



- (51) **International Patent Classification:**
F04D 13/08 (2006.01) *F04D 15/00* (2006.01)
- (21) **International Application Number:**
PCT/US2015/036669
- (22) **International Filing Date:**
19 June 2015 (19.06.2015)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
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- (81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).
- Published:**
— with international search report (Art. 21(3))

(54) **Title:** ELECTRIC SUBMERSIBLE PUMP MOTOR MONITORING USING MAGNETS

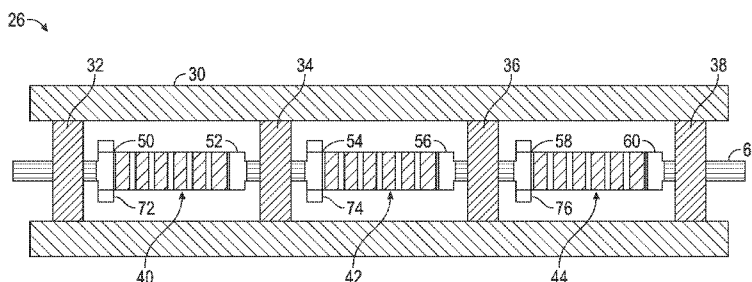


FIG. 3

(57) **Abstract:** A method and system for determining a mechanical status of a downhole induction motor of an electric submersible pump (ESP) are provided. The method includes converting a time series signal of a multi-bearing induction motor to a frequency domain data set. A permanent magnet having a number of pole pairs is positioned on or near each bearing, and the number of pole pairs being different from magnet to magnet. From the frequency domain data set, the shaft speed of the multi-bearing induction motor can be determined. Further, for at least one bearing having a permanent magnet positioned on or near such bearing and the permanent magnet having an odd number of pole pairs, the twist angle and a vibration frequency are determined using the frequency domain set, the determined shaft speed and the odd number of pole pairs of the at least one permanent magnet.

ELECTRIC SUBMERSIBLE PUMP MOTOR MONITORING USING MAGNETS**CROSS-REFERENCE TO RELATED APPLICATIONS**

[0001] Not applicable.

**STATEMENT REGARDING FEDERALLY SPONSORED
RESEARCH OR DEVELOPMENT**

[0002] Not applicable.

BACKGROUND

[0003] Some oil and as gas production rigs employ an artificial lift electrical submersible pump (ESP) to increase pressure within a reservoir to thereby encourage oil to the surface. When the natural drive energy of the reservoir is not sufficient to push the oil to the surface, artificial lift is employed to recover more production. An artificial lift system often includes an electric submersible pump (ESP) driven by an induction motor. The ESP and induction motor are placed downhole and the motor is driven by an electric current produced by surface power equipment.

[0004] Downhole ESPs and their motors operate in harsh environments and may fail over time. Even if such equipment does not completely fail, the performance of the motor and ESP may be impaired due to, for example, bearing wear, impeller wear, and the like. If such problems are not detected quickly, there can be a catastrophic mechanical failure of the motor. Some operators simply wait for the ESP and/or motor to completely fail before retrieving the equipment to the surface and replacing it.

SUMMARY

[0005] An induction motor for use in, for example, an electric submersible pump includes a stator, multiple longitudinally arranged rotor segments (each rotor segment including a rotor end ring), and multiple radial bearings. A permanent magnet is provided on each radial bearing or on the rotor end ring adjacent to each such radial bearing. Each permanent magnet includes a number of pole pairs, and the number of pole pairs is different across the permanent magnets. By having a different number of pole pairs on the various permanent magnets, a signal of the motor (e.g., drive current) can be processed in the frequency domain to determine various parameters at each corresponding radial bearing such as shaft speed, vibration frequency, and/or twist angle. In one embodiment, a method includes converting a time series signal of a multi-

bearing induction motor to a frequency domain data set and, from the frequency domain data set, determining the shaft speed of the multi-bearing induction motor. Further, the method includes, for at least one bearing having a corresponding permanent magnet with an odd number of pole pairs, determining a twist angle and a vibration frequency using the frequency domain set, the determined shaft speed and the odd number of pole pairs of the permanent magnet. A non-transitory storage device may include software that, when executed by a processing system, causes the processing system to convert a time series signal of a multi-bearing induction motor to a frequency domain data set. From the frequency domain data set, the processing system may determine the shaft speed of the multi-bearing induction motor. For at least one bearing having an odd number of pole pairs, the processing system may determine a twist angle and a coefficient of eccentricity using the frequency domain set, the determined shaft speed and the odd number of pole pairs of the at least one permanent magnet. This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Embodiments of the disclosure are described with reference to the following figures:

[0007] Fig. 1 illustrates an electric submersible pump including an induction motor and an associated control and monitoring system deployed in a wellbore environment in accordance with various embodiments of the present disclosure;

[0008] Fig. 2 shows an example of an induction motor including multiple radial bearings and a permanent magnet provided on each bearing in accordance with various embodiments;

[0009] Fig. 3 shows another example of a multi-bearing induction motor in which permanent magnets are provided on the rotor end rings near each bearing in accordance various embodiments;

[0010] Fig. 4 illustrates a cross section of the induction motor with rotor center orbital motion (e.g., due to bearing wear, external vibration, etc.);

[0011] Fig. 5 shows a method for determining various parameters about the multi-bearing induction motor in accordance with various embodiments;

[0012] Fig. 6 provides an example of calculating the shaft speed of the induction motor in accordance with various embodiments;

[0013] Fig. 7 provides an example of calculating the vibration frequency at or near individual radial bearings in accordance with various embodiments; and

[0014] Fig. 8 shows a system diagram of a motor monitor processing system in accordance with various embodiments.

DETAILED DESCRIPTION

[0015] One or more embodiments of the present disclosure are described below. These embodiments are merely examples of the presently disclosed techniques. Additionally, in an effort to provide a concise description of these embodiments, all features of an actual implementation may not be described in the specification. It should be appreciated that in the development of any such implementation, as in any engineering or design project, numerous implementation-specific decisions are made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which may vary from one implementation to another. Moreover, it should be appreciated that such development efforts might be complex and time consuming, but would nevertheless be a routine undertaking of design, fabrication, and manufacture for those of ordinary skill having the benefit of this disclosure.

[0016] When introducing elements of various embodiments of the present disclosure, the articles "a," "an," and "the" are intended to mean that there are one or more of the elements. The embodiments discussed below are intended to be examples that are illustrative in nature and should not be construed to mean that the specific embodiments described herein are necessarily preferential in nature. Additionally, it should be understood that references to "one embodiment" or "an embodiment" within the present disclosure are not to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features. The drawing figures are not necessarily to scale. Certain features and components disclosed herein may be shown exaggerated in scale or in somewhat schematic form, and some details of conventional elements may not be shown in the interest of clarity and conciseness.

[0017] The terms “including” and “comprising” are used herein, including in the claims, in an open-ended fashion, and thus should be interpreted to mean “including, but not limited to... .” Also, the term “couple” or “couples” is intended to mean either an indirect or direct connection. Thus, if a first component couples or is coupled to a second component, the connection between the components may be through a direct engagement of the two components, or through an indirect connection that is accomplished via other intermediate components, devices and/or connections. If the connection transfers electrical power or signals, the coupling may be through wires or other modes of transmission. In some of the figures, one or more components or aspects of a component may be not displayed or may not have reference numerals identifying the features or components that are identified elsewhere in order to improve clarity and conciseness of the figure.

[0018] Electric submersible pumps (ESPs) may be deployed for any of a variety of pumping purposes. For example, where a substance does not readily flow responsive to existing natural forces, an ESP may be implemented to artificially lift the substance. Commercially available ESPs (such as the REDATM ESPs marketed by Schlumberger Limited, Houston, Tex.) may find use in applications that require, for example, pump rates in excess of 4,000 barrels per day and lift of 12,000 feet or more.

