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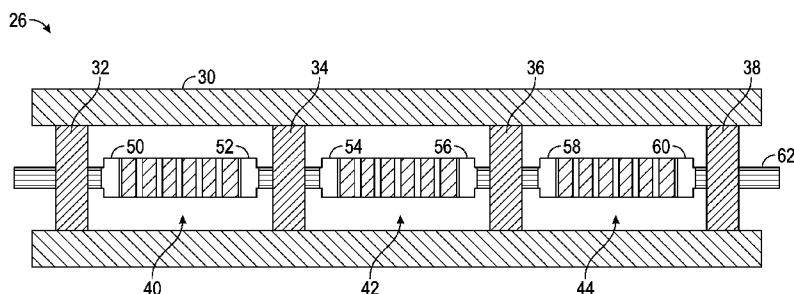


FIG. 2

(57) Abstract: Methods and systems for estimating temperature and/or fluid flow rate of an electric submersible pump (ESP) are provided. Positive and negative voltage and current sequences are generated based on the motor terminal voltage estimates and measured surface currents. Temperature can then be estimated for example by computing an estimate of rotor resistance from the extracted positive sequence voltage and current and then computing an estimate of temperature based on the estimated rotor resistance. Flow rate can be estimated by estimating the direct current (DC) torque of the positive and negative voltage and current sequences, subtracting out a viscosity drag force estimate to estimate the total DC torque, computing output power of the motor based on the estimated total DC torque, and using power and motor speed as inputs to a flow rate determination operation. The operation of the ESP is adjustable based on the estimated temperature and/or fluid flow rate.



ELECTRIC SUBMERSIBLE PUMP TEMPERATURE AND FLOW RATE**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, temperature hotspots internal to the ESP's motor, 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] Various performance parameters associated with a downhole induction motor and electric submersible pump are determined based on surface measurements of current and voltage. In one embodiment, a method is described by which rotor temperature and/or pump flow rate is estimated. If either of these estimated parameters are determined to be outside of a normal operating condition, a corrective action may be taken (e.g., turning of the pump). The parameters may be determined by measuring the voltage and current of each phase of a multi-phase distribution system to the downhole motor and, based on the measured voltage and current, estimating the voltage at the motor terminals. Positive and negative voltage and current sequences are extracted based on the motor terminal voltage estimates and measured currents. Temperature can then be estimated for example by computing an estimate of rotor resistance from the extracted positive sequence voltage and current and then computing an estimate of temperature based on the estimated rotor resistance. Flow rate can be estimated by estimating the direct current (DC) torque of the positive and negative voltage and current sequences, subtracting out a viscosity drag force estimate to estimate the total DC torque, computing output power of the motor based on the estimated total DC torque, and using power and motor speed as inputs to a flow rate determination operation. A non-transitory storage device may include software that, when executed by a processing system, may cause the processing system to estimate temperature and/or fluid flow rate of electric submersible pump. A system also is disclosed for estimating temperature and/or flow rate.

[0006] 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

[0007] Embodiments of the disclosure are described with reference to the following figures:

[0008] 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;

[0009] Fig. 2 shows an example of an induction motor including multiple radial bearings in accordance with various embodiments;

[0010] Fig. 3 shows an example of a method for estimating temperature of a rotor of an induction motor used down-hole to drive a pump in accordance with various embodiments;

[0011] Fig. 4 shows an example of an approximately equivalent circuit model of the motor described herein in accordance with various embodiments;

[0012] Fig. 5 illustrates an example of the estimation of rotor resistance in accordance with various embodiments;

[0013] Fig. 6 illustrates another example of the estimation of rotor resistance in accordance with various embodiments;

[0014] Fig. 7 depicts multiple series-connected motors for which individual rotor temperatures can be estimated in accordance with various embodiments;

[0015] Fig. 8 shows an example of a method for estimating temperature of individual rotors in a multi-rotor motor configuration in accordance with various embodiments;

[0016] Fig. 9 shows an example of a method for estimating flow rate of a downhole pump in accordance with various embodiments;

[0017] Fig. 10 shows a technique for computing total DC torque from torques computed from positive and negative sequences; and

[0018] Fig. 11 shows a system diagram of a motor monitor processing system in accordance with various embodiments.

DETAILED DESCRIPTION

[0019] 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.

[0020] 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.

[0021] References to “based on” should be interpreted as “based at least on.” For example, if the calculation of parameter X is “based on” value Y, then the calculation of X is based at least on the value of Y; the calculation of X may be based on other values as well.

[0022] 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.

[0023] 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.

[0024] As explained above, ESPs operated down-hole may experience any of a variety of failures due at least in part to the harsh environments in which the ESPs operate. An ESP may include a pump that is driven by an electric induction motor. A symptom of a failure or a potential future failure of a pump or motor is the temperature of the motor's rotor becoming excessive (e.g., greater than a threshold acceptable limit). Another symptom of a problem or potential problem is a change in flow rate of the fluid being lifted by the ESP such that the flow rate is outside an expected range of normal values.

[0025] The disclosed embodiments include a processing system provided at the surface that analyzes an electric signal of the induction motor and, from that signal, estimates rotor temperature and/or fluid flow rate. In some embodiments, the current and voltage at the surface to be provided to the downhole motor are measured. The terminal voltage of the downhole motor is estimated based on the surface measurement of current and voltage. The estimated motor terminal voltage and the current are further processed to extract positive sequence voltage and current and, from the positive sequence values, the rotor's resistance is estimated. Temperature then can be estimated based on the rotor's estimated resistance. In some embodiments, a series connected set of multiple motors is provided downhole and the temperature of each such motor's rotor(s) is estimated. To estimate fluid flow rate of the ESP, motor input torque is estimated based on extracted positive and negative sequences of current and voltage. Motor speed also can be estimated and, with the estimated torque, used to compute motor power. Flow rate can be estimated based on the estimates of motor power and speed. Temperature and/or flow rate then

can be compared to their normal operating ranges and corrective actions (e.g., turning off the motor and pump) can be taken upon detecting a deviation from the normal range.

[0026] 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 systems and methods disclosed herein may be focused on hydrocarbon wells, it is understood that these and other 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, hydrocarbons from a sump, and so on. In the case of an oil well, an ESP 24 may be deployed in the completion 10 in order to improve production of hydrocarbons.

[0027] 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.

[0028] 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 and thus may be a multi-phase power drive. 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 VSD 90 and digitizes the signal. The signal may include measurements of voltage and current for each of multiple phases 92. The digital acquisition system 95 may include one or more analog-to-digital converts (DACs) to convert analog VSD signals to digital form. The digitized signals are then provided to a motor monitor processing system 100 for the computation of estimates of motor temperature and pump flow rate.

[0029] The motor monitor processing system 100 thus receives the digitized surface current and voltage measurement and processes them to estimate the temperature of the motor's rotor as well as fluid flow rate as is explained in detail below. An alert 101 may be generated by the motor monitor processing system 100 to announce the detection of a problem (e.g., temperature and/or flow rate being outside a corresponding nominal range). The motor monitor processing system 100 alternatively or additionally may generate a feedback signal 103 to be provided to the VSD 90 to change the operation of the motor 26 (e.g., reduce the speed of the motor, turn the motor off, etc.).

[0030] The motor 26 may be implemented as an induction motor (and thus may also be referred to as induction motor 26). 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 what is 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, shaft speed, and/or motor 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.

[0031] Fig. 3 shows an example of a method for estimating temperature of a downhole induction motