirable effects of SSTIs and aberrant torques arising therefrom in turbomachinery systems; (c) reducing torque imbalances in electrical machines employed in turbomachinery systems; (d) reducing operating and maintenance costs and increasing operational efficiency of turbomachinery systems; (e) providing less complex and less expensive SSTI mitigation devices, systems, and methods that are easier to operate and integrate into existing plant designs; and (f) enabling installation and maintenance of SSTI mitigation devices and systems without shutting down turbomachinery system operations.

Exemplary embodiments of electrical actuator devices for reduction of torsional oscillations in turbomachinery systems and associated systems and methods are not limited to the specific embodiments described herein, but rather, components of systems and/or steps of the methods may be utilized independently and separately from other components and/or steps described herein. For example, the methods, systems, and apparatus may also be used in combination with other systems requiring reduction of torsional oscillations of shafts and rotating machinery coupled thereto including, without limitation, rotating machinery trains not including electrical machines, and the associated methods are not limited to practice with only the systems and methods as described herein. Rather, the exemplary embodiments can be implemented and utilized in connection with many other applications, equipment, and systems that may benefit from using the above-described embodiments electrical actuator devices for reduction of torsional oscillations and associated systems and methods to improve the effectiveness and efficiency of operation for rotating machinery trains and other related systems in various applications.

Although specific features of various embodiments of the disclosure may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the disclosure, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

Some embodiments involve the use of one or more electronic or computing devices. Such devices typically include a processor, processing device, or controller, such as a general purpose central processing unit (CPU), a graphics processing unit (GPU), a microcontroller, a reduced instruction set computer (RISC) processor, an application specific integrated circuit (ASIC), a programmable logic circuit (PLC), a field programmable gate array (FPGA), a digital signal processing (DSP) device, and/or any other circuit or processing device capable of executing the functions described herein. The methods described herein may be encoded as executable instructions embodied in a computer-readable medium, including, without limitation, a storage device and/or a memory device. Such instructions, when executed by a processing device, cause the processing device to perform at least a portion of the methods described herein. The above examples are exemplary only, and thus are not intended to limit in any way the definition and/or meaning of the term processor and processing device.

This written description uses examples to disclose the embodiments, including the best mode, and also to enable any person skilled in the art to practice the embodiments, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

CLAIMS:

1. An actuator for a turbomachinery system that includes a turbomachine and an electrical machine coupled to the turbomachine by a shaft extending therebetween, said actuator comprising:

a rotor coupled to the shaft and comprising a plurality of rotor magnetic field-generating elements; and

a stator configured to receive at least a portion of the shaft proximate said rotor, said stator comprising a plurality of stator magnetic field-generating elements proximate said plurality of rotor magnetic field-generating elements, said plurality of stator magnetic field-generating elements configured to alternately energize and de-energize to alternately apply and remove, respectively, a corrective torque to the shaft to dampen torsional oscillations thereof.

2. The actuator in accordance with Claim 1, wherein:

said rotor further comprises a rotor disk having a rotor circumference, a first rotor side, and a second rotor side opposite the first rotor side, each of the first rotor side and the second rotor side extending radially outward from the shaft to the rotor circumference, said plurality of rotor magnetic field-generating elements coupled to the first rotor side with a predetermined spacing therebetween; and

said stator defines a cavity, said stator further configured to receive the at least a portion of the shaft through the cavity, said stator further comprising a stator disk having a stator circumference, a first stator side, and a second stator side opposite the first stator side, each of the first stator side and the second stator side extending radially inward from the stator circumference to the cavity, said plurality of stator magnetic field-generating elements coupled to the second stator side, the second stator side positioned proximate the first rotor side to define an air gap between said plurality of rotor magnetic-field generating elements and said plurality of stator magnetic field-generating elements.

3. The actuator in accordance with Claim 1 or Claim 2, wherein:

said rotor further comprises a rotor disk having a rotor circumference, said plurality of rotor magnetic field-generating elements positioned along the rotor circumference with a predetermined spacing therebetween; and

said stator defines a cavity, said stator further configured to receive the at least a portion of the shaft through the cavity, said stator further comprising an annular ring having a stator circumference and an inner radius, said plurality of stator magnetic field-generating elements positioned along the inner radius with a predetermined spacing therebetween, said stator positioned proximate said rotor to define an air gap between said plurality of rotor magnetic-field generating elements and said plurality of stator magnetic field-generating elements.

4. The actuator in accordance with any preceding Claim, wherein:

said rotor further comprises at least two annular rotor rings coupled circumferentially to the shaft, said plurality of rotor magnetic field-generating elements coupled to said at least two rotor rings and extending axially therebetween proximate the shaft; and

said stator defines a cavity, said stator further configured to receive the at least a portion of the shaft through the cavity, said stator further comprising an annular ring having a stator circumference and an inner radius, said plurality of stator magnetic field-generating elements positioned along the inner radius with a predetermined spacing therebetween, said stator positioned proximate said rotor to define an air gap between said plurality of rotor magnetic-field generating elements and said plurality of stator magnetic field-generating elements.

5. The actuator in accordance with any preceding Claim, wherein:

the shaft has a shaft circumference and includes a slot defined circumferentially therein; and

said rotor is positioned in said slot substantially flush with the shaft circumference.

6. The actuator in accordance with any preceding Claim, further comprising a coupling layer having a lower thermal conductivity than both of said rotor and the shaft, said coupling layer positioned between the shaft and at least one of said at least two rotor rings and said plurality of rotor magnetic-field generating elements, said rotor coupled to the shaft through said coupling layer.

7. The actuator in accordance with any preceding Claim, wherein said plurality of rotor magnetic field-generating elements comprises a plurality of permanent magnets.

8. The actuator in accordance with any preceding Claim, wherein said stator further comprises an alternating current stator configured to induce a rotating magnetic field through said plurality of stator magnetic field-generating elements.

9. A turbomachinery system comprising:

a turbomachine;

an electrical machine;

a shaft coupled to said electrical machine and coupled to said turbomachine and extending therebetween; and

an actuator comprising:

a rotor coupled to said shaft and comprising a plurality of rotor magnetic field-generating elements; and a stator configured to receive at least a portion of said shaft proximate said rotor, said stator comprising a plurality of stator magnetic field-generating elements proximate said plurality of rotor magnetic field-generating elements, said plurality of stator magnetic field-generating elements configured to alternately energize and de-energize to alternately apply and remove, respectively, a corrective torque to said shaft to dampen torsional oscillations thereof.

10. The turbomachinery system in accordance with Claim 9, wherein:

said rotor further comprises a rotor disk having a rotor circumference, a first rotor side, and a second rotor side opposite the first rotor side, each of the first rotor side and the second rotor side extending radially outward from said shaft to the rotor circumference, said plurality of rotor magnetic field-generating elements coupled to the first rotor side with a predetermined spacing therebetween; and

said stator defines a cavity, said stator further configured to receive said at least a portion of said shaft through the cavity, said stator further comprising a stator disk having a stator circumference, a first stator side, and a second stator side opposite the first stator side, each of the first stator side and the second stator side extending radially inward from the stator circumference to the cavity, said plurality of stator magnetic field-generating elements coupled to the second stator side, the second stator side positioned proximate the first rotor side to define an air gap between said plurality of rotor magnetic-field generating elements and said plurality of stator magnetic field-generating elements.

11. The turbomachinery system in accordance with Claim 9 or Claim 10, wherein:

said rotor further comprises a rotor disk having a rotor circumference, said plurality of rotor magnetic field-generating elements positioned along the rotor circumference with a predetermined spacing therebetween; and

said stator defines a cavity, said stator further configured to receive said at least a portion of said shaft through the cavity, said stator further comprising an annular ring having a stator circumference and an inner radius, said plurality of stator magnetic field-generating elements positioned along the inner radius with a predetermined spacing therebetween, said stator positioned proximate said rotor to define an air gap between said plurality of rotor magnetic-field generating elements and said plurality of stator magnetic field-generating elements.

12. The turbomachinery system in accordance with any of Claims 9 to 11, wherein:

said rotor further comprises at least two annular rotor rings coupled circumferentially to said shaft, said plurality of rotor magnetic field-generating elements coupled to said at least two rotor rings and extending axially therebetween proximate said shaft; and

said stator defines a cavity, said stator further configured to receive said at least a portion of said shaft through the cavity, said stator further comprising an annular ring having a stator circumference and an inner radius, said plurality of stator magnetic field-generating elements positioned along the inner radius with a predetermined spacing therebetween, said stator positioned proximate said rotor to define an air gap between said plurality of rotor magnetic-field generating elements and said plurality of stator magnetic field-generating elements.

13. The turbomachinery system in accordance with any of Claims 9 to 12, wherein:

said shaft has a shaft circumference and includes a slot defined circumferentially therein; and

said rotor is positioned in said slot substantially flush with the shaft circumference.

14. The turbomachinery system in accordance with any of Claims 9 to 13, further comprising a coupling layer having a lower thermal conductivity than both of said rotor and said shaft, said coupling layer positioned between said shaft and at least one of said at

least two rotor rings and said plurality of rotor magnetic-field generating elements, said rotor coupled to said shaft through said coupling layer.

15. The turbomachinery system in accordance with any of Claims 9 to 14, wherein said plurality of rotor magnetic field-generating elements comprises a plurality of permanent magnets.

16. The turbomachinery system in accordance with any of Claims 9 to 15, wherein said stator is coupled to said turbomachinery system.

17. The turbomachinery system in accordance with any of Claims 9 to 16, wherein said stator further comprises a detachment link configured to facilitate removal of said stator from said shaft.

18. The turbomachinery system in accordance with any of Claims 9 to 17, further comprising a power supply coupled to said plurality of stator magnetic-field generating elements, said stator further comprising an alternating current (AC) stator configured to induce a rotating magnetic field through said plurality of stator magnetic field-generating elements.

19. The turbomachinery system in accordance with any of Claims 9 to 18, further comprising an actuator power converter coupled to said power supply and said actuator.

20. The turbomachinery system in accordance with any of Claims 9 to 19, further comprising:

an actuator controller coupled to said actuator; and

a sensor coupled to said actuator controller, said sensor configured to detect a physical characteristic of said turbomachinery system representative of torsional oscillations and transmit a control signal to said actuator controller to alternately apply and remove the corrective torque to said shaft through said actuator, wherein said sensor is further coupled to at least one of said turbomachine, said electrical machine, and said shaft.

21. The turbomachinery system in accordance with any of Claims 9 to 20, wherein said electrical machine comprises at least one of a motor and a generator.

22. The turbomachinery system in accordance with any of Claims 9 to 21, wherein said rotor is coupled to said shaft proximate said electrical machine.

23. The turbomachinery system in accordance with any of Claims 9 to 22, further comprising:

an auxiliary machine;

a plurality of shafts coupled to said electrical machine, said turbomachine, and said auxiliary machine; and

a plurality of actuators coupled to at least two said shafts of said plurality of shafts.

24. The turbomachinery system in accordance with any of Claims 9 to 23, further comprising:

an auxiliary machine;

a plurality of shafts coupled to said electrical machine, said turbomachine, and said auxiliary machine;

a plurality of actuators coupled to at least two said shafts of said plurality of shafts;

a plurality of actuator controllers, each said actuator controller of said plurality of actuator controllers coupled to a respective actuator of said plurality of actuators; and a plurality of sensors coupled to said plurality of actuator controllers, wherein said respective actuator is controlled by a respective actuator controller of said plurality of actuator controllers.

25. A method of damping torsional oscillations of a shaft in a turbomachinery system that includes an electrical machine coupled to a turbomachine by the shaft extending therebetween and an actuator including a stator and a rotor coupled to the shaft proximate the stator, said method comprising:

detecting, through a sensor coupled to the turbomachinery system, a physical characteristic of the turbomachinery system representative of torsional oscillations;

determining, through data transmitted by the sensor, a presence of torsional oscillations; and

energizing the stator of the actuator to apply a corrective torque to the shaft to dampen torsional oscillations thereof.

26. The method in accordance with Claim 25, wherein:

determining a presence of torsional oscillations comprises:

receiving, at an actuator controller coupled to the actuator, the data as a control signal; and

comparing a value of the data with a predetermined set point value indicative of the presence of torsional oscillations; and

energizing the stator of the actuator comprises:

energizing the stator when the value of the data is indicative of the presence of torsional oscillations.