[0019] As explained above, ESPs operated down-hole may fail due to wear and tear in the harsh environments in which the ESPs operate. An ESP may include a pump that is driven by an electric induction motor. Such motors may be fairly long and have multiple rotor segments arranged sequentially. Multiple radial bearings may be included to enable the rotor to rotate within a fixed stator. Due to the multiple rotor segments and the overall length of the ESP's induction motor, it is possible for bearings to wear unevenly thereby causing a vibration, the rotor to twist, etc. A bearing that has worn unevenly may experience an eccentric rotating mode which causes a vibration characterized by a vibration frequency. The length of such induction motors is such that shaft twist, vibration frequency and the coefficient of eccentricity of the rotating rotor can be quite different at various locations along the motor.

[0020] The disclosed embodiments include a processing system provided at the surface that analyzes an electric signal of the induction motor. The signal may be a signal related to the motor's drive current and/or voltage. The motor includes a permanent magnet at or near each of

the radial bearings. Each permanent magnet has a number of north-south pole pairs. In some embodiments, the number of pole pairs varies from magnet to magnet. At least one of the permanent magnets has an even number of pole pairs and at least one other permanent magnet has an odd number of pole pairs. In one example, one permanent magnet has an even number of pole pairs, while all other permanent magnets have odd numbers of pole pairs. In accordance with the disclosed embodiments, no two permanent magnets on or near different radial bearings have the same number of pole pairs. The permanent magnets provided on or near each radial bearing cause a current to be induced in the stator's electrical winding. The effects of the induced current and electromotive force (EMF) voltage can be detected and analyzed in a frequency domain representation of the motor's electrical signal. Further, the varying numbers of pole pairs of each permanent magnet causes the frequency spectrum of the motor's electrical signal to have content at different frequencies which are functions of the number of pole pairs. In other words, the various permanent magnets with varying numbers of pole pairs instruments the various radial bearings of the motor so as to generate a signature of the corresponding bearing in the frequency domain. These signatures can be analyzed to compute the rotor's shaft speed as well as, for each bearing having an odd number of pole pairs, the twist angle at that particular bearing, the vibration frequency at that particular bearing, and the coefficient of eccentricity at that particular bearing. Thus, twist angle, vibration frequency, and/or the coefficient of eccentricity can be computed based on the frequency domain representation of the motors' electrical signal.

[0021] Any of the values for twist angle, vibration frequency, and/or coefficient of eccentricity for any of the bearings can be compared to a known range of acceptable limits. If any value is outside of its acceptable limit range, the system can generate an alert. Alerts may include audible alerts, text messages, emails, pop-up warnings on a graphical user interface, etc. Further, the system may automatically slow down or even shut off an ESP's induction motor that is determined to experience an out-of-band value of twist angle, vibration frequency, or the coefficient of eccentricity for any of the bearings.

[0022] Fig. 1 depicts one example of a completion 10 within a well bore 12. The completion 10 incorporates an electric submersible pump (ESP) 24. There are many examples of possible well completion architectures which incorporate various other downhole tools such as packers, by-pass tubing and ESP encapsulation, which are a few such tools. The presently disclosed systems and methods are independent of the completion architecture used in the specific

application outside of the use of an ESP. While the system and method disclosed herein may be focused on hydrocarbon wells, it is understood that embodiments may be used for any type of liquid being pumped with an ESP. Non-limiting examples include: hydrocarbons from an oil well, water from a water well, water from a geothermal well, water from a gas well, or hydrocarbons from a sump. In the case of an oil well, an ESP 24 may be deployed in the completion 10 in order to improve production of hydrocarbons.

[0023] The ESP 24 includes a motor 26 and a pump 30. The motor 26 may be housed within the same housing as the pump 30, or may be housed separately. The motor 26 operates to drive the pump 30 in order to increase hydrocarbon production to the surface. The ESP 24 further includes an intake pressure gauge 32 which measures the pressure upstream of the ESP 24. The ESP 24 further includes a discharge pressure gauge 34 which measures the pressure downstream of the ESP 24.

[0024] The motor 26 of the ESP 24 receives electrical energization from a switch gear such as a variable speed drive (VSD) 90 typically located at the surface, outside of the well completion. The VSD 90 controls the power to, and thus the speed of, the motor 26. The VSD 90 may be driven by a three-phase power source. The VSD 90 delivers energization to the ESP 24 through an electrical conduit 38. A digital acquisition system 95 also is included that receives an electrical signal of the motor 26 and digitizes the signal. The digital acquisition system 95 may include one or more analog-to-digital converts (DACs) to convert analog motor signals to digital form. The digitized signals are then provided to a motor monitor processing system 100.

[0025] The motor monitor processing system 100 converts the digitized motor signal to the frequency domain and processes the frequency domain data as explained below to determine the rotor's shaft speed, as well as the twist angle, vibration frequency, and coefficient of eccentricity for the various bearings to which permanent magnets have been provided (on or near). An alert 101 may be generated by the motor monitor processing system 100 to announce the detection of a problem with the motor 26. The motor monitor processing system 100 also may generate a feedback signal 103 to be provided back to the VSD 90 to change the operation of a motor 26 for which a problem has been detected (e.g., slow the motor down, turn off the motor, etc.).

[0026] The motor 26 may be implemented as an induction motor. Fig. 2 shows a schematic of one example of induction motor 26. In this example, induction motor 26 includes four radial

bearings 32, 34, 36, and 38 and three rotor segments 40, 42, and 44. The rotor segments 40-44 are arranged sequentially along their longitudinal axes. A radial bearing (34, 36) is provided between each pair of adjacent rotor segments, and a radial bearing (32, 38) is provided at each end of the longitudinally-arranged rotor segments 40-44. Any number of rotor segments and radial bearings can be provided other than shown in the example of Fig. 2. On opposing ends of each rotor segment are rotor end rings. Thus, rotor segment 40 includes end rings 50 and 52. Rotor segment 42 includes end rings 54 and 56. Rotor segment 44 includes end rings 58 and 60. A shaft 62 is provided through the center of the rotor segments 40-44. As the rotor segments are caused to turn, the shaft 62 also turns. The speed at which the shaft 62 turns is referred to as the rotor shaft speed or simply shaft speed. Shaft speed may be expressed in units of revolutions per unit of time (e.g., revolutions per second). The rotor segments 40-44 and radial bearings 32-38 are contained within a generally cylindrical stator 30. Alternating magnetic fields in the stator 30, caused by current from the VSD 90, cause the rotor segments 40-44 to turn.

[0027] Referring still to Fig. 2, one or permanent magnets are provided on each radial bearing 32-38. For example, radial bearing 32 includes one or more permanent magnets 64. Radial bearing 34 includes one or more permanent magnets 66. Radial bearing 36 includes one or more permanent magnets 68. Radial bearing 38 includes one or more permanent magnets 70. Each permanent magnet generally may be a ring magnet provided on a surface of the bearing as shown. The permanent magnets may be provided on only one surface of a radial bearing or, as is shown in Fig. 2, on opposing surfaces of each radial bearing. The shaft 62 passes through a central opening in each permanent magnet. The permanent magnets 64-70 may be attached to the respective bearings by, for example, adhesive.

[0028] Each permanent magnet 64-70 has a number of pole pairs as noted above. In accordance with the disclosed examples, no two permanent magnets have the same number of pole pairs, thus the number of pole pairs varies from magnet to magnet on or near the various radial bearings. At least one of the permanent magnets has an even number of pole pairs, and at least one has an odd number. For example, one of the permanent magnets 64-70 has an even number of pole pairs, while the other three permanent magnets have an odd number.

[0029] Fig. 3 shows a schematic of another example of the induction motor 26. Most of the components in Fig. 3 are the same as in Fig. 2 and their description is not repeated here. A

difference between Figs. 2 and 3 is that in Fig. 2 the permanent magnets 64-70 are attached directly to the radial bearings 32-38, while in Fig. 3 the permanent magnets are attached to the rotor end rings. In the example, shown, a permanent magnet 72 is provided on the left rotor end ring 50 of the leftmost rotor segment 40. Similarly, a permanent magnet 74 is provide on the left rotor end ring 54 of the center rotor segment 42, and a permanent magnet 76 is provide on the left rotor end ring 58 of the rightmost rotor segment 44. Alternatively, the permanent magnets can be placed on the right-side rotor end rings 52, 56, and 60. Further still, permanent magnets can be placed on both rotor end rings of each rotor segment 40-44. In yet another embodiment, permanent magnets can be positioned on a mix of right-side rotor end rings 52, 56, and 60 and left-side rotor end rings 50, 54, and 58.

[0030] Figs. 2 and 3 thus illustrate that a permanent magnet is placed on or near each radial bearing 32-38. Fig. 2 is an example of permanent magnets that are placed on each radial bearing, while Fig. 3 is an example of permanent magnets that are placed near, but not directly on, each radial bearing.

[0031] Fig. 4 illustrates a schematic cross section of the induction motor 26. While this discussion is for a two-pole induction motor, the principles can be extended to an induction motor with any number of poles (e.g., a 6 pole induction motor) as well. The schematic shows a stator core 80, a stator winding distribution 82, and a permanent magnet 84. The permanent magnet 84 may be one of the permanent magnets of Figs. 2 or 3. In the example of Fig. 4, the rotor turns eccentrically about its central axis 86 which is in a different location as the stator central axis 88. This motion may be due to bearing wear, external vibration, etc. The stator radius is shown as r_s and is the distance between the stator central axis 88 and the stator core 80 as shown. The eccentric rotor 84 has a radius of r_r . The air-gap length l_g is the distance between the outer surface 85 of rotor 84 and the stator core, and varies over the stator periphery. The stator winding orientation angle, θ_μ , is the physical location of two sides of any winding on the stator periphery. For each of the three phases of the power source from VSD 90, the value of this angle will be different and 120° shifted. The stator angle is designated as θ and is measured relative to a fixed point, such as that shown in Fig. 4 ($\theta = 0^\circ$)

[0032] The following mathematical explanation is based on the following assumptions:

- The rotor has a single frequency dynamic eccentricity and, as a result, rotates about its own central axis 86 instead of the stator's central axis 88; and
- The impact of stator slots and air-gap saturation is negligible.

Since a permanent magnet does not have any slots, the air-gap relative permeance, Λ , experienced by the rotor and stator interaction can be expressed as a function of time, t , and stator angle, Θ , as:

$$\Lambda(\theta, t) \approx \Lambda_0[1 + \epsilon_d \cos(\omega_\epsilon t - \theta)] \quad (\text{Eq. 1})$$

where ϵ_d is the coefficient of dynamic eccentricity (also referred to herein as the “coefficient of eccentricity”), Λ_0 is the air-gap relative permeance with no eccentricity present for the rotor, and ω_ϵ is the vibration frequency (also the frequency of rotation of the rotor center about the stator's center). Letting p designate the number of pole pair for a given permanent magnet, the air-gap magnetic flux density due to the permanent magnet with respect to rotor center (rotor reference frame) as a function of rotor angle, θ_r , at a healthy condition (no bearing wear, no eccentricity, etc.) can be expressed as:

$$B_{hr}(\theta_r) = B_n \cos(p\theta_r) \quad (\text{Eq. 2})$$

where B_n is the peak value of the magnetic flux density. The value B_n is known *a priori*.

[0033] Assuming that the rotor rotates around its own center at speed ω_r , the stator angle can be expressed as:

$$\theta \approx \theta_r + \omega_r t \quad (\text{Eq. 3})$$

The air-gap magnetic flux density due to the permanent magnet with respect to stator center as a function of stator angle, θ , for a healthy rotor condition can be expressed as:

$$B_{hs}(\theta) = B_n \cos(p\omega_r t - p\theta) \quad (\text{Eq. 4})$$

[0034] The air-gap magnetic flux density due to a given permanent magnet with respect to stator center as a function of rotor angle, θ_r , with rotor dynamic eccentricity, ϵ_d (vibration) and shaft twist with twist angle, γ (faulty condition) can be expressed as:

$$B_s(\theta, t) = B_{hs}(\theta - \gamma) \times \Lambda(\theta, t) \quad (\text{Eq. 5})$$

With trigonometric simplification, the air-gap magnetic flux density due to the permanent magnet with respect to stator center can be expressed as:

$$B_s(\theta, t) = B_n \Lambda_0 \left[\cos(p\omega_r t - p\theta + p\gamma) + \frac{\epsilon_d}{2} \cos((p\omega_r + \omega_\epsilon)t - (p+1)\theta + p\gamma) + \frac{\epsilon_d}{2} \cos((p\omega_r - \omega_\epsilon)t - (p-1)\theta + p\gamma) \right] \quad (\text{Eq. 6})$$

This air-gap flux due to a given permanent magnet induces an EMF in the stator winding along the stator's periphery conductions and can be derived using Maxwell's equation: Faraday's Law as:

$$\oint \vec{E} \cdot d\vec{l} = -\frac{\partial}{\partial t} \int \vec{B} \cdot d\vec{S} \quad (\text{Eq. 7})$$

[0035] Thus, the EMF induced in a conductor on the stator's periphery located at an angle θ is given by:

$$E(\theta, t) = r_s \int \frac{\partial B_s(\theta, t)}{\partial t} d\theta \quad (\text{Eq. 8})$$

where r_s is the radius of stator as shown in Fig. 4.

[0036] In a full-pitched coil in the stator winding, extending from $\theta = \theta_\mu$ to $\theta = \pi + \theta_\mu$ (as shown in Fig. 4), the voltage induced due to the flux of this permanent magnet can be expressed as:

$$v_{\theta_\mu}(t) = w_{PM} r_s \int_{\theta_\mu}^{\pi + \theta_\mu} \frac{\partial B_s(\theta, t)}{\partial t} d\theta \quad (\text{Eq. 9})$$

where w_{PM} is the width of the given permanent magnet along the longitudinal axis of the rotor.

[0037] Thus, each permanent magnet causes an EMF voltage to be induced in the stator's winding—a voltage which can be detected and analyzed by the motor monitor processing system 100. For a given permanent magnet, if the number of pole pairs, p , is an even number, the voltage induced in the stator's winding due to the permanent magnet flux can be expressed as:

$$v_{\theta_\mu}(t) = 2B_n \Lambda_0 w_{PM} r_s [\omega_r \cos(p\omega_r t - p\theta_\mu + p\gamma)] \quad (\text{Eq. 10})$$

[0038] For permanent magnets in the motor for which the number of pole pairs, p , is an odd number, the voltage induced in the winding due to the permanent magnet's flux can be expressed as:

$$v_{\theta_\mu}(t) = B_n \Lambda_0 w_{PM} r_s \epsilon_d \left[\frac{p\omega_r - \omega_\epsilon}{p-1} \cos((p\omega_r - \omega_\epsilon)t - (p-1)\theta_\mu + p\gamma) + \frac{p\omega_r + \omega_\epsilon}{p+1} \cos((p\omega_r + \omega_\epsilon)t - (p+1)\theta_\mu + p\gamma) \right] \quad (\text{Eq. 11})$$

[0039] Equation (10) applies to a permanent magnet has an even number of pole pairs, p . In that situation, from Eq. (10), the shaft speed, ω_r , can be calculated. Once the shaft speed, ω_r , is calculated, Eq. (11) can be used to determine the coefficient of eccentricity, ϵ_d , vibration frequency, ω_ϵ , and twist angle, γ , associated with each radial bearing to which a permanent magnet having an odd number of pole pairs is attached or near. These calculations are performed by the motor monitor processing system 100 as explained in greater detail below.

[0040] An electric signal is obtained of the motor. The electric signal may be the terminal voltage and/or current of the motor, as measured by the VSD 90. The electric signal is digitized by the digital acquisition system 95 and provided to the motor monitor processing system 100. If the motor's terminal voltage is obtained, the induced EMF is calculated based on the terminal voltage. In one example, the induced EMF is determined by computing the Fast Fourier Transform (FFT), or other suitable transform, of the time series terminal voltage signal. The induced EMF vector is computed as:

$$\overrightarrow{E(f)} = \overrightarrow{V(f)} + \overrightarrow{I(f)}xZ(f) \quad (\text{Eq. 12})$$

where $\overrightarrow{V(f)}$ includes the real and imaginary portions of the complex FFT of the terminal voltage vector, and $\overrightarrow{I(f)}$ includes the real and imaginary portions of the complex FFT of the terminal current vector, and further where:

$$Z(f) = R_{dc}x\frac{1.1x\sqrt{f}}{\sqrt{5}0} + j2\pi L \quad (\text{Eq. 13})$$

R_{dc} is the DC resistance of the motor and L is the inductance of the motor, both quantities of which are known *a priori* based on the particular induction motor being used.

[0041] Either the induced EMF or current to the motor can be used as the electric signal to be analyzed by the motor monitor processing system 100 to determine the shaft speed, ω_r , eccentricity, ϵ_d , vibration frequency, ω_ϵ , and twist angle, γ .

[0042] Fig. 5 illustrates a method 200 for determining these parameters. The illustrated method may be performed by the motor monitor processing system 100. The disclosed operations may be performed in the order shown, or in a different order, and two or more of the operations may be performed in parallel rather than sequentially.

[0043] At 202, the method includes converting a time series signal of a multi-bearing induction motor (e.g., motor 26) to the frequency domain to produce a frequency domain data set. As

explained above, a permanent magnet having a number of pole pairs is positioned on or near each bearing, and the number of pole pairs may be different from magnet to magnet. This conversion operation may include determining the induced EMF as described above based on the motor's terminal voltage and current. The motor monitor processing system 100 may compute the FFT of the time series motor signal, or may use another suitable transform process.

[0044] At 204, the method includes, from the frequency domain data set, determining the shaft speed, ω_r , of the multi-bearing induction motor. As is explained below, the determination of the shaft speed is based on the use of a permanent magnet on or near a radial bearing that has an even number of pole pairs.

[0045] At 206, for at least one bearing having a permanent magnet positioned on or near such bearing having an odd number of pole pairs, the method includes determining a twist angle, γ , and a vibration frequency, ω_e , using the frequency domain set, the determined shaft speed and the odd number of pole pairs of the at least one permanent magnet. In some embodiments, this operation is performed for all permanent magnets having an odd number of pole pairs. The varying number of pole pairs, p , between the various permanent magnets causes spectral content associated with the induced EMF to be separated sufficiently in the frequency domain so that calculations of the twist angle and vibration frequency can be performed for each magnet and thus their corresponding radial bearings. Further, in some embodiments, any one or more of twist angle, γ , vibration frequency, ω_e , and coefficient of eccentricity, ϵ_d , can be calculated for each permanent magnet having an odd number of pole pairs, p . In one example, twist angle and coefficient of eccentricity is calculated, and in another embodiment, each of twist angle, coefficient of eccentricity, and vibration frequency is calculated for each permanent magnet (radial bearing) having an odd number of pole pairs.

[0046] At 208, an alert can be generated if any of the calculated parameters are out of their normal limits. The limits may be programmed apriori into the motor monitor processing system 100 and may be determined ahead of time based on data sheets, empirical data, etc. For example, a magnitude of a vibration frequency for a particular radial bearing 32-38 may be higher than a threshold limit, which may then trigger an alert. The alert may indicate any number of problems such as that the bearing on the motor 26 is starting to fail and the ESP 24 should be pulled up to the surface and repaired or replaced, that an abnormal vibration has been detected generated internal to the motor or from another part of the ESP (e.g., the pump 30) and transmitted to the

motor, etc.. The alert may also cause the VSD 90 to slow down the speed of the motor or turn it off completely to avoid a catastrophic failure downhole.

[0047] It is possible that a mistake will occur in the phase-sequence. For example, a phase sequence reverse rotation of the shaft 62 may occur by the surface operator. The phase difference of the induced voltage at a frequency $p\omega_r$ (where p is an even number) can be used as an indicator of rotational direction change.

[0048] Fig. 6 provides an example of operation 20 in which the rotor's shaft speed, ω_r , is calculated. At 220, the shaft speed is estimated. This operation can be performed based on the frequency of the motor's drive current. That is, the frequency of the drive current can be used as the estimate of the shaft speed. Due to slip inherent in an induction motor between the drive frequency, ω_s , and the shaft speed, the drive current's frequency is not exactly equal to the shaft speed but is generally close enough for purposes of the method of Fig. 6. The drive frequency, ω_s , represents the supply frequency of the VSD 90.

[0049] At 222, the method includes multiplying the estimated shaft speed by the number of pole pairs of a permanent magnet for which the number of pole pairs is an even number. At least one of the permanent magnets has an even number of pole pairs, p , and in some embodiments, only one permanent magnet has an even number of pole pairs.

[0050] At 224, the method includes identifying a peak magnitude of the frequency domain data set at a frequency within a predetermined frequency range of a frequency equal to the estimated shaft speed multiplied by the even number of pole pairs ($p \cdot \text{estimated } \omega_s$). The predetermined frequency range is included due to the fact that the shaft speed is estimated in operation 220. The predetermined frequency range may be a fixed size frequency band on either side of ($p \cdot \text{estimated } \omega_s$), such as $(p)(\text{estimated } \omega_s) +/\!-\!X$, where X is a fixed number. In one embodiment X may be 5% of the ($p \cdot \text{estimated } \omega_s$), or different percentages in other embodiments. In one example, the drive frequency may be 60 Hz and the p is 2. In this example, $p \cdot \text{estimated } \omega_s = 120$. As such, a peak amplitude is sought in the range of $120+/-5\%$ (114 Hz to 126 Hz).

[0051] At 226, the method then calculates the actual shaft speed based on the identified peak magnitude. Based on Eq. (10) above, the magnitude of the detected peak is given by:

$$\text{detected peak} = 2B_n\Lambda_0w_{PM}r_s\omega_r \quad (\text{Eq. 14})$$

from which ω_r can be computed as:

$$\omega_r = \frac{\text{detected peak}}{2B_n\Lambda_0w_{PM}r_s} \quad (\text{Eq. 15})$$

The detected peak is determined from operation 224 as described above, and the values in the denominator are known as well. Thus, the shaft speed, ω_r , can be calculated based on the identified peak magnitude, a peak value of magnetic flux density, B_n , an air gap relative permeance value, w_{PM} , a width dimension of the permanent magnet having an even number of pole pairs, and the stator's radius, r_s . The shaft speed, ω_r , also can be determined from the frequency of the peak, $p\omega_r$.

[0052] Fig. 7 shows an example of how the vibration frequency, ω_ϵ , can be calculated. This calculation can be performed for each odd number of pole pairs, p , among the various permanent magnets in motor 26. Eq. (11) above shows that a sideband on either side of each frequency equal to $p\omega_r$ is present and at separated from $p\omega_r$ by ω_ϵ . Thus, one sideband is at $p\omega_r - \omega_\epsilon$ and another side band is at $p\omega_r + \omega_\epsilon$. At 230, the method includes identifying a frequency substantially equal to the product of the odd number of pole pairs and the determined shaft speed, that is, $p\omega_r$, where p is an odd number and ω_r is computed by the motor monitor processing system 100 as illustrated in the example of Fig. 6.

[0053] At 232, the method includes identifying a frequency side band associated with $p\omega_r$. This operation may be performed by analyzing the frequency domain data set in a predetermined range $p\omega_r$ to identify one or both of the sidebands at $p\omega_r + \omega_\epsilon$ and $p\omega_r - \omega_\epsilon$. Only one sideband may be identified in the frequency domain data set or both sidebands may be identified. Identification of the sidebands includes identifying the particular frequency at which the sideband was found. At 234, the method includes computing a difference (e.g., absolute value of the difference) between the sideband frequency and $p\omega_r$ to determine the vibration frequency, ω_ϵ . If only one sideband frequency is identified, then the vibration frequency is computed based on that one sideband frequency as $\text{abs}(\text{sideband frequency} - p\omega_r)$. If both sideband frequencies are identified, then the absolute value of the difference between each sideband frequency and $p\omega_r$ is calculated and the two absolute value results can be averaged together.

[0054] The twist angle, γ , can be calculated based on the odd number of pole pairs, p , the winding orientation angle of the stator, θ_μ , and a phase angle (PHI) of a frequency sideband. Based on Eq. (11) above, the twist angle can be calculated as:

$$\gamma = \frac{PHI + (p \pm 1)\theta_\mu}{p} \quad (\text{Eq. 16})$$

The minus sign (-) in Eq. (16) is used with the phase of the lower side frequency sideband at $p\omega_r - \omega_\epsilon$, and the plus sign (+) is used with the phase of the upper side frequency sideband at $p\omega_r + \omega_\epsilon$.

[0055] The coefficient of eccentricity, ϵ_d , can be calculated based on the odd number of pole pairs, the frequency domain data set, and the shaft speed, ω_r . Each of the two sidebands has a magnitude (M). Based on Eq. (11), the coefficient of eccentricity can be calculated as:

$$\epsilon_d = \frac{M*(p \pm 1)}{B_n \Lambda_0 w_{PM} r_s (p\omega_r \pm \omega_\epsilon)} \quad (\text{Eq. 17})$$

where M is the magnitude of the spectrum at a corresponding sideband frequency. The minus sign (-) in Eq. (17) is used with the magnitude M of the lower side frequency sideband at $p\omega_r - \omega_\epsilon$, and the plus sign (+) is used with the phase of the upper side frequency sideband at $p\omega_r + \omega_\epsilon$. From the example of Eq. (17), it can be seen that the coefficient of eccentricity, ϵ_d , can be calculated based on a magnitude of a frequency side band, M , the odd number of pole pairs, p , a peak value of magnetic flux density, B_n , an air gap relative permeance, Λ_0 , a width dimension, w_{PM} , of the permanent magnetic having the odd number of pole pairs, and a stator radius, r_s .

[0056] Fig. 8 provides a system schematic of the motor monitor processing system 100 in accordance with an embodiment. The system 100 includes a processing resource 102 coupled to a non-transitory storage device 110. The processing resource 102 may be a single processor, a multicore processor, a single computer (desktop computer, notebook computer, tablet computer, etc.) multiple computing devices coupled together in a network, or any other type of computing device. The non-transitory storage device 110 includes volatile storage such as random access memory (RAM), non-volatile storage such as a magnetic storage (e.g., hard disk drive), an optical storage device (e.g., compact disc), or solid state storage (e.g., flash storage). The non-transitory storage device 110 may be a single device or collection of multiple devices, and be either stand-alone storage devices or storage devices contained within the processing resources 102.

[0057] The non-transitory storage device 110 contains motor assessment software 112 that, when executed by the processing resource 102, cause the processing resource to perform some or

all of the functionality described herein. The processing resource 102 can calculate the shaft speed, ω_r , based on the even number of pole pairs for a permanent magnet having an even number of pole pairs. Further, for each radial bearing 32-38 whose corresponding permanent magnet has an odd number of pole pairs, when executed the motor assessment software 112 causes the processing resource 102 to compute the twist angle, coefficient of eccentricity, ϵ_d , and vibration frequency, ω_ϵ . Alerts also can be generated or caused to be generated by the processing resource 102 as described above.

[0058] Although only a few example embodiments have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the example embodiments without materially departing from the electrical connector assembly. Features shown in individual embodiments referred to above may be used together in combinations other than those which have been shown and described specifically. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims.

[0059] The embodiments described herein are examples only and are not limiting. Many variations and modifications of the systems, apparatus, and processes described herein are possible and are within the scope of the disclosure. Accordingly, the scope of protection is not limited to the embodiments described herein, but is only limited by the claims that follow, the scope of which shall include all equivalents of the subject matter of the claims.

CLAIMS

What is claimed is:

1. A method, comprising:
converting a time series signal of a multi-bearing induction motor to a frequency domain data set, wherein a permanent magnet having a number of pole pairs is positioned on or near each bearing, and wherein the number of pole pairs being different from magnet to magnet;
from the frequency domain data set, determining the shaft speed of the multi-bearing induction motor; and
for at least one bearing having a permanent magnet positioned on or near such bearing, and the permanent magnet having an odd number of pole pairs, determining a twist angle and a vibration frequency using the frequency domain set, the determined shaft speed and the odd number of pole pairs of the at least one permanent magnet.
2. The method of claim 1, wherein determining the shaft speed of the multi-bearing induction motor includes:
estimating the shaft speed;
multiplying the estimated shaft speed by the number of pole pairs of a permanent magnet for which the number of pole pairs is an even number;
identifying a peak magnitude of the frequency domain data set at a frequency within a predetermined frequency range of a frequency equal to the estimated shaft speed multiplied by the even number of pole pairs;
calculating an actual shaft speed based on the identified peak magnitude.
3. The method of claim 2, wherein calculating the actual shaft speed based on the identified peak magnitude includes calculating the actual shaft speed based on the identified peak magnitude, a peak value of magnetic flux density, an air gap relative permeance, a width dimension of the permanent magnetic having the even number of pole pairs, and a stator radius.

4. The method of claim 1, wherein for each permanent magnet having an odd number of pole pairs, determining a twist angle by based on the odd number of pole pairs, a winding orientation angle of a stator, and a phase angle of a frequency side band.
5. The method of claim 4, wherein determining the twist angle for each permanent magnet having an odd number of pole pairs includes adding the phase angle to a product of the winding orientation angle of the stator and the odd number of pole pairs plus or minus 1 to produce a sum, and dividing the sum by the odd number of pole pairs of the respective permanent magnet.
6. The method of claim 1, wherein for each permanent magnet having an odd number of pole pairs, determining the vibration frequency by:
 - identifying a frequency substantially equal to the product of the odd number of pole pairs and the determined shaft speed;
 - identifying a frequency side band associated with the identified frequency substantially equal to the product; and
 - computing a difference between the frequency substantially equal to the product and the frequency side band to determine the vibration frequency.
7. The method of claim 1 further including, for each permanent magnet having an odd number of pole pairs, determining a coefficient of eccentricity based on the odd number of pole pairs, the frequency domain data set, and the determined shaft speed.
8. The method of claim 7 wherein, for each permanent magnet, determining the coefficient of eccentricity includes computing the coefficient of eccentricity based on a magnitude of a frequency side band, the odd number of pole pairs, a peak value of magnetic flux density, an air gap relative permeance, a width dimension of the permanent magnetic having the odd number of pole pairs, and a stator radius.
9. The method of claim 1 wherein the time series signal includes either a motor drive current or an induced electromotive force (EMF) voltage.

10. A non-transitory storage device containing software that, when executed by a processing system, causes the processing system to:

convert a time series signal of a multi-bearing induction motor to a frequency domain data set, wherein a permanent magnet having a number of pole pairs is positioned on or near each bearing, and wherein the number of pole pairs being different from magnet to magnet;

from the frequency domain data set, determine the shaft speed of the multi-bearing induction motor; and

for at least one bearing having a permanent magnet positioned on or near such bearing, and the permanent magnet having an odd number of pole pairs, determine a twist angle and a coefficient of eccentricity using the frequency domain set, the determined shaft speed and the odd number of pole pairs of the at least one permanent magnet.

11. The non-transitory storage device of claim 10, wherein, when executed, the software causes the processing system to determine the shaft speed of the multi-bearing induction motor by:

multiplying an estimated shaft speed by the number of pole pairs of a permanent magnet for which the number of pole pairs is an even number;

identifying a peak magnitude of the frequency domain data set at a frequency within a predetermined frequency range of a frequency equal to the estimated shaft speed multiplied by the even number of pole pairs;

calculating an actual shaft speed based on the identified peak magnitude.

12. The non-transitory storage device of claim 11, wherein, when executed, the software causes the processing system to calculate the actual shaft speed based on the identified peak magnitude by calculating the actual shaft speed based on the identified peak magnitude, a peak value of magnetic flux density, an air gap relative permeance, a width dimension of the permanent magnetic having the even number of pole pairs, and a stator radius.

13. The non-transitory storage device of claim 10, wherein for each permanent magnet having an odd number of pole pairs, when executed, the software causes the processing system to determine a twist angle based on the odd number of pole pairs, a winding orientation angle of a stator, and a phase angle of a side frequency band.

14. The non-transitory storage device of claim 13, wherein, when executed, the software causes the processing system to determine the twist angle for each permanent magnet having an odd number of pole pairs by adding the phase angle to a product of the winding orientation angle of the stator and the odd number of pole pairs plus or minus 1 to produce a sum, and dividing the sum by the odd number of pole pairs of the respective permanent magnet.

15. The non-transitory storage device of 10, wherein for each permanent magnet having an odd number of pole pairs, when executed, the software causes the processing system to determine a vibration frequency by:

identifying a frequency substantially equal to the product of the odd number of poles and the determined shaft speed;

identifying a frequency side band associated with the identified frequency substantially equal to the product; and

computing a difference between the frequency substantially equal to the product and the frequency side band to determine the vibration frequency.

16. The non-transitory storage device of claim 10 wherein, for each permanent magnet, when executed, the software causes the processing system to determine the coefficient of eccentricity based on a magnitude of a frequency side band, the odd number of pole pairs, a peak value of magnetic flux density, an air gap relative permeance, a width dimension of the permanent magnetic having the odd number of pole pairs, and a stator radius.

17. The non-transitory storage device of claim 16 wherein the width dimension of the permanent magnet is the width dimension along a longitudinal axis of a rotor of the multi-bearing induction motor.

18. An induction motor, comprising:
a stator;
a plurality of longitudinally arranged rotor segments, each rotor segment including a rotor end ring;
a plurality of radial bearings including a radial bearing between each adjacent pair of rotor segments and a radial bearing on either end of the longitudinally arranged rotor segments; and
a plurality of permanent magnets including a permanent magnet on each radial bearing or on the rotor end ring adjacent to each such radial bearing;
wherein each permanent magnet includes a number of pole pairs and wherein the number of pole pairs is different across the permanent magnets.
19. The induction motor of claim 18, wherein the number of pole pairs of at least one permanent magnet is an even number and the number of pole pairs of at least one other permanent magnet is an odd number.
20. The induction motor of claim 18, wherein the number of pole pairs of one permanent magnet is an even number and the number of pole pairs of all other permanent magnets is an odd number.

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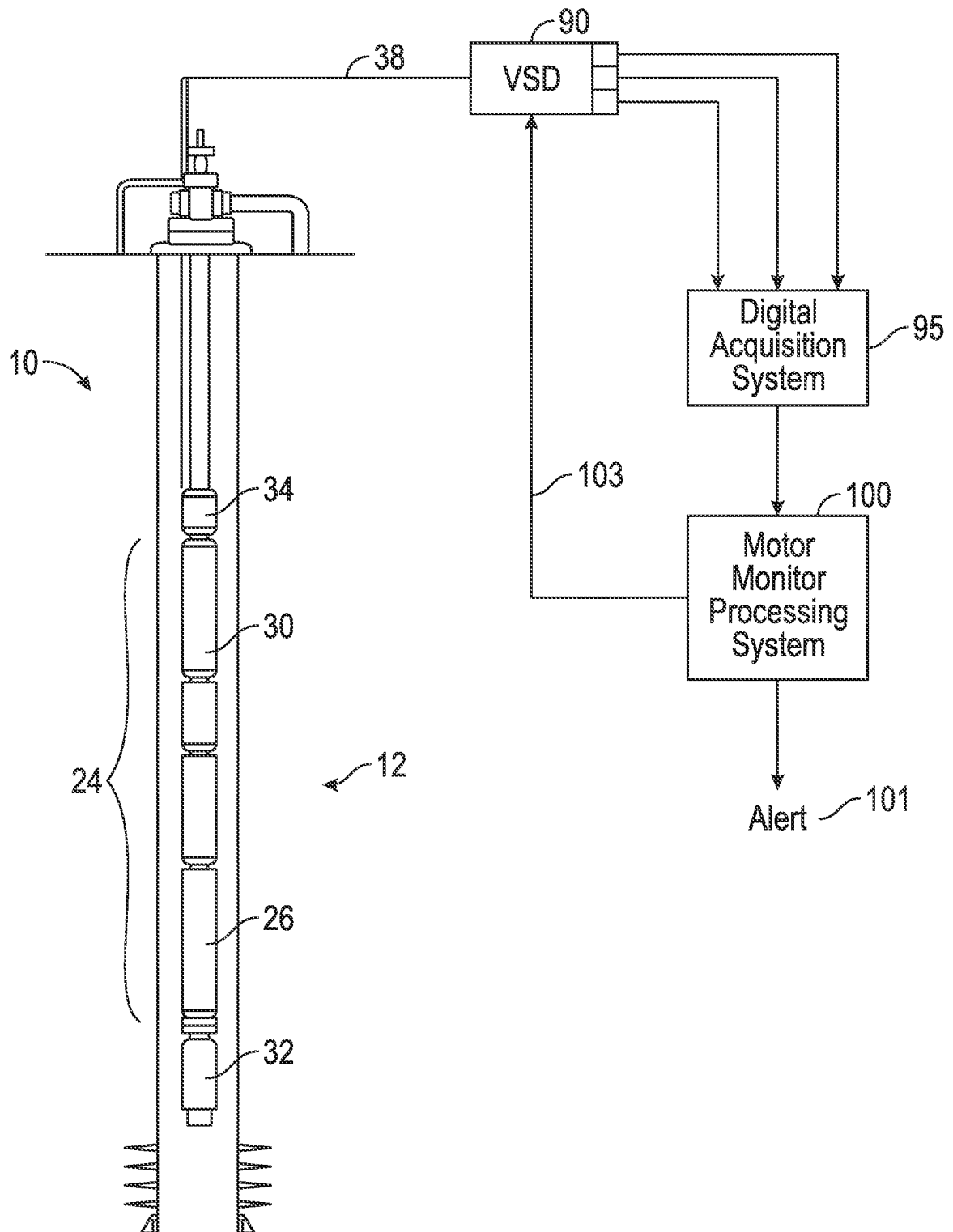


FIG. 1

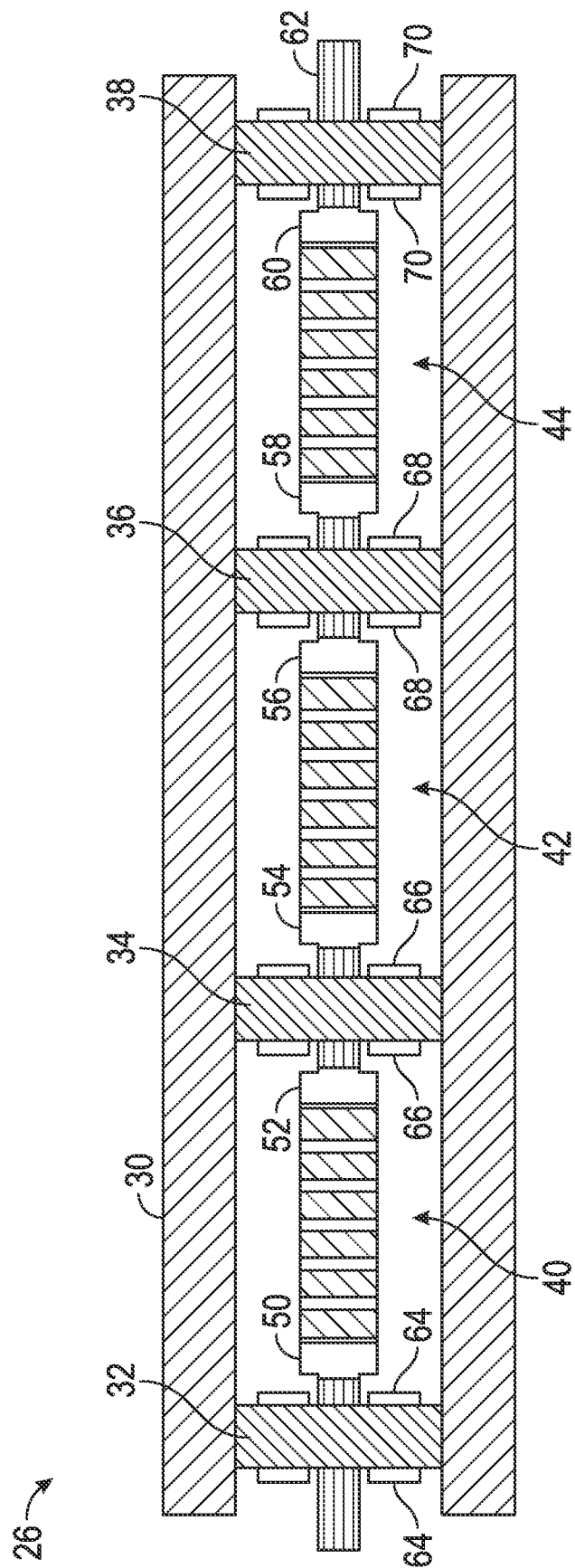


FIG. 2

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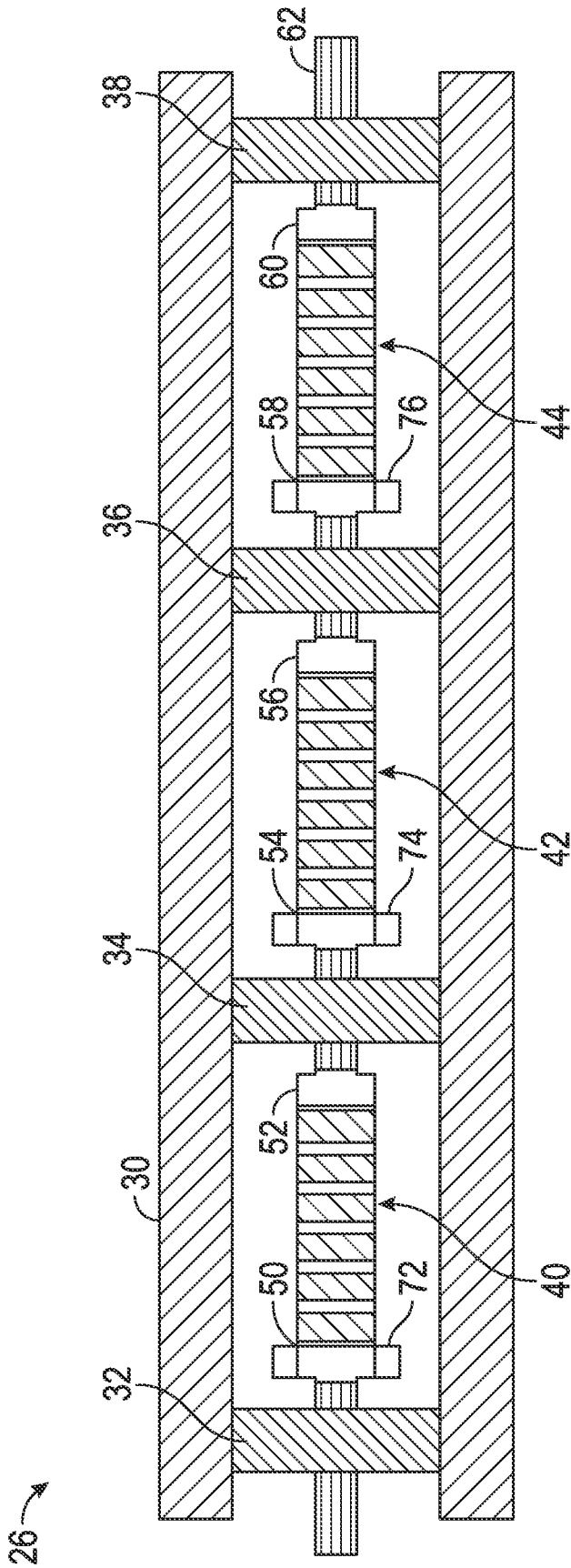


