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(71) Applicant (for all designated States except US): **SMITH INTERNATIONAL, INC.** [US/US]; 1310 Rankin Rd., Houston, TX 77073 (US).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **MOORE, Robert, Anthony** [US/US]; 3234 Canvasback Dr., Katy, TX 77493 (US).

(74) Agent: **STEINHEIDER, Matthew, F.**; Smith International, Inc., 1310 Rankin Rd., Houston, TX 77073 (US).

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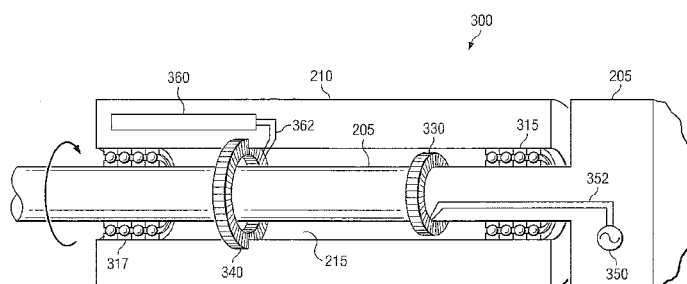


FIG. 3

(57) Abstract: A downhole tool includes a non-contact, electrical coupling device configured to transmit electrical power and/or data between relatively rotating components. In one embodiment, the coupling device includes at least first and second wound toroidal cores deployed about a shaft. At least one of the wound toroidal cores is rotationally fixed to the shaft, while at least one other is rotationally fixed to a housing in which the shaft is deployed. The shaft forms a portion of a conductive loop that extends through the toroids. A non-contact electrical pathway is advantageously provided for high power electrical transmission and/or high speed data transmission across a gap between first and second rotating members of a downhole assembly.



APPARATUS FOR ELECTRICAL POWER AND/OR DATA TRANSFER BETWEEN ROTATING COMPONENTS IN A DRILL STRING

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RELATED APPLICATIONS

This application claims priority to the filing date of U.S. Patent Application Serial Number 12/399,496, filed March 6, 2009.

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FIELD OF THE INVENTION

The present invention relates generally to downhole tools having rotating components, for example, including directional drilling tools such as a steering tool or a mud motor. More particularly, embodiments of this invention relate to a downhole assembly including a non-contact apparatus for transmitting electrical power and/or data between first and second members
15 of the assembly that are disposed to rotate with respect to one another (such as a shaft rotating in a housing).

BACKGROUND OF THE INVENTION

As is well-known in the industry, hydrocarbons are recovered from subterranean reservoirs by drilling a borehole (wellbore) into the reservoir. Such boreholes are commonly
20 drilled using a rotating drill bit attached to the bottom of a drilling assembly (which is commonly referred to in the art as a bottom hole assembly or a BHA). The drilling assembly is commonly connected to the lower end of a drill string including a long string of sections (joints) of drill pipe that are connected end-to-end via threaded pipe connections. The drill bit, deployed at the lower end of the BHA, is commonly rotated by rotating the drill string from the surface and/or by a
25 mud motor deployed in the BHA. Mud motors are also commonly utilized with flexible, spoolable tubing referred to in the art as coiled tubing. During drilling a drilling fluid (referred to in the art as mud) is pumped downward through the drill string (or coiled tubing) to provide

lubrication and cooling of the drill bit. The drilling fluid exits the drilling assembly through ports located in the drill bit and travels upward, carrying debris and cuttings, through the annular region between the drilling assembly and borehole wall.

In recent years, directional control of the borehole has become increasingly important in the drilling of subterranean oil and gas wells, with a significant proportion of current drilling activity involving the drilling of deviated boreholes. Such deviated boreholes often have complex profiles, including multiple doglegs and a horizontal section that may be guided through thin, fault bearing strata, and are typically utilized to more fully exploit hydrocarbon reservoirs. Deviated boreholes are often drilled using downhole steering tools, such as two-dimensional and three-dimensional rotary steerable tools. Certain rotary steerable tools include a plurality of independently operable blades (or force application members) that are disposed to extend radially outward from a tool housing into contact with the borehole wall. The direction of drilling may be controlled, for example, by controlling the magnitude and direction of the force or the magnitude and direction of the displacement applied to the borehole wall. In such rotary steerable tools, the blade housing is typically deployed about a rotatable shaft, which is coupled to the drill string and disposed to transfer weight and torque from the surface (or from a mud motor) through the steering tool to the drill bit assembly. Other rotary steerable tools are known that utilize an internal steering mechanism and therefore don't require blades (e.g., the Schlumberger PowerDrive rotary steerable tools).

Directional wells are also commonly drilled by causing a mud motor power section to rotate the drill bit through a displaced axis while the drill string remains stationary (non-rotating). The displaced axis may be achieved, for example, via a bent sub deployed above the mud motor or alternatively via a mud motor having a bent outer housing. The bent sub or bent motor housing cause the direction of drilling to deviate (turn), resulting in a well section having a predetermined curvature (dogleg severity) in the direction of the bend. A drive shaft assembly

deployed below the power section transmits downward force and power (rotary torque) from the drill string and power section through a bearing assembly to the drill bit. Common drive shaft assemblies include a coaxial shaft (mandrel) deployed to rotate in a housing.

The non-rotating sections (e.g., the above described housings) commonly include MWD
5 and/or LWD sensors, electronic components and controllers, and electrical actuators (e.g., solenoid actuated valves and switches used to control steering blades). In the above described drilling assemblies a gap typically exists between the rotating and non-rotating sections (e.g., between the shaft and housing). Thus electrical power must be stored and/or generated in the non-rotating section or transferred across the gap from the rotating section to the non-rotating
10 section. Moreover, in order to provide electronic communication between the rotating and non-rotating sections, data must also be transferred back and forth across the gap.

Techniques for transmitting electrical power and electronic data across the gap between rotating and non-rotating tool sections are known in the art. For example, sealed slip rings are sometimes utilized. While slip rings have been used commercially, failure of certain slip ring
15 components is a known cause of downhole tool failure. For example, slip ring seals have been known to fail, which can result in a loss of communication with the tool and the need to trip out of the borehole. Loss of electrical contact between the slip ring contact members (e.g., due to wear) is also a known cause of tool failure. The electrical performance of slip rings is also susceptible to both long term and short term degradation when exposed to oil. Furthermore,
20 when used with heavier grade lubricating oils, liftoff of the contacts may occur. Interruption of the electrical current can then cause burning of the oil and contamination to the contacts. Slip ring assemblies can also be difficult to assemble between a shaft and sleeve.

Inductive coupling devices are also known for transferring power and/or data between rotating and non rotating tool sections. For example, U.S. Patent 6,540,032 to Krueger discloses
25 an inductive coupling for transferring power and data between rotating and non-rotating sections

of a downhole drilling assembly. While inductive coupling devices are known in commercial oilfield applications, there remains a need for improved devices for non-contact transmission of data and electrical power between tool sections. For example, inductive couplings are known to be highly sensitive to the spacing between the transmitter and receiver (i.e., the clearance
5 between the shaft and sleeve). In rotary steerable deployments, inductive couplings tend to exhibit low transmission efficiencies owing to the relatively large gap between the shaft and the blade housing. Owing to the demand for smaller diameter and less expensive rotary steerable tools (and downhole tools in general) and to the increased demand for electrical power in such tools, there is a need for improved non-contact power and/or data transmission devices.

10 It is therefore desirable to provide an improved arrangement which addresses the above described problems and/or which more generally offers improvements or an alternative to existing arrangements.

SUMMARY OF THE INVENTION

According to the present invention there is therefore provided a downhole tool as
15 described in the accompanying claims.

The present invention addresses the need for improved non-contact power and data transmission devices in downhole tools including downhole drilling assemblies. Aspects of this invention include a non-contact electrical coupling device suitable for transmitting electrical power and/or data across a gap between rotating components in a downhole tool. Exemplary
20 embodiments of the invention include at least first and second wound toroidal cores deployed about a shaft. At least one of the wound toroidal cores is rotationally fixed to the shaft, while at least another is rotationally fixed to a housing deployed about the shaft. The shaft forms a portion of a conductive loop that extends through the toroids. The invention may be thought of as including first and second transformers that share a single turn winding (the conductive loop).