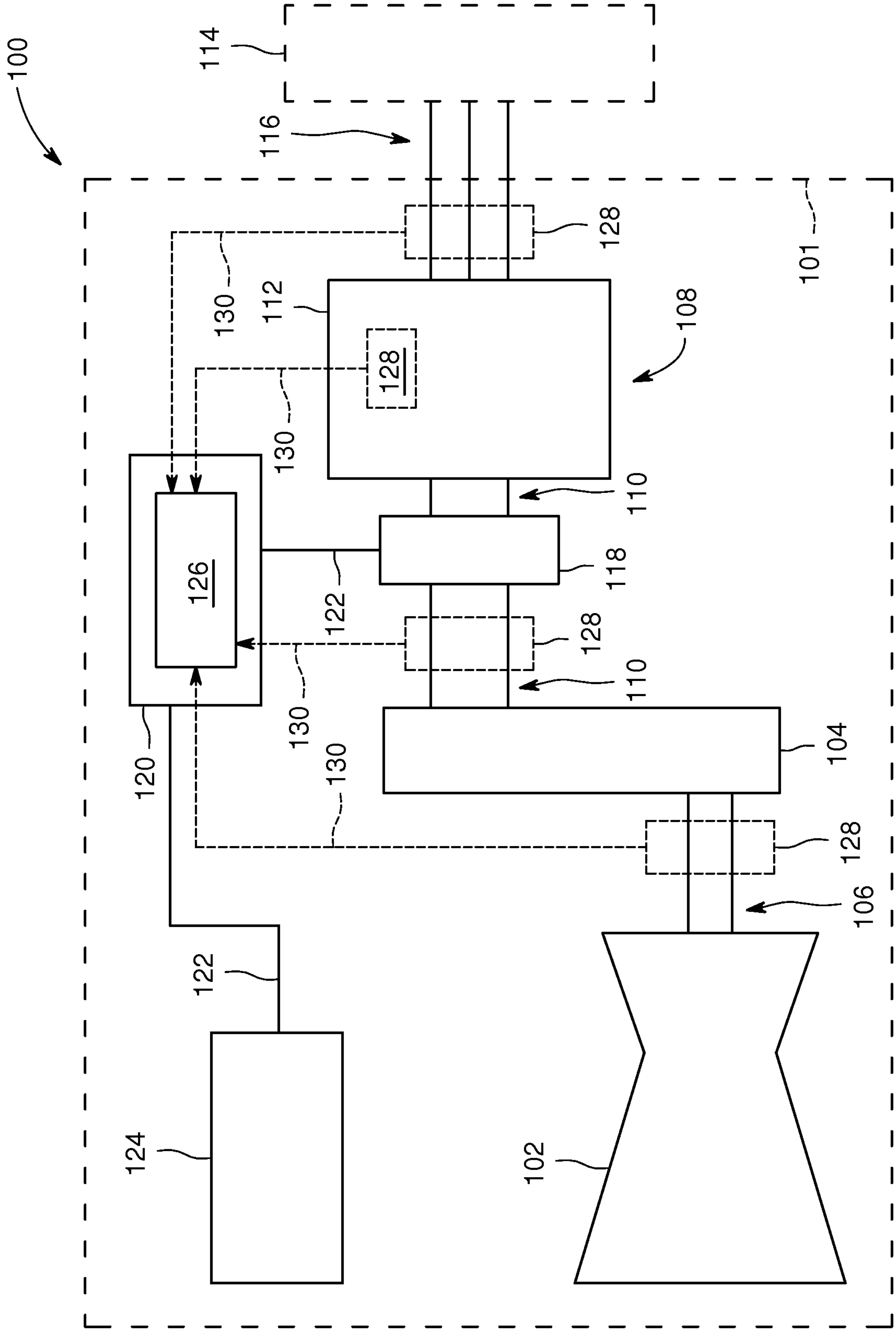
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FIG. 1

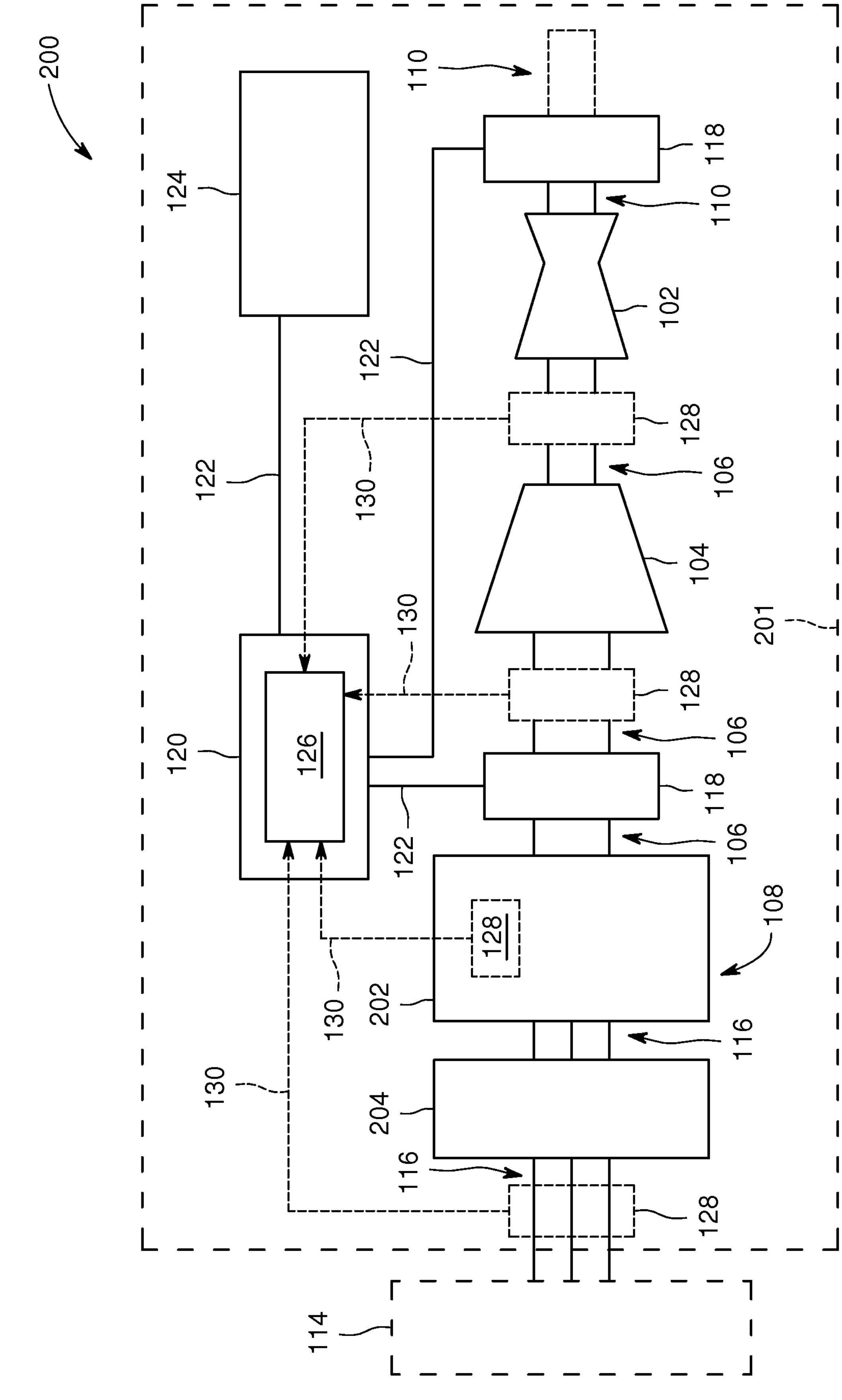
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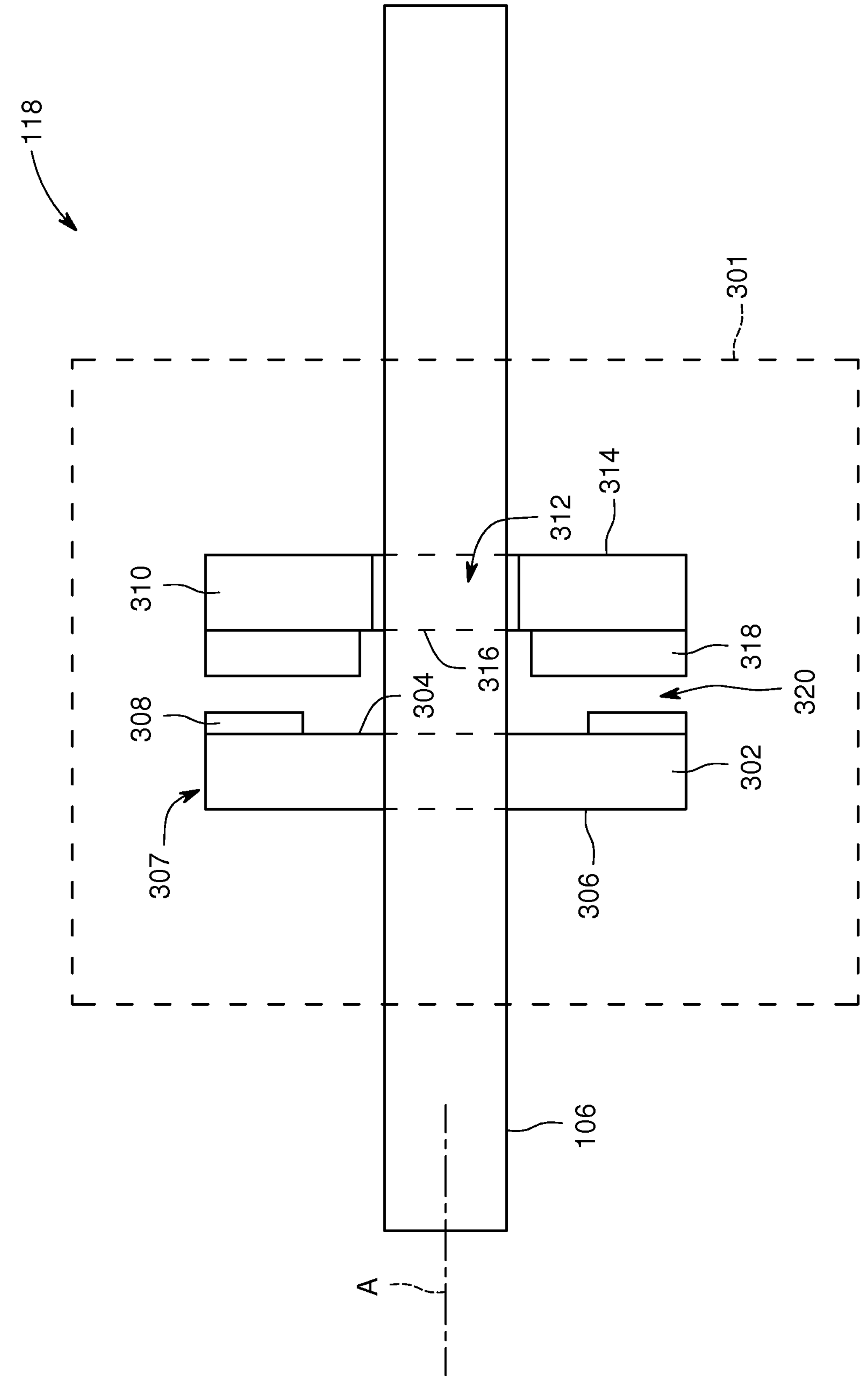
FIG. 2



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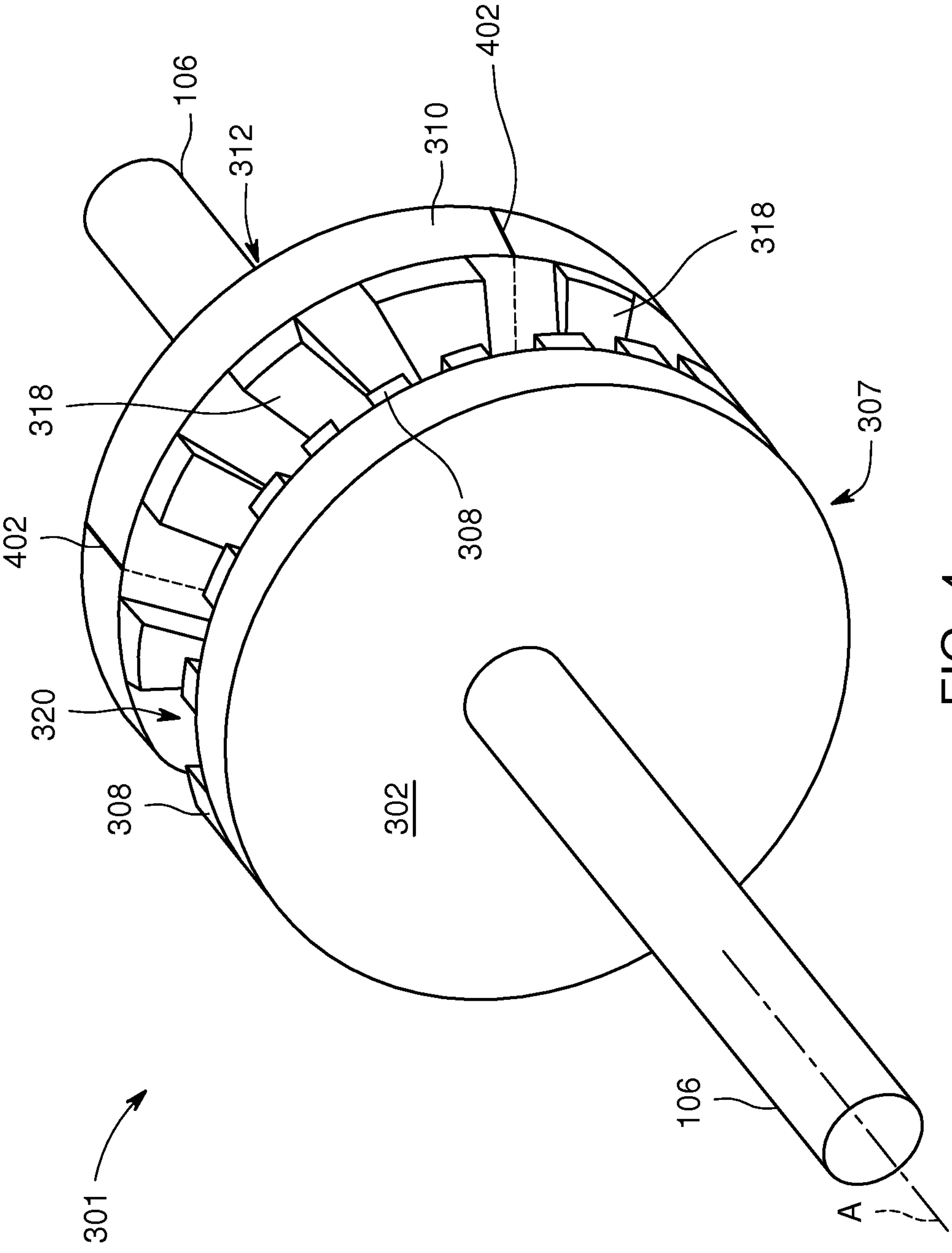

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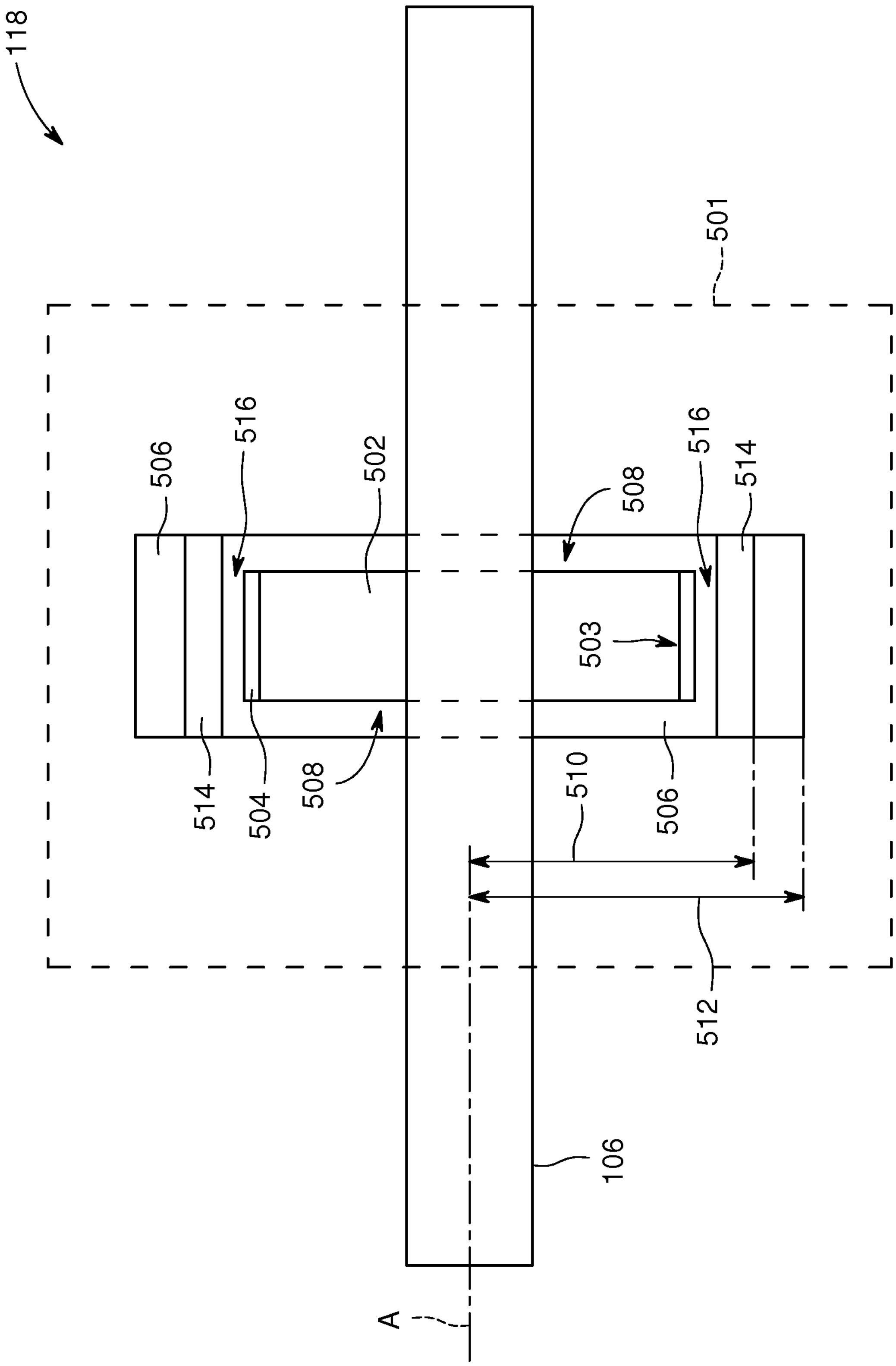

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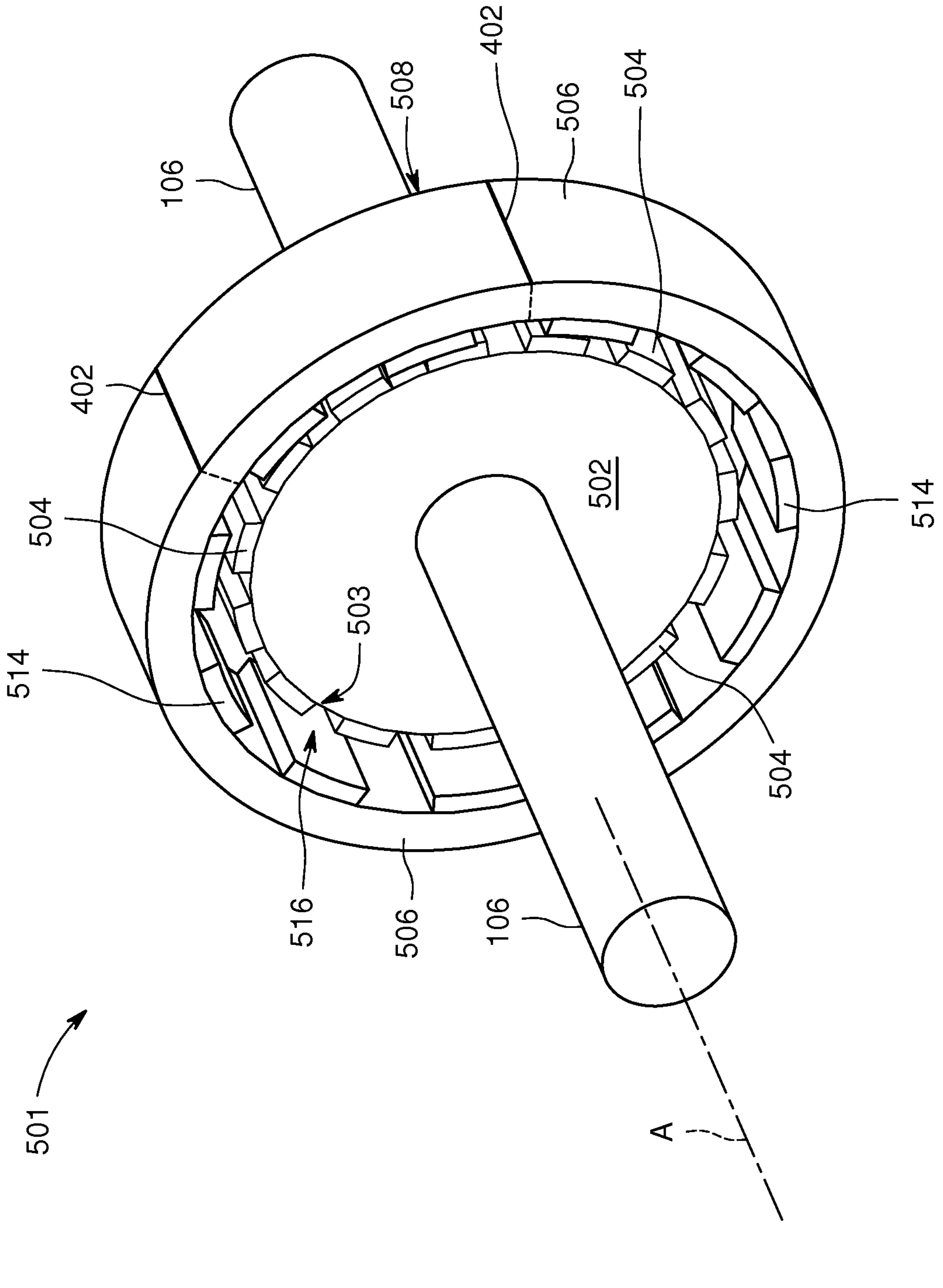

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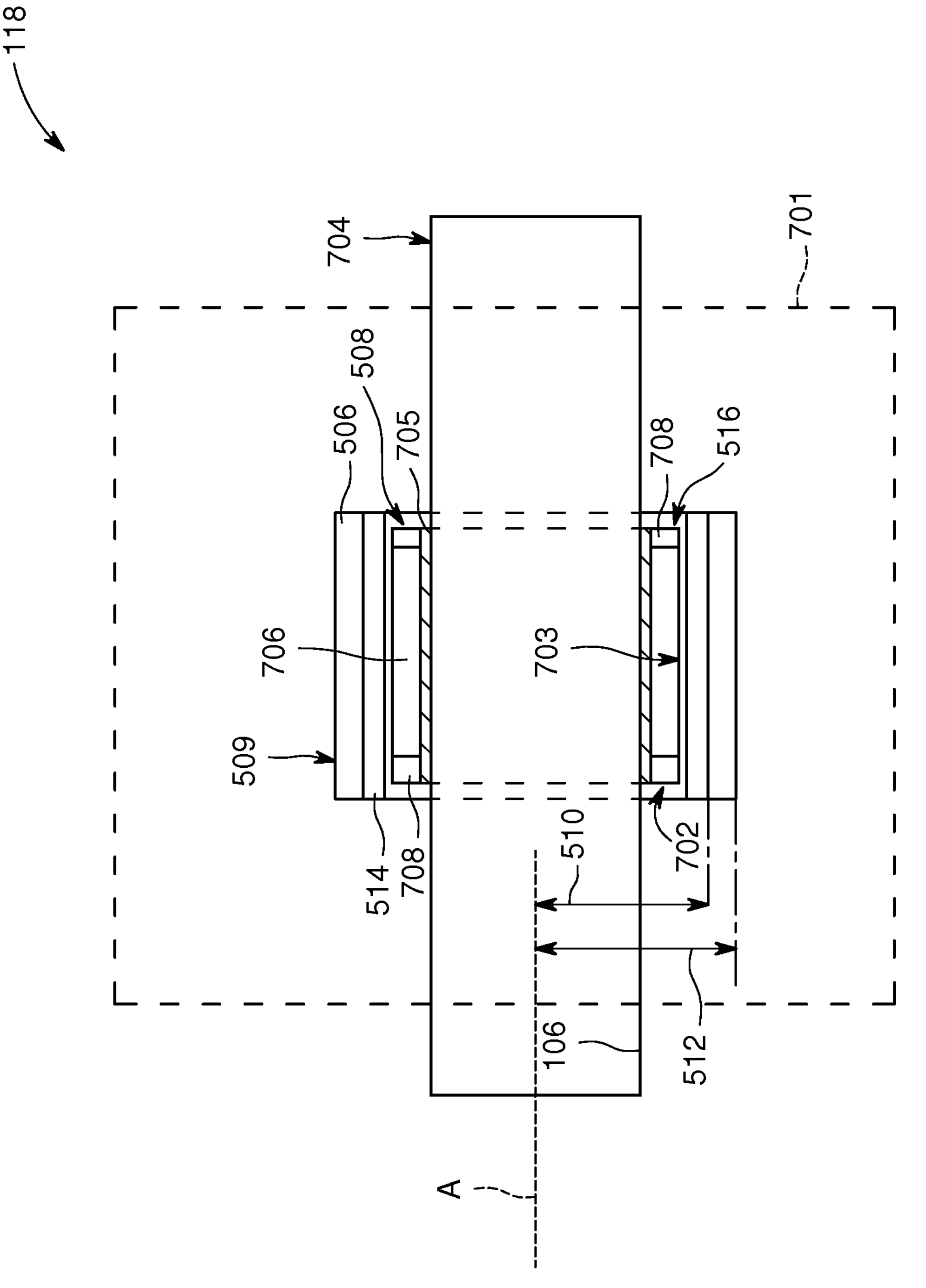
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FIG. 7

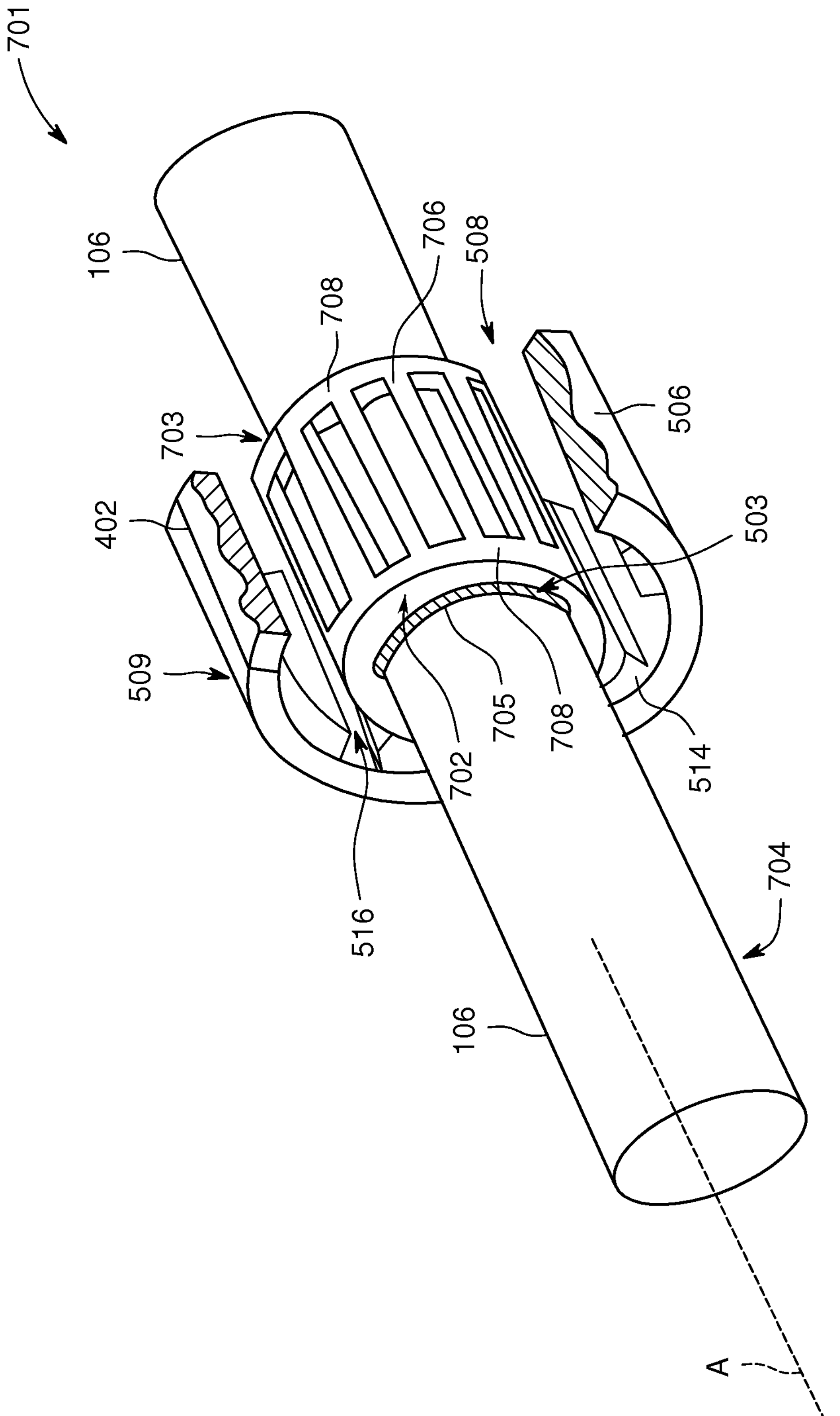
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FIG. 8