FIG. 3

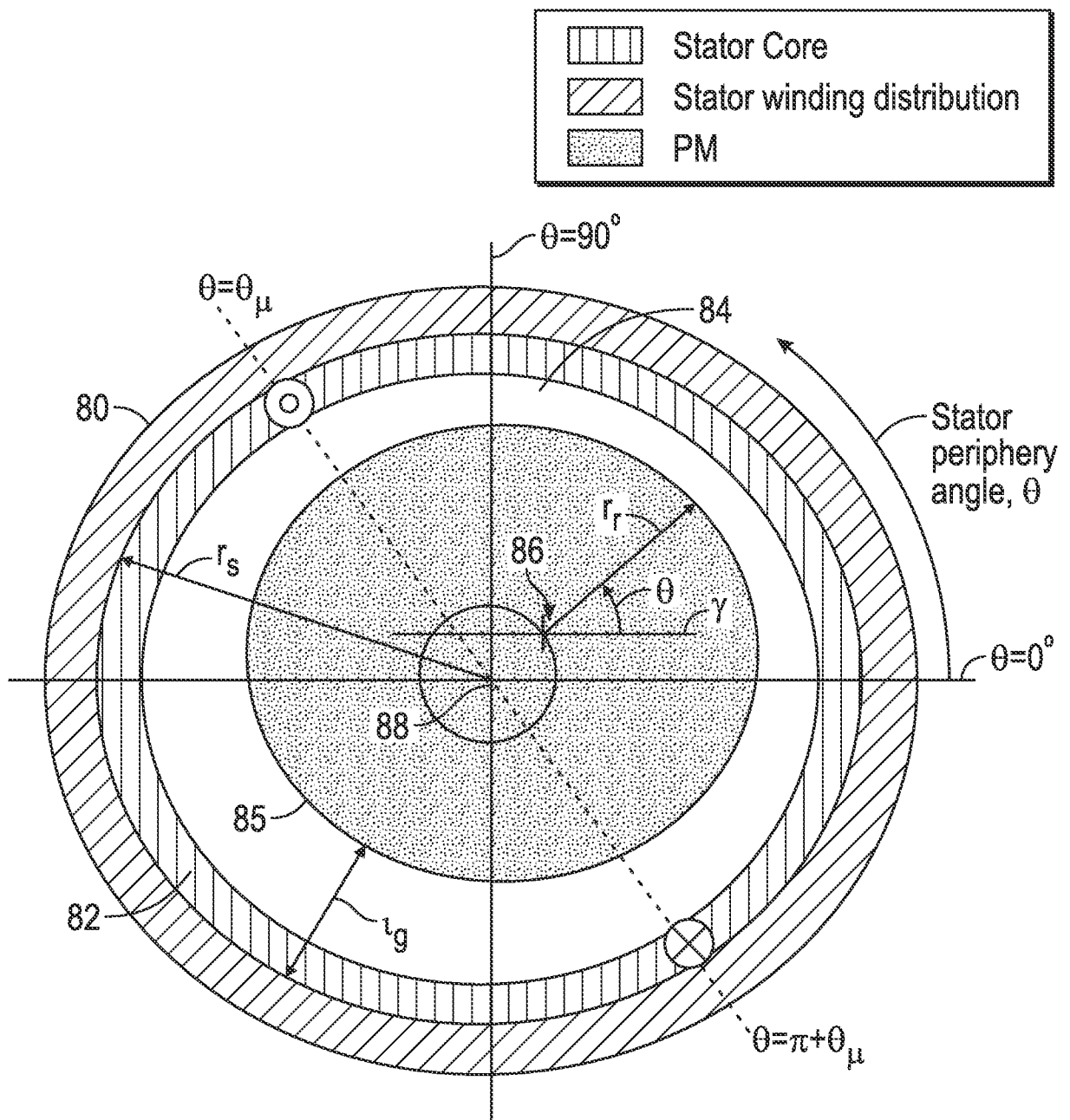


FIG. 4

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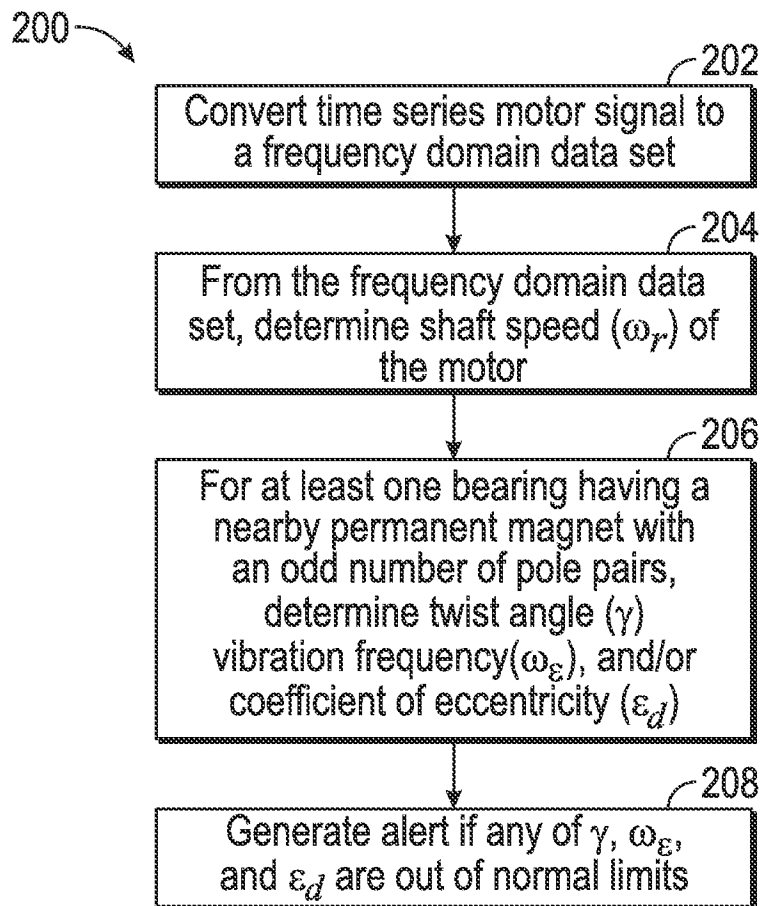


FIG. 5

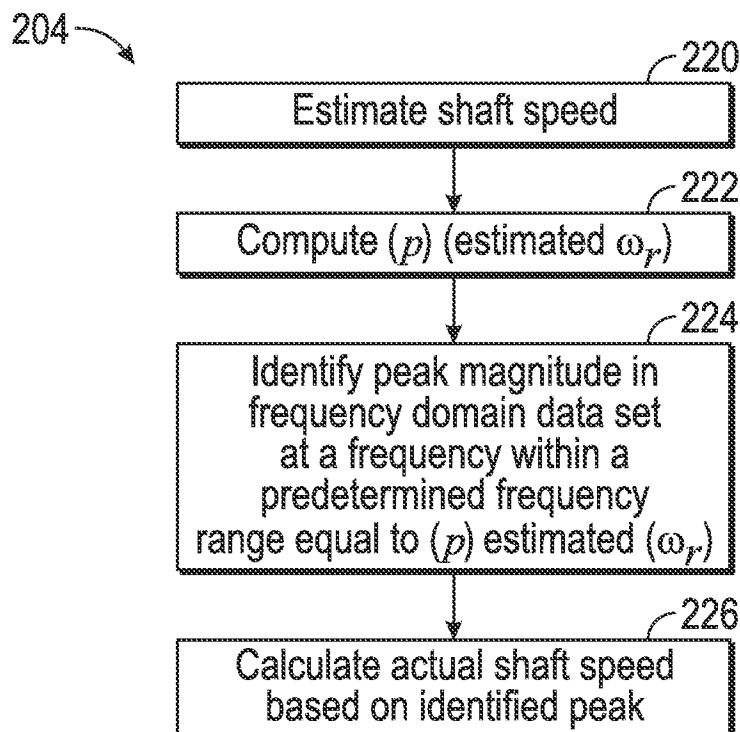


FIG. 6

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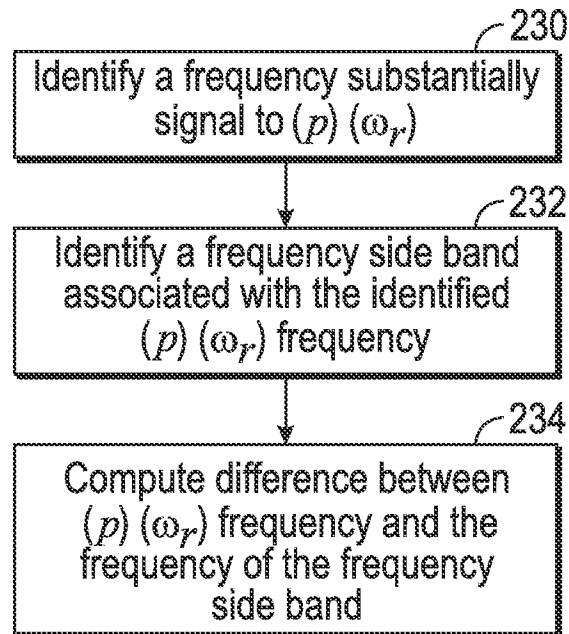


FIG. 7

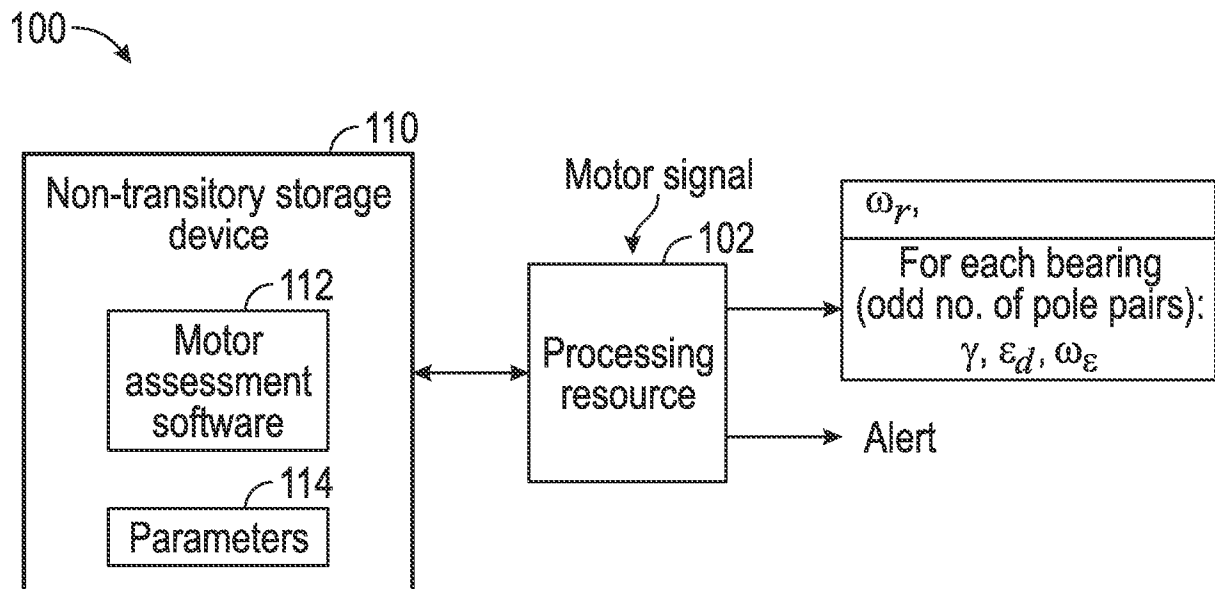


FIG. 8

A. CLASSIFICATION OF SUBJECT MATTER**F04D 13/08(2006.01)i, F04D 15/00(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHEDMinimum documentation searched (classification system followed by classification symbols)
F04D 13/08; E21B 43/12; E21B 43/00; G01R 31/06; H02K 5/24; F16C 41/00; F04D 15/00Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility modelsElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: electrical submersible pump, induction motor, permanent magnet, frequency domain, shaft speed, twist angle, and vibration frequency**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2012-0098358 A1 (PRIETO, CARLOS A.) 26 April 2012 See paragraphs [0015]-[0020] and figure 1.	1-20
A	US 2006-0006879 A1 (MIRAFZAL et al.) 12 January 2006 See abstract and claim 1.	1-20
A	US 2015-0159475 A1 (PRIETO et al.) 11 June 2015 See paragraphs [0016]-[0019] and figures 1-5.	1-20
A	US 2006-0175064 A1 (YURATICH, MICHAEL ANDREW) 10 August 2006 See paragraphs [0078]-[0084], [0091] and figures 2-6.	1-20
A	US 2014-0205222 A1 (BAKER HUGHES INCORPORATED) 24 July 2014 See paragraphs [0026]-[0035] and figures 1-5.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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"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

26 February 2016 (26.02.2016)

Date of mailing of the international search report

02 March 2016 (02.03.2016)

Name and mailing address of the ISA/KR

International Application Division

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/036669

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