25 The first wound toroidal core forms the primary of the first transformer. The conductive loop

forms a single-turn secondary of the first transformer and a single-turn primary of the second transformer. The second wound toroidal core forms the secondary of the second transformer. Aspects of the invention typically further include electronic control circuitry for transmitting and receiving the electrical power and/or data.

5 Exemplary embodiments of the present invention may advantageously provide several technical advantages. For example, exemplary embodiments of this invention provide a non-contact, high-power electrical transmission path and a high-speed data communication channel across a gap between first and second rotating members of a downhole assembly. Moreover, exemplary embodiments of the invention also provide for simultaneous non-contact transmission
10 of electrical power between the first and second tool members.

Exemplary embodiments of the invention may be advantageously configured for high-power and high-efficiency electrical transmission (especially as compared with conventional inductive coupling devices). Moreover, the invention does not utilize a magnetic field to transmit electrical energy across an air gap (as with prior art inductive couplings). Those of
15 ordinary skill in the art will appreciate that the presence of the air gap in an inductive coupling reduces the effective magnetic permeability of the magnetic path, which can significantly reduce the overall efficiency of the coupling. The invention utilizes the afore-mentioned low impedance conductive loop to transmit electrical energy between the rotating components and is therefore advantageously unaffected by the clearance (the size of the gap) between the rotating
20 components (e.g., between the shaft and housing on a rotary steerable tool) or between similar parts of a rotary transformer.

In one aspect the present invention includes a downhole tool. The downhole tool includes a shaft deployed in a housing and configured to rotate with respect to the housing. The downhole tool further includes a non-contact electrical coupling device configured to transmit an
25 electrical signal between the shaft and the housing. The electrical coupling device includes at

least first and second axially spaced wound toroidal cores deployed about the shaft. The first wound toroidal core is rotationally coupled with the shaft and the second wound toroidal core is rotationally coupled with the housing.

In another aspect the invention includes a downhole tool. The tool includes a shaft
5 deployed in a housing, the shaft disposed to rotate with respect to the housing. The tool further includes first and second transformers sharing a single-turn conductive loop. At least a first wound toroidal core forms a primary of the first transformer, the first wound toroidal core being deployed about the shaft and rotationally coupled with the shaft. At least a second wound toroidal core forms a secondary of the second transformer, the second wound toroidal core being
10 deployed about the shaft and rotationally coupled with the housing. The second wound toroidal core is axially spaced from the first wound toroidal core. The conductive loop forms both a single-turn secondary of the first transformer and a single-turn primary of the second transformer. The conductive loop includes a portion of the shaft that extends through central windows of the first and second wound toroidal cores.

15 In still another aspect the present invention includes a downhole tool having a shaft deployed in a housing and configured to rotate with respect to the housing. The shaft is supported in the housing by at least first and second longitudinally spaced bearings. A non-contact electrical coupling device is configured to transmit an electrical signal between the shaft and the housing. The electrical coupling device includes first and second longitudinally spaced
20 sets of wound toroidal cores deployed about the shaft and between the first and second bearings. Each of the sets includes a plurality of longitudinally spaced wound toroidal cores, the first set of wound toroidal cores being rotationally coupled with the shaft and the second set of wound toroidal cores being rotationally coupled with the housing. The shaft, the first bearing, the housing, and the second bearing, in combination, form a conductive loop that passes through a
25 central window of each of the wound toroidal cores.

In yet another aspect the present invention includes a rotary steerable tool having a shaft deployed in a steering tool housing and configured to rotate with respect to the housing. The shaft is supported in the housing by at least first and second longitudinally spaced bearings. A plurality of blades are deployed on the housing and disposed to extend radially outward from the housing and engage a wall of a borehole. Engagement of the blades with the borehole wall is operative to eccentric the housing in the borehole. A non-contact electrical coupling device is configured to transmit electrical power from the shaft to the housing. The electrical coupling device includes first and second longitudinally spaced sets of wound toroidal cores deployed about the shaft and between the first and second bearings. Each of the sets includes a plurality of longitudinally spaced wound toroidal cores, the first set of wound toroidal cores being rotationally coupled with the shaft and the second set of wound toroidal cores being rotationally coupled with the housing. The shaft, the first and second bearings, and the housing in combination forming a conductive loop that passes through a central window of each of the wound toroidal cores.

The foregoing has outlined rather broadly the features of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and the specific embodiments disclosed may be readily utilized as a basis for modifying or designing other methods, structures, and encoding schemes for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIGURE 1 depicts a drilling rig on which exemplary embodiments of the present invention may be deployed.

FIGURE 2 is a perspective view of one exemplary embodiment of the steering tool shown on FIGURE 1.

FIGURE 3 depict a longitudinal cross section of an exemplary embodiment of a non-contact electrical coupling device in accordance with the present invention.

FIGURE 4 depicts an electrical equivalent circuit of the non-contact electrical coupling device depicted on FIGURE 3.

FIGURE 5 depicts an alternative embodiment of a non-contact electrical coupling device in accordance with the invention.

FIGURE 6 depicts an electrical equivalent circuit of the non-contact electrical coupling device depicted on FIGURE 5.

FIGURE 7 depicts a block diagram of an exemplary electronic circuit for transmitting data and power across the exemplary non-contact electrical coupling devices depicted on FIGURES 3 and 5.

FIGURE 8 depicts a longitudinal section of one exemplary embodiment of the invention deployed in the steering tool shown on FIGURE 2.

DETAILED DESCRIPTION

Referring first to FIGURES 1 through 8, it will be understood that features or aspects of the embodiments illustrated may be shown from various views. Where such features or aspects are common to particular views, they are labeled using the same reference numeral. Thus, a

feature or aspect labeled with a particular reference numeral on one view in FIGURES 1 through 8 may be described herein with respect to that reference numeral shown on other views.

FIGURE 1 illustrates a drilling rig 10 suitable for the deployment of exemplary embodiments of the present invention. In the exemplary embodiment shown on FIGURE 1, a semisubmersible drilling platform 12 is positioned over an oil or gas formation (not shown) disposed below the sea floor 16. A subsea conduit 18 extends from deck 20 of platform 12 to a wellhead installation 22. The platform may include a derrick 26 and a hoisting apparatus 28 for raising and lowering the drill string 30, which, as shown, extends into borehole 40 and includes a drill bit 32 and a steering tool 100 (such as a three-dimensional rotary steerable tool). In the exemplary embodiment shown, steering tool 100 includes a plurality of blades 150 (e.g., three) disposed to extend outward from the tool 100. The extension of the blades 150 into contact with the borehole wall is intended to eccentric the tool in the borehole, thereby changing an angle of approach of the drill bit 32 (which changes the direction of drilling). Exemplary embodiments of steering tool 100 further include hydraulic 130 and electronic 140 control modules (FIGURE 2) configured to control extension and retraction of the blades 150. It will be appreciated that control modules 130 and 140 typically include various electrical power consuming devices, such as, but not limited to, solenoid controllable valves, sensors (e.g., including accelerometers, pressure transducers, temperature sensors, rotation rate sensors, and the like), and other electronic components (e.g., including microprocessors, electronic memory, timers, and the like). The drill string 30 may also include various electronic devices, e.g., including a telemetry system, additional sensors for sensing downhole characteristics of the borehole and the surrounding formation, and microcontrollers disposed to be in electronic communication with electronic control module 140. The invention is not limited in regards to specific types or makes of electrical and/or electronic devices.

It will be understood by those of ordinary skill in the art that methods and apparatuses in accordance with this invention are not limited to use with a semisubmersible platform 12 as illustrated in FIGURE 1. This invention is equally well suited for use with any kind of subterranean drilling operation, either offshore or onshore. While exemplary embodiments of this invention are described below with respect to rotary steerable embodiments, it will be appreciated that the invention is not limited in this regard. For example, as described in more detail below, embodiments of the invention may also be utilized with mud motors (e.g., deployed below the power section) or any other downhole tool deployments in which electrical power and/or electronic data are transferred between first and second components that rotate relative to one another.

Turning now to FIGURE 2, one exemplary embodiment of steering tool 100 from FIGURE 1 is illustrated in perspective view. In the exemplary embodiment shown, steering tool 100 is substantially cylindrical and includes threaded ends 102 and 104 (threads not shown) for connecting with other bottom hole assembly (BHA) components (e.g., connecting with the drill bit at end 104 and upper BHA components at end 102). The steering tool 100 further includes a housing 110 and at least one blade 150 deployed, for example, in a recess (not shown) in the housing 110. Control modules 130 and 140 are deployed in the housing 110. In general, the control modules 130 and 140 are configured for measuring and controlling the direction of drilling. Control modules 130 and 140 may include substantially any devices known to those of skill in the art, such as those disclosed in U.S. Patent 5,603,386 to Webster or U.S. Patent 6,427,783 to Krueger et al.

To steer (i.e., change the direction of drilling), one or more of blades 150 are extended into contact with the borehole wall. The steering tool 100 is moved away from the center of the borehole by this operation, thereby altering the drilling path. It will be appreciated that the tool 100 may also be moved back towards the borehole axis if it is already eccentric. To facilitate

controlled steering, the rotation rate of the housing is desirably less than 0.1 rpm during drilling, although the invention is not limited in this regard. By keeping the blades 150 in a substantially fixed position with respect to the circumference of the borehole (i.e., by preventing rotation of the housing 110), it is possible to steer the tool without constantly extending and retracting the blades 150. Non-rotary steerable embodiments are thus typically only utilized in sliding mode (although they may be rotated when steering is not desired). In rotary steerable embodiments, the tool 100 is constructed so that the housing 110, which houses the blades 150, remains stationary, or substantially stationary, with respect to the borehole during directional drilling operations. The housing 110 is therefore constructed in a rotationally non-fixed (or floating) fashion with respect to a shaft 115 (FIGURE 7). The shaft 115 is connected with the drill string and is disposed to transfer both torque (rotary power) and weight to the bit.

The above-described control and manipulation of the blades 150 is known to consume electrical power. For example, in one commercially serviceable embodiment, the blades 150 are extended via hydraulic actuation with solenoid-actuated controllable valves being utilized to increase or decrease hydraulic fluid pressure at the individual blades. Electrically-powered hydraulic pumps have also been disclosed for controlling blade actuation (U.S. Patent 6,609,579). The steering tool housing 110 typically further includes electronic components for sensing and controlling the position of each of the blades. Steering tool embodiments typically further include one or more microcontrollers, electronic memory, and like. Such electronics typically consume relatively little electrical power as compared to the solenoids and/or electrical pumps described above, although the invention is not limited in regard to electric power consuming components deployed in the tool housing 110.

It will be appreciated that steering tool functionality is advantageously enhanced by providing improved data transmission between housing 110 and rotating shaft 115. For example, closed-loop steering techniques, such as geo-steering techniques, commonly require

communication with LWD sensors deployed elsewhere in the drill string. Typical geo-steering applications make use of directional formation evaluation measurements (azimuthally sensitive LWD measurements) made very low in the BHA, for example, in a rotating stabilizer located just above the drill bit and/or even in the drill bit. To enable true closed-loop control, such

5 directional formation evaluation measurements are advantageously transmitted in substantially real time to electronic module 140. Electronic module 140 is also advantageously disposed in electronic communication with a downhole telemetry system (e.g., a mud pulse telemetry system) for transmitting various steering tool data up-hole. Such telemetry systems are typically deployed at the upper end of the BHA.

10 Turning now to FIGURE 3, one exemplary embodiment of a non-contact, electrical coupling device 300 in accordance with the present invention is depicted in longitudinal cross section. In the exemplary embodiment shown, coupling device 300 is configured to transmit electrical power (energy) and/or data in either direction across the gap 215 between housing 210 and shaft 205. As depicted, the shaft 205 is disposed to rotate with respect to the housing 210

15 (e.g., the shaft may rotate in the housing or the housing may rotate about the shaft). As such, conventional radial bearing stacks 315 and 317 are deployed in the gap 215, for example, at longitudinally opposed ends of the housing 210. Either one or both of the housing 210 and shaft 205 may be disposed to rotate with respect to the borehole. It will be understood that the invention as depicted in FIGURE 3 may be deployed in substantially any suitable downhole tool

20 in which it is desirable to transmit electrical power and/or data between relatively rotating components (e.g., between a shaft and a housing as depicted).

In the exemplary embodiment shown, coupling device 300 includes at least first and second substantially coaxial, axially offset wound toroidal cores 330 and 340 deployed about the shaft 205. The first wound toroidal core 330 is rotationally fixed to the shaft 205 (i.e., is

25 disposed to rotate with the shaft). The second wound toroidal core 340 is rotationally fixed to

the housing 210 (i.e., is disposed to rotate with the housing). It will therefore be appreciated that the first and second wound toroidal cores are disposed to rotate relative to one another about the longitudinal axis of the shaft 205. Each of the wound toroidal cores 330 and 340 further includes a magnetically permeable toroidal core having multiple windings of insulated wire wrapped thereabout. The insulated wires wound about the first toroidal core are electrically connected (as depicted at 352) to an AC power source 350 (e.g., a downhole turbine or an inverter that is further coupled to a battery pack). The insulated wires wound about the second toroidal core are electrically connected (as depicted at 362) to electrical load 360.

In the exemplary embodiment depicted on FIGURE 3, coupling device 300 is configured to transmit electrical power from the shaft 205 (e.g., from power source 350) to the housing 210 (e.g., to load 360). The invention is, of course, not limited in this regard as power may also be transmitted from the housing 210 to the shaft 205. Moreover, as described in more detail below with respect to FIGURE 7, exemplary embodiments of coupling device 300 may additionally (or alternatively) be configured to transmit data back and forth across the gap 215 between the shaft 205 and housing 210. In exemplary embodiments in which the coupling device 300 is deployed in rotary steerable tools, it is often advantageous to simultaneously transmit electrical power and data.

With continued reference to FIGURE 3, and further reference to FIGURE 4, each of the wound toroidal cores 330 and 340, when combined with the shaft 205 (conducting loop 390 as described below), is equivalent to a transformer. The invention may therefore be thought of as including first and second transformers 370 and 380 that share a single-turn winding as depicted on FIGURE 4. The first wound toroidal core 330 forms an N-turn primary of the first transformer 370. The shaft 205, radial bearings 315 and 317, and housing 210 form a single-turn secondary of the first transformer 370 and a single-turn primary of the second transformer 380. The second wound toroidal core 340 forms an M-turn secondary of the second transformer 380.

In the exemplary embodiment shown, electrical power is transmitted from the shaft 205 to the housing 210. Therefore, the first transformer 370 may be thought of as the transmitting transformer while the second transformer 380 may be thought of as the receiving transformer.

With continued reference to FIGURES 3 and 4, the shaft 205, radial bearings 315 and 317, and housing 210 provide an electrically conductive loop 390 that forms the single-turn secondary of the first transformer 370 and the single-turn primary of the second transformer 380. As depicted, the shaft 205 provides an electrically conductive path through the central window of the wound toroidal cores 330 and 340. The housing 210 provides an electrically conductive path external to the wound toroidal cores. The radial bearings 315 and 317 provide first and second conductive paths between the housing 210 and shaft 205 (on opposing sides of the wound toroidal cores 330 and 340) and therefore provide for a conductive loop 390 that extends through both wound toroidal cores 330 and 340. There is no electrical contact between the shaft 205 and housing 210 at any position longitudinally between the wound toroidal cores 330 and 340. A low resistance electrical connection can be readily maintained between the shaft 205 and housing 210 in a typical downhole environment due to the large radial bearing (and/or bushing) areas.

It will be appreciated that wound toroidal cores 330 and 340 may be wound with the insulated wire to include substantially any number of turns. As depicted on FIGURE 3, the toroidal cores are wound such that for every turn the insulated wire passes once through the central window of the toroid. The first and second wound toroidal cores 330 and 340 may include the same number of turns ($N=M$) or a different number of turns ($N \neq M$). The invention is not limited in these regards. It will be understood that the voltage at the power supply may be stepped up or stepped down to the electrical load by the appropriate selection of N and M . Those of skill in the art will readily appreciate that the ratio of the voltage at the power supply to the voltage at the load equals the ratio of N to M (N/M) in the absence of losses. In exemplary

embodiments suitable for electrical power transmission, N and M are typically in the range from about 20 to about 200.

As described above, exemplary embodiments of electrical coupling device 300 may be configured for transmitting electrical power and data in either direction across gap 215 (from the shaft 205 to the housing 210 or from housing 210 to the shaft 205). It will be appreciated that data transmission requires the transmission of significantly less electrical energy (typically many orders of magnitude less energy) than that of power transmission. For example, data transmission often only requires an electrical current on the order of a few microamps or less. Useful power transmission, on the other hand, typically involves transferring at least a milliamp of electrical current and often involves the transmission of multiple amps of electrical current. Thus it will be appreciated that exemplary embodiments of the invention intended for data transmission only may be configured differently than embodiments that are intended for electrical power transmission (or both electrical power and data transmission).

Exemplary embodiments of the invention may be advantageously configured for high power electrical transmission (e.g., up to about 200 Watts). One difficulty in achieving high power transmission is that the electrical current in the primary of the transmitting transformer 270 is stepped up by a factor of N in the single-turn secondary (the conductive loop 390 including the shaft 205, radial bearings 315 and 317, and the housing 210). In other words, in an exemplary embodiment in which N=100, a primary current of 5 amps in the primary of the transmitting transformer 370 is stepped up to about 500 amps in the single-turn secondary. Such large electrical currents in the single-turn secondary (conductive loop 390) can result in significant IR losses even when the resistance of the shaft, bearings, and housing are extremely low (which they typically are owing to the large cross sectional area of those components). Those of skill in the art will readily recognize that such power losses are proportional to the square of the electrical current ($P_{\text{loss}}=I_2^2 \cdot R$).

Therefore, in certain embodiments it may be advantageous to configure the electrical coupling device so as to reduce the electrical current induced in the single-turn secondary (the shaft, bearings, and housing). This may be accomplished, for example, by reducing the number of turns N in the primary of the transmitting transformer 380. However, when it is desirable to
5 step down the voltage from the power supply to the electrical load (e.g., when a high voltage turbine is utilized as the power supply), there is a limit as to how far N can be reduced and still achieve the desired ratio of N to M.

With reference now to FIGURE 5, one exemplary embodiment is depicted in which each of the transmitting and receiving transformers includes a plurality of (or a set of) wound toroidal
10 cores 330A-F and 340A-F electrically connected in parallel. Each of the wound toroidal cores 330A-F and 340A-F includes a magnetically permeable toroidal core having multiple windings of insulated wire wrapped thereabout as described above with respect to FIGURE 3. The insulated wires wound about each of the first set of toroidal cores are electrically connected in parallel (as shown at 352) to the AC power source 350. The insulated wires wound about each
15 of the second set of toroidal cores are electrically connected in parallel (as shown at 362) to electrical load 360.

While the exemplary embodiment depicted on FIGURE 5 includes six wound toroidal cores 330A-F and 340A-F (referred to collectively as 330 and 340) in each of the transmitting and receiving transformers 370 and 380, the invention is not limited in this regard. Substantially
20 any suitable number of wound toroidal cores may be utilized in either set. In general, increasing the number of wound toroidal cores in each set advantageously proportionally decreases the electrical current induced in the single-turn secondary. For example, the use of ten wound toroidal cores in the example given above reduces the current in the single-turn secondary by a factor of ten (from 500 to 50 amps), which in turn reduces the power loss in the secondary by a
25 factor of 100. In theory, there is no limit to the number of wound toroidal cores that can be

connected in parallel as depicted on FIGURES 5 and 6. In practice, however, the number of wound toroidal cores that can be utilized is limited by the width of each of the wound toroidal cores 330, 340 and the shaft length that can be made available for their deployment in any particular downhole tool configuration. While the invention is not limited in these regards, the number of wound toroidal cores is preferably in the range from about 5 to about 20 in each of the transmitting and receiving transformers, with each wound toroidal core having a width (along the tool axis) in the range from about 0.25 to about 1 inch (6.35mm to about 25.4mm).

It will further be appreciated by those of skill in the art that the wound toroidal cores 330 and 340 advantageously utilize a highly magnetically permeable core so as to reduce transformer losses (the use of a highly permeable core ensures that substantially all of the magnetic flux produced by the electrical current in the winding remains in the core). While toroidal cores having substantially any suitable magnetic permeability may be utilized, those having a relative magnetic permeability of greater than about 10,000 are preferred. Preferred core materials also advantageously have a high Curie temperature (e.g., greater than about 150 degrees C or greater than about 200 degrees C) and a high magnetic field saturation so as to reduce losses at the particular frequencies utilized. Preferred embodiments of the invention may include toroidal cores fabricated from, for example, Superalloy, Amorphous Alloy E, Permalloy 80, and Magnesil (available from Magnetics, Inc., Pittsburg, PA) and Metglas® 2714A and Metglas® 2605 (available from Allied-Signal), although the invention is not limited in this regard. Preferred toroidal core embodiments may also include tape wound cores, e.g., as available from Magnetics (which is a division of Spang & Co., Pittsburg, Pennsylvania). Such tape wound cores may be advantageously deployed in a metallic or non-metallic casing so as to prevent mechanical damage to the core during downhole deployment. Encased and/or encapsulated tape wound cores are also available from Magnetics.

With reference now to FIGURE 6, an electrical equivalent circuit is depicted for the non-contact electrical coupling device shown on FIGURE 5. As described above with respect to FIGURE 5, wound toroidal cores 330A-F are electrically connected 352 in parallel with AC power supply 350. As also described above, wound toroidal cores 340A-F are electrically connected 362 in parallel with load 360. The conductive loop 390, as depicted, may be thought of as including a plurality of series connected, single-turn secondaries magnetically coupled with corresponding ones of the wound toroidal cores 330A-F. The conductive loop may further be thought of as including a second plurality of series connected, single-turn primaries magnetically coupled with corresponding ones of wound toroidal cores 340A-F. As depicted, the portion of the conductive loop 390 extending from point A clockwise about the loop 390 to point B represents the shaft 205. The portion of the loop 390 extending clockwise from point B to point A represents the housing 210 and bearings 315 and 317.

Turning now to FIGURE 7, a block diagram of exemplary control circuitry utilized for transmitting both electrical power and electronic data between shaft 205 and housing 210 is shown (shaft 205 and 210 are depicted on FIGURES 3, 5, and 8). The exemplary embodiment shown enables electronic data transfer in both directions; i.e., from shaft 205 to housing 210 and from housing 210 to shaft 205. The exemplary embodiment shown also enables electrical power transmission from shaft 205 to housing 210, although the invention is not limited in this regard. The invention may alternatively be configured to transmit power from housing 210 to shaft 205. Moreover, those of ordinary skill in the art will readily recognize that control circuitry may be configured that enables power transmission in both directions (e.g., at distinct frequencies and/or during distinct time intervals). It will also be appreciated that the invention is not limited to embodiments in which both data and power may be transmitted. Alternative embodiments may readily be configured for exclusive data transmission or exclusive power transmission.