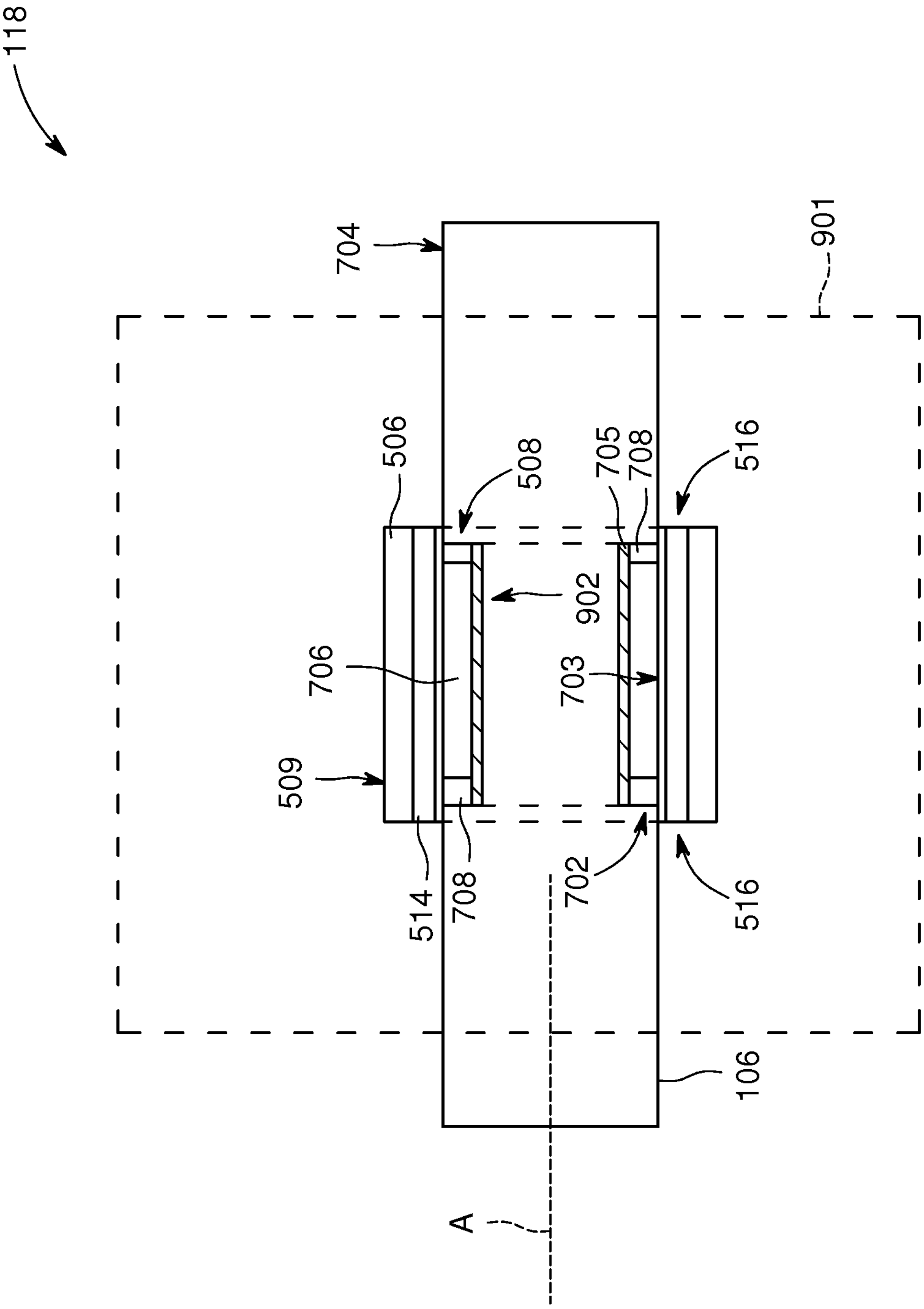
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FIG. 9