With continued reference to FIGURE 7, the exemplary embodiment shown includes first and second data transceiver circuits 410 electronically connected to the coupling device 300 (FIGURE 4) on opposing sides of gap 215 (i.e., to wound toroidal cores 330 and 340) (FIGURES 3 and 4). The exemplary embodiment of transceiver circuits 410 depicted on

5 FIGURE 7 is configured to provide bi-directional communication of conventional serial communication signals at 19,200 bits/sec, with each byte including 11 bits (one start bit, nine data bits, and one stop bit). The invention is, of course, not limited in regard to data communication rates and/or formats. It is expected that communication rates up to (and even exceeding) 1 megabit/sec will be readily achievable using exemplary embodiments of the

10 invention. In the exemplary embodiment shown, data transceiver circuits 410 each include a tuning circuit 412 (e.g., a conventional band pass filter) electrically coupled to a corresponding wound toroidal core 330, 340 (FIGURES 3 and 4). In one advantageous embodiment, tuning circuit 412 has a pass-band centered in the range from about 10 to about 100 kHz, although the invention is not limited in this regard. Tuning circuit 412 is electronically connected to amplifier

15 filter 414 and antenna driver 416 which are in turn electronically connected to a digital control circuit 418. The digital control circuit 418 is further electronically connected to a serial communication driver and protection circuit 420, which is in turn connected to a communication bus 430 for communicating with other BHA components.

When transmitting data, a data signal is received at the serial communication driver 420

20 from bus 430. The digital control circuit 418 converts the digital signal to an analog signal which is used to modulate a carrier frequency at the antenna driver 416. It will be understood that substantially any known modulation techniques may be utilized, for example, including amplitude, frequency, and phase modulation. Conventional digital modulation schemes, for example, including QAM, DSL, ADSL, TDMA, FDMA, and the like, may also be utilized. In

25 one advantageous embodiment, a carrier frequency in the range from about 10 to about 100 kHz

is utilized, although the invention is not limited in this regard. Antenna driver 416 transmits the On-Off Keying modulated data signal through the tuning circuit 412 to the corresponding wound toroidal core 330, 340 (FIGURES 3 and 4). The data signal is received at the other wound toroidal core 340, 330 and tuning circuit 412 and amplified via amplifier filter 414. The digital
5 control circuit converts the modulated analog signal to a corresponding digital signal (e.g., a 19,200 bit per second, 5 volt signal) which is received by the serial communication driver 420.

As stated above, the exemplary embodiment shown is also configured to transmit electrical power from the rotating shaft 205 to the tool housing 210, i.e., from wound toroidal core 330 to wound toroidal core 340 (or analogously from transformer 370 to transformer 380)
10 (FIGURES 3 and 4). As also stated above, the invention is not limited in this regard. FIGURE 7 shows a power source at 350. Power source 350 may include substantially any suitable downhole power source, e.g., including a battery pack including conventional lithium batteries, a mud-driven turbine alternator, and/or a shaft-driven turbine alternator. The power source 350 is electrically connected to a power control circuit 470 (e.g., a voltage regulator) which is in turn
15 connected to a power transmitting circuit 480. The power control circuit 470 is typically further connected to (and provides power to) other electronic and electrical components deployed on the shaft 205, for example, including data transceiver circuit 410. The power transmitting circuit 480 includes a low frequency generator 484 (e.g., capable of generating a carrier signal with a frequency in the range from about 200 Hz to about 2 kHz in one advantageous embodiment) for
20 converting electrical energy from the power controller 470 to alternating current. It will be appreciated that data and power may be advantageously transmitted at mutually distinct frequencies, thereby enabling simultaneous data and power transmission. The oscillator 484 is connected to an amplifier circuit 482 which may be electrically connected to wound toroidal core 330 via a low frequency coupling network (or frequency-selective circuit) 462.

With continued reference to FIGURE 7, wound toroidal core 340 (FIGURES 3 and 4) is electrically connected to a power receiver circuit 460, which receives the transmitted electrical energy. In the exemplary embodiment shown, receiver circuit 460 includes a low frequency coupling circuit 462 and a rectifier circuit 464 configured to convert the AC power to DC power.

5 A low-pass filter and bypass capacitors may be used with the rectifier circuit 464 to generate substantially noise-free DC power as is known to those of ordinary skill in the art. Power controller 470 receives the DC power from circuit 460 and typically provides power to various electrical and electronic components (e.g., including data transceiver circuit 410, solenoid controlled hydraulic valves, latch circuits, and various other electronic circuitry disposed in the
10 housing 210). Electrical power received at the controller may also optionally be utilized to charge rechargeable batteries 472.

Referring now to FIGURE 8, another exemplary embodiment of the invention is shown deployed on a rotary steerable tool. In the exemplary embodiment shown coupling device 300 is disposed to transmit electrical power and/or data as described above in either direction across the
15 gap 215 between rotary steerable housing 110 and shaft 115 in downhole steering tool 100. As described above with respect to FIGURE 3, coupling device 300 includes at least first and second substantially coaxial wound toroidal cores 330 and 340 deployed about the shaft 115. The first wound toroidal core 330 is rotationally fixed to the shaft 115 (i.e., is disposed to rotate with the shaft and drill bit 32). The second wound toroidal core 340 is rotationally fixed to the
20 housing 110 (and is therefore generally substantially non-rotating with respect to the borehole as described above). Each of the wound toroidal cores 330 and 340 further includes a magnetically permeable toroidal core having multiple windings of insulated wire wrapped thereabout. The insulated wires wound about the first toroidal core are electrically connected (as depicted at 352) to AC power source 350 deployed in a rotating portion of the tool 100. The insulated wires

wound about the second toroidal core are electrically connected (as depicted at 362) to electrical load 360 in the housing 110.

As stated above, the invention is not limited to rotary steerable or even steering tool embodiments. Exemplary embodiments in accordance with the invention may also be utilized, for example, in downhole motors (mud motors). Conventional mud motors typically include a bearing housing deployed below the power section, the bearing housing typically including a mandrel deployed to rotate in an outer housing. In one exemplary embodiment of the invention, a first wound toroidal core 330 may be deployed on the outer surface of the mandrel and a second wound toroidal core 340 may be deployed on an inner surface of the housing (similar to the embodiment depicted on FIGURE 3).

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alternations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims.

CLAIMS

1. A downhole tool (100) comprising:
a shaft (205) deployed in a housing (210) and configured to rotate with respect to the housing (110); and
a non-contact electrical coupling device (300) configured to transmit an electrical signal between the shaft (205) and the housing (210), the electrical coupling device (300) including at least first and second axially spaced wound toroidal cores (330,340) deployed about the shaft (205), the first wound toroidal core (330) being rotationally coupled with the shaft (205), the second wound toroidal core (34) being rotationally coupled with the housing (210).
2. A downhole tool (100) of claim 1, wherein the non-contact electrical coupling device (300) comprises a conductive loop (390) formed at least partially formed from a portion of the shaft (205) and that passes through a central window of each of the wound toroidal cores (330,340).
3. The downhole tool (100) of claim 2, wherein:
the housing (210) is supported on the shaft (205) by first and second axially spaced bearings (315, 317), the first and second wound toroidal cores being deployed between the first and second bearings; and
the shaft (205), the first bearing (315), the housing (210), and the second bearing (317), in combination, forming the conductive loop (390) that passes through a central window of each of the wound toroidal cores (330,340).
4. A downhole tool (100) of claim 2 or 3, wherein the non-contact electrical coupling device (300) comprises first and second transformers (370, 380), wherein the at least

first wound toroidal core (330) forms a primary of the first transformer (370), and the at least second wound toroidal core (340) forms a secondary of the second transformer (390), and the conductive loop (390) forms both a single-turn secondary of the first transformer (370) and a single-turn primary of the second transformer (380).

5. A downhole tool (100) of any preceding claim, wherein:

the at least first wound toroidal core (330) comprises a first plurality of axially spaced electrically connected wound toroidal cores (330A-F); and

the at least second wound toroidal core (340) comprises a second plurality of axially spaced electrically connected wound toroidal cores (340A-F).

6. A downhole tool (100) of claim 5, wherein the first plurality of axially spaced wound toroidal cores (330A-F) are electrically connected in parallel, and the second plurality of axially spaced wound toroidal cores (340A-F) are electrically connected in parallel.

7. The downhole tool (100) of any preceding claim, wherein each of the at least first and second wound toroidal cores (330,340) includes from about 5 to about 20 wound toroidal cores.

8. The downhole tool (100) of any preceding claim, wherein each of the wound toroidal cores (330,340) comprises a toroidal core having a relative magnetic permeability of at least 10,000 and a Curie Temperature of at least 150 degrees C.

9. The downhole tool (100) of any preceding claim wherein the electrical signal the electrical coupling device (300) is configured to transmit comprises data and/or power transmitted back and forth between the shaft (205) and the housing (210).

10. The downhole tool (100) of any preceding claim, wherein the electrical coupling device (300) is configured to simultaneously transmit electrical power and data at mutually exclusive frequencies.

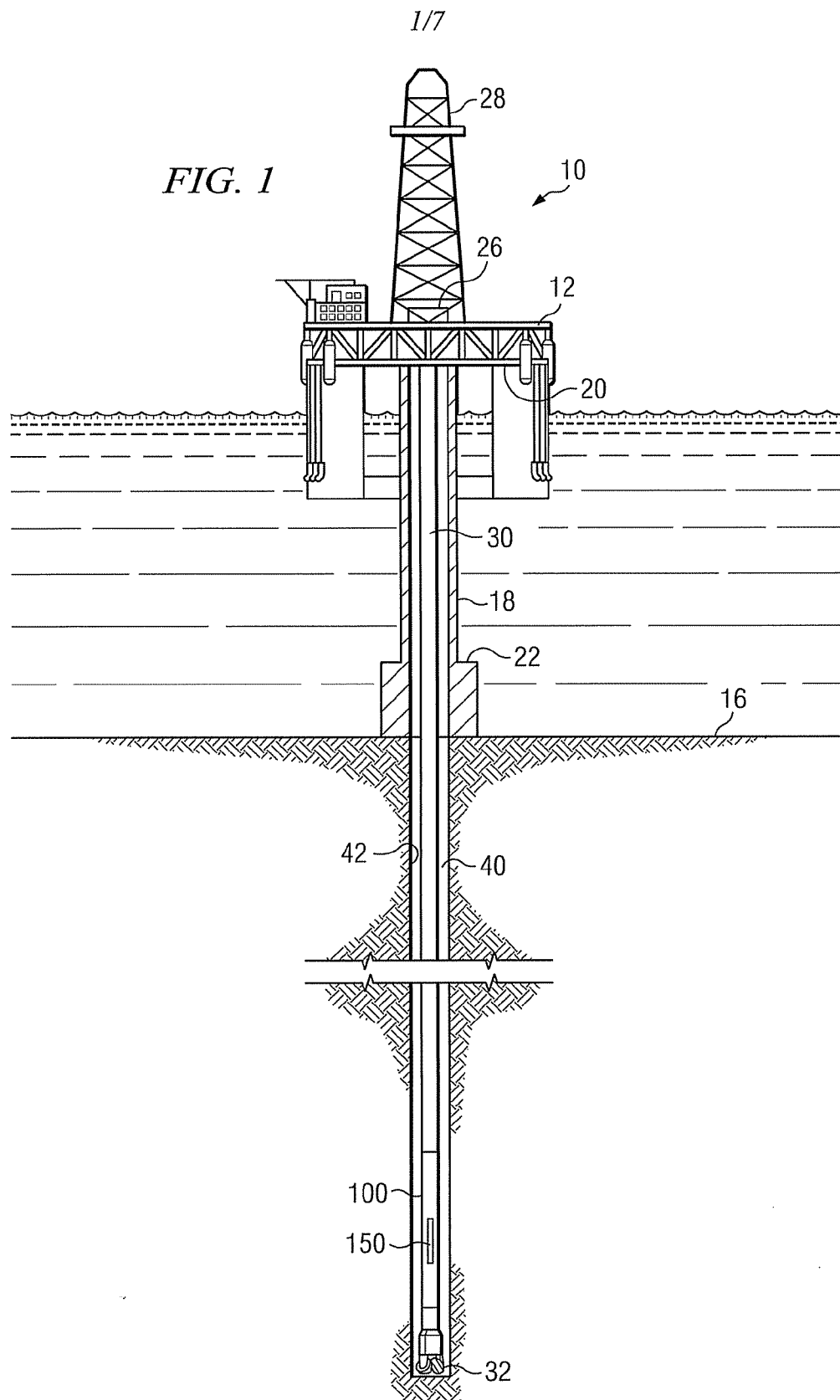
11. The downhole tool (100) of any preceding claim, wherein:
the at least first wound toroidal core (330) is electrically connected to a first transceiver circuit (410) deployed on the shaft (205); and
the at least second wound toroidal core (340) is electrically connected to a second transceiver circuit (410) deployed on the housing (210).

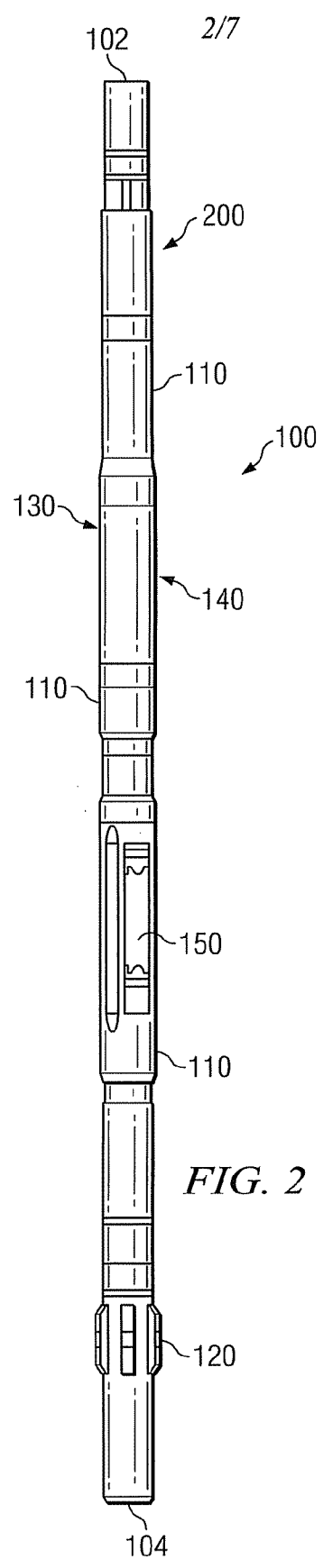
12. The downhole tool (100) of claim 11, wherein:
the first transceiver circuit (410) is configured to transmit electrical power and to transmit and receive electronic data; and
the second transceiver circuit (410) is configured to receive electrical power and to transmit and receive electronic data.

13. The downhole tool (100) of any preceding claim, further comprising:
a plurality of blades (150) deployed on a housing (110), the blades (150) disposed to extend radially outward from the housing (110) and engage a wall of the borehole (40), said engagement of the blades (150) with the borehole wall operative to eccentric the housing (110) in the borehole (40).

14. The downhole tool (100) of claim 13, wherein the blades (150) are configured to be actuated via electrical power transmitted from the shaft (205) to the housing (110) through the electrical coupling device (300).

15. The downhole tool (100) of any preceding claim wherein the downhole tool is a rotary steerable tool or a mud motor.





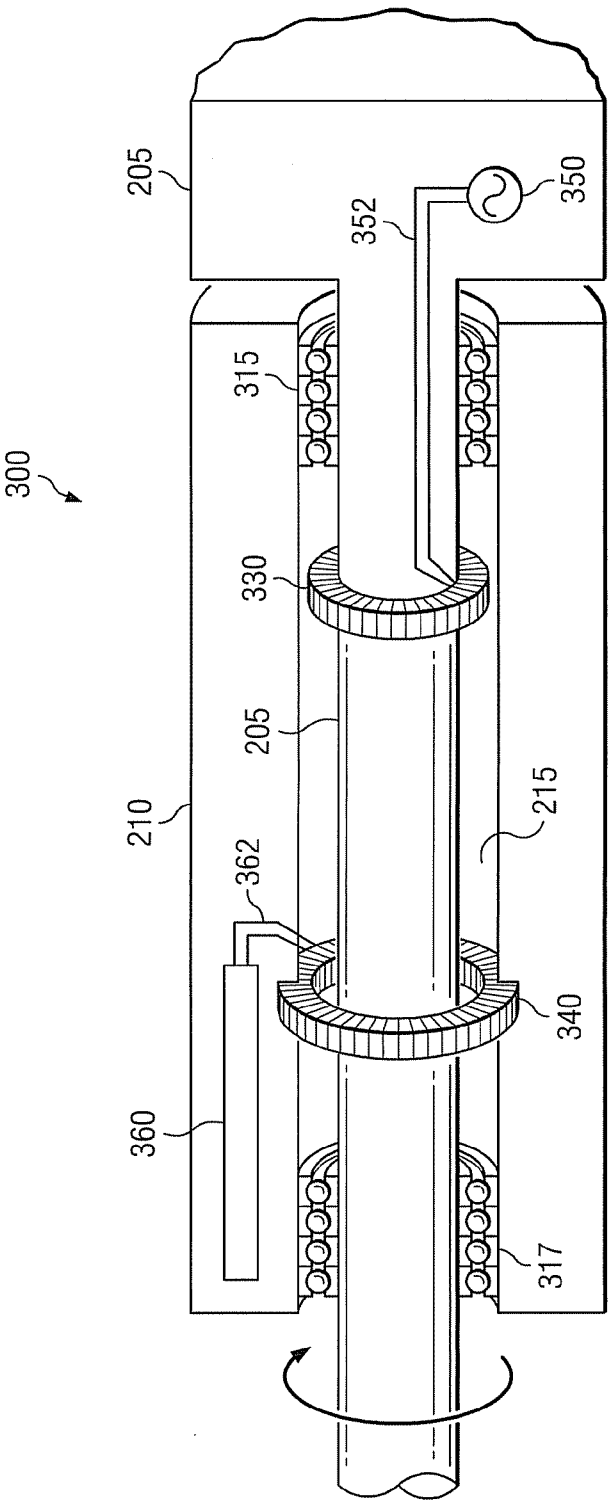


FIG. 3

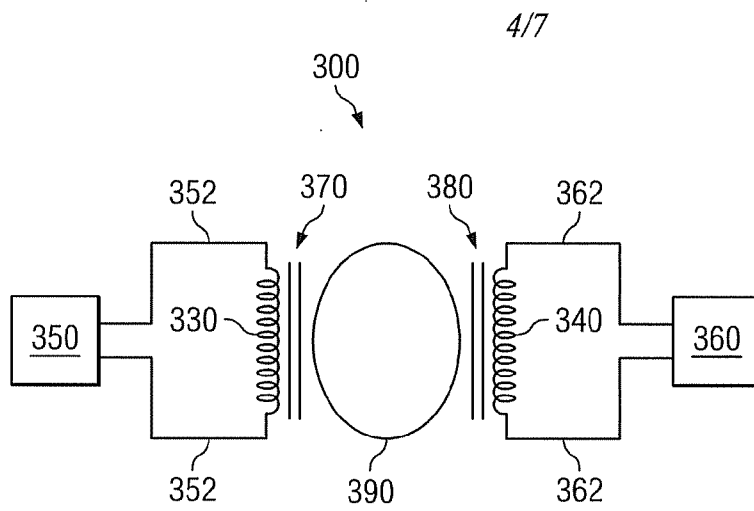


FIG. 4

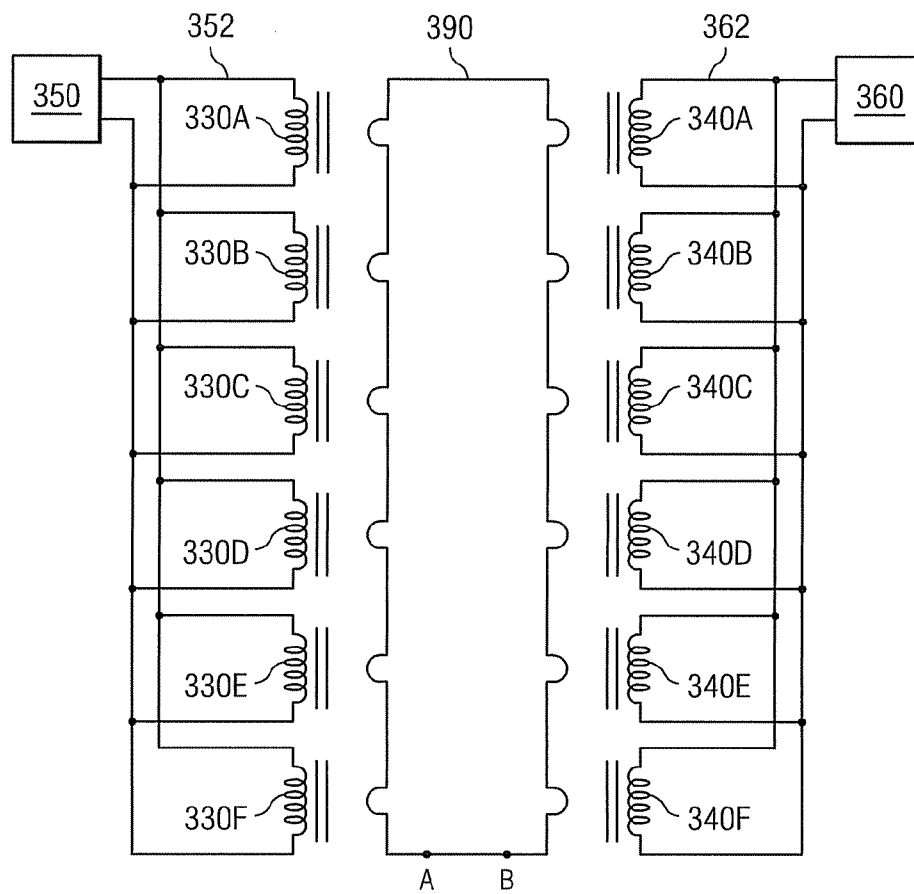
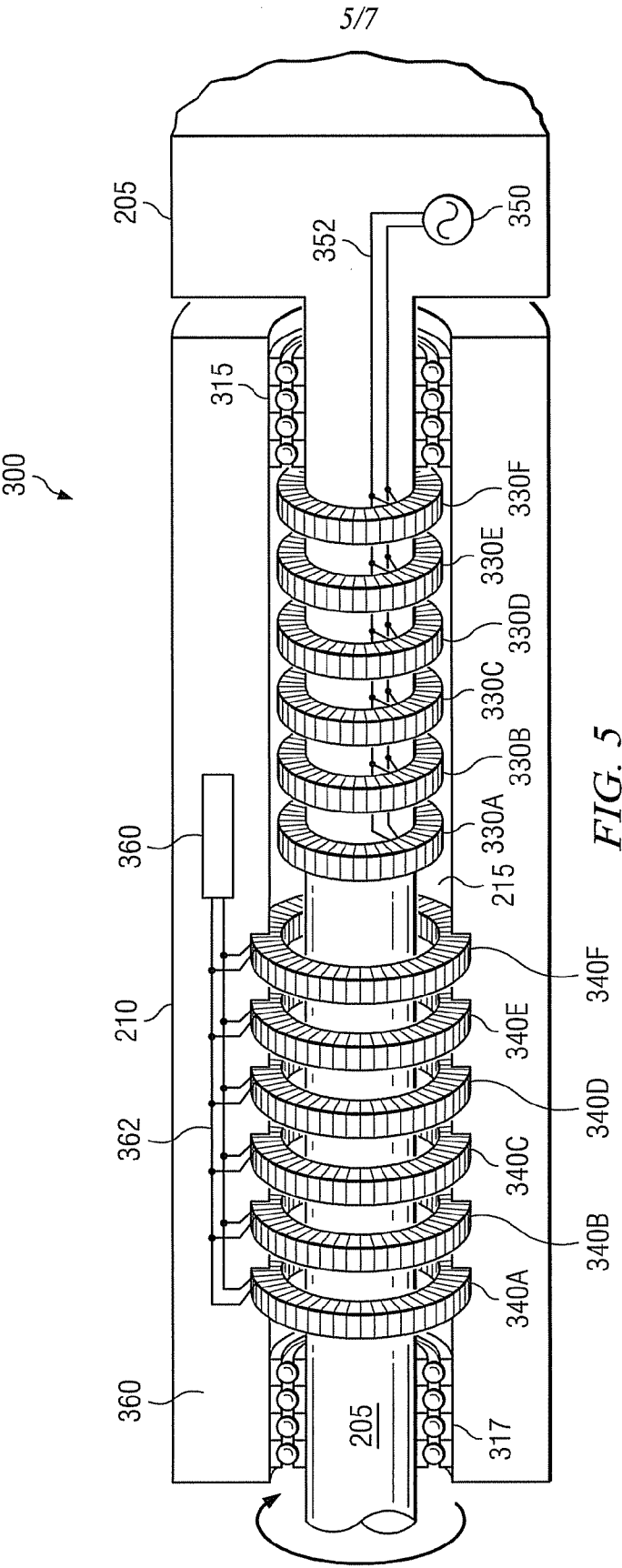


FIG. 6



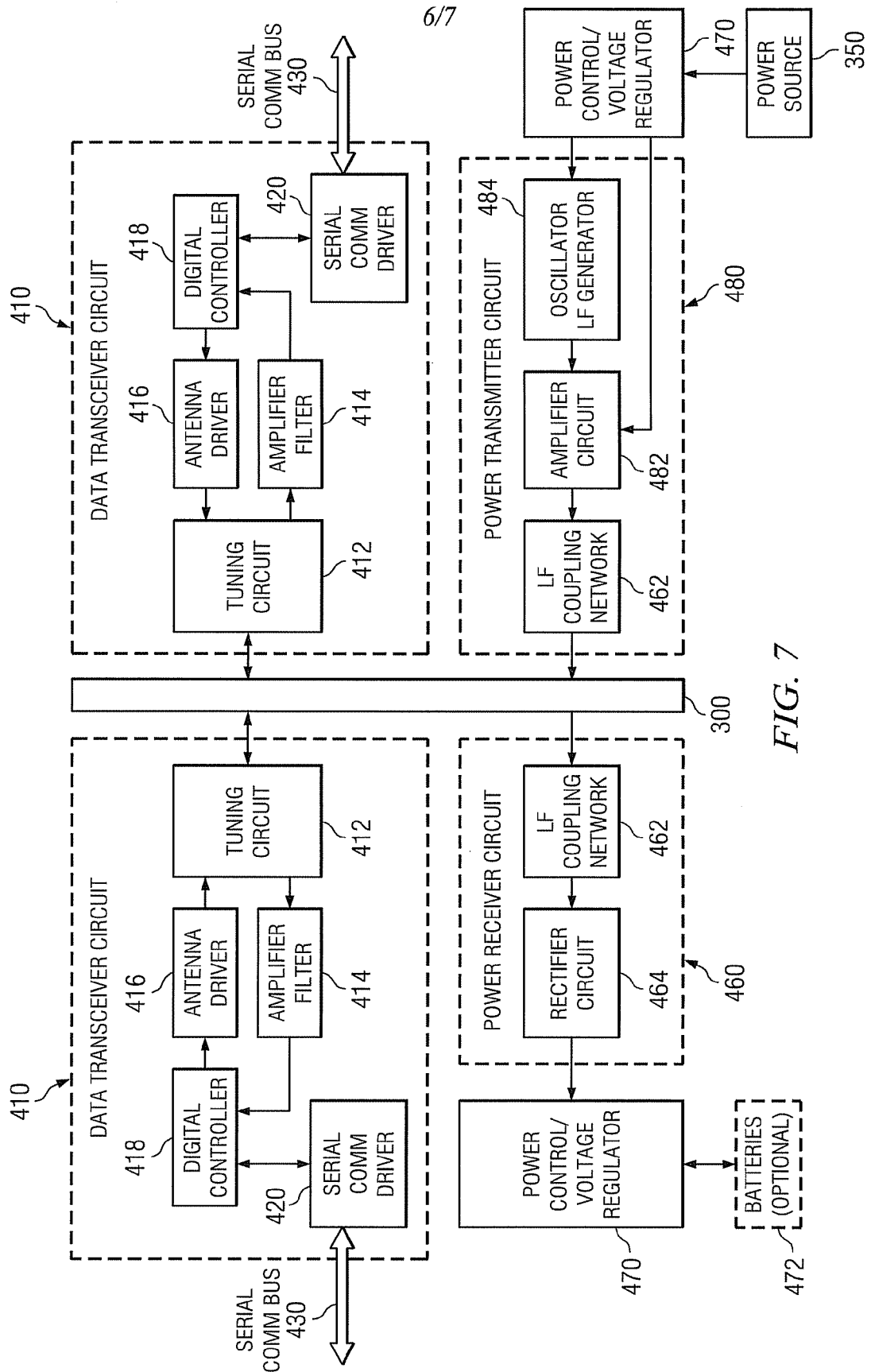


FIG. 7

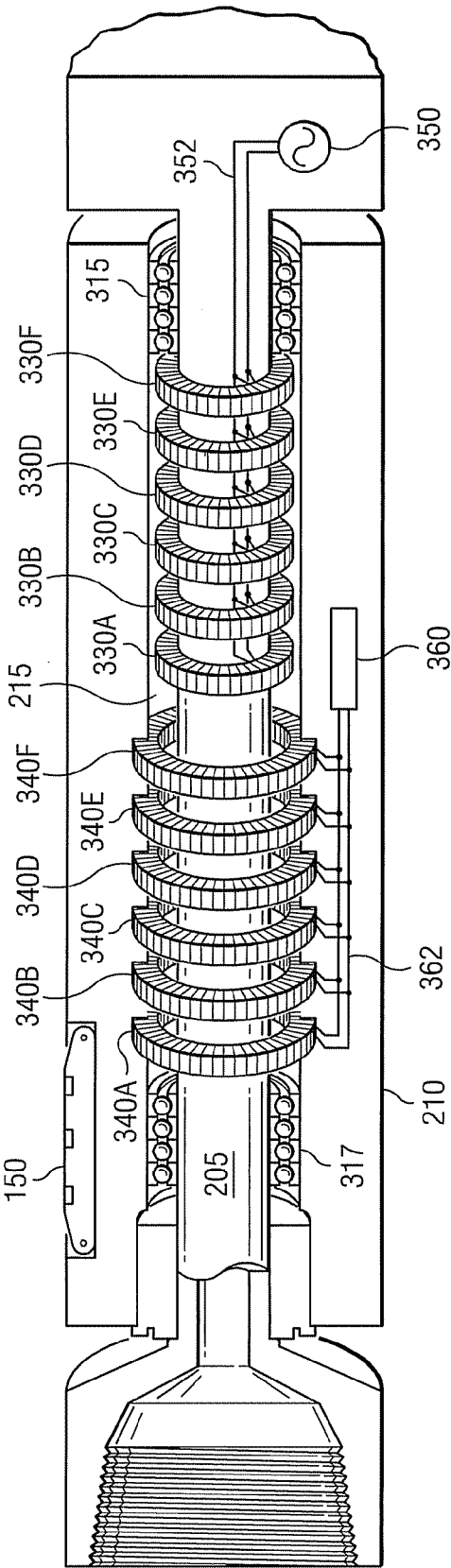


FIG. 8