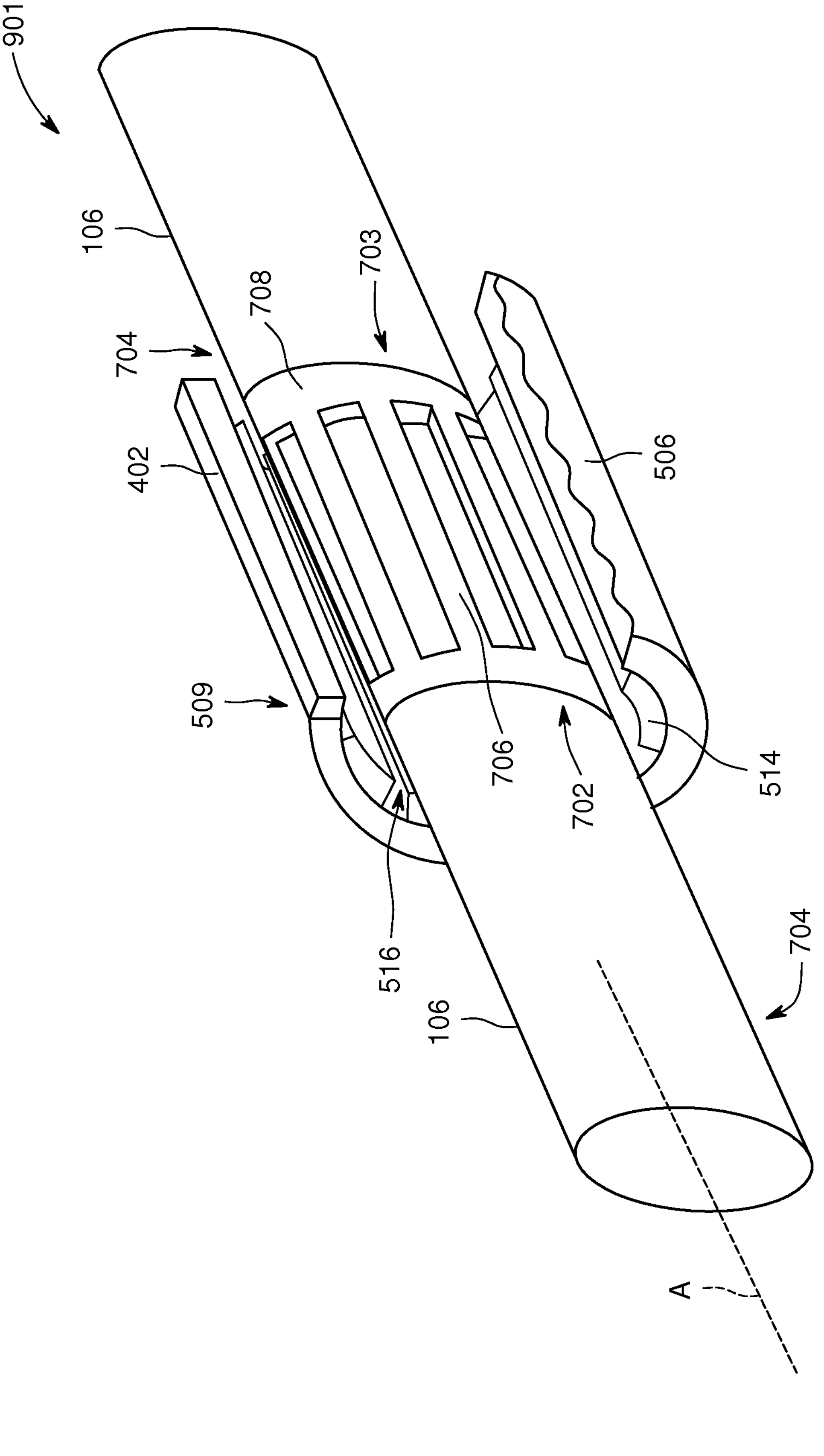
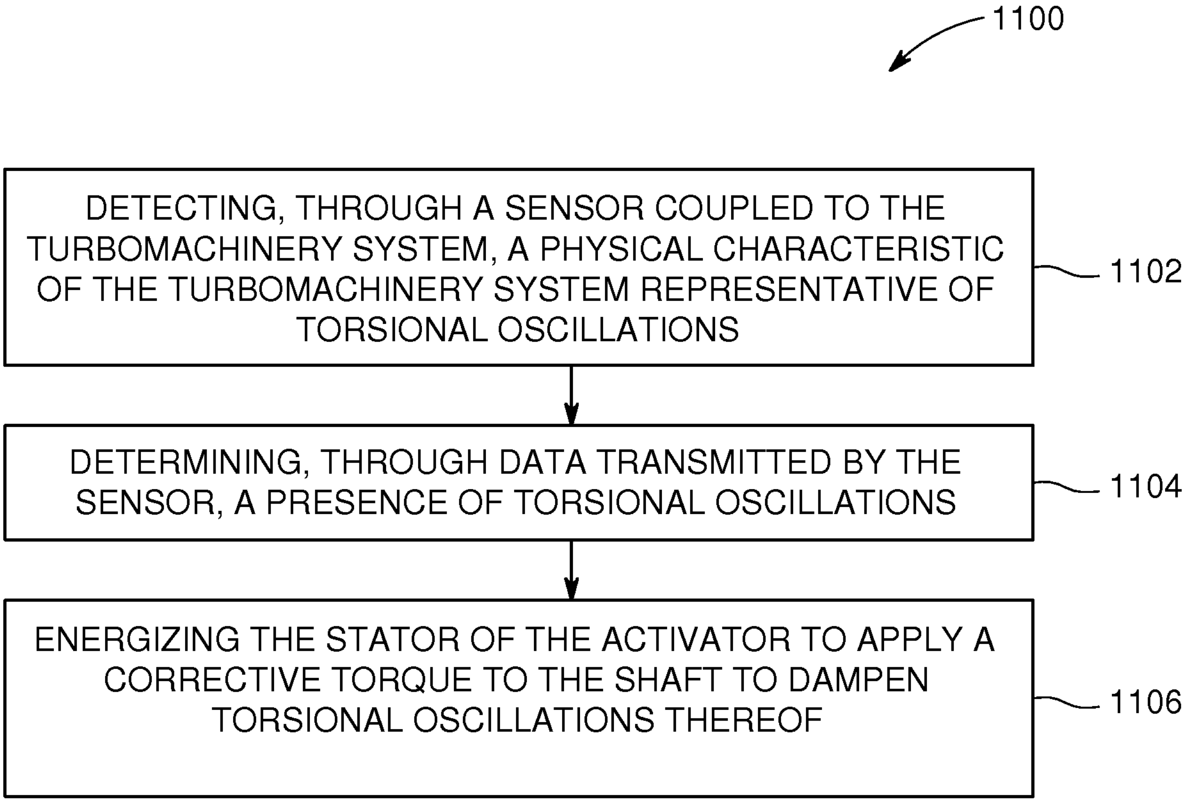


FIG. 10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DETECTING, THROUGH A SENSOR COUPLED TO THE TURBOMACHINERY SYSTEM, A PHYSICAL CHARACTERISTIC OF THE TURBOMACHINERY SYSTEM REPRESENTATIVE OF TORSIONAL OSCILLATIONS
1102
DETERMINING, THROUGH DATA TRANSMITTED BY THE SENSOR, A PRESENCE OF TORSIONAL OSCILLATIONS
1104
ENERGIZING THE STATOR OF THE ACTIVATOR TO APPLY A CORRECTIVE TORQUE TO THE SHAFT TO DAMPEN TORSIONAL OSCILLATIONS THEREOF
1106

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/064210

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02K7/20 F16F15/00 H02P9/00
ADD.

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 F16F H02P

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.
A	WO 2004/112234 A1 (MAX PLANCK GESELLSCHAFT [DE]; SIHLER CHRISTOF [DE]) 23 December 2004 (2004-12-23) page 1, line 13 - line 30 page 4, line 32 - page 5, line 2 page 6, line 8 - line 17 page 8, line 30 - page 9, line 5 page 13, line 1 - line 6 -----	1-26
A	EP 1 643 122 A2 (GEN ELECTRIC [US]) 5 April 2006 (2006-04-05) abstract paragraphs [0018], [0019] -----	1-26
A	DE 196 14 470 A1 (OSER ERWIN DR [DE]) 16 October 1997 (1997-10-16) column 2, line 18 - line 36 claims 1-3 page 1; figure 1 -----	1-26

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

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
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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	Date of mailing of the international search report
19 October 2016	27/10/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Maas, Erik

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2016/064210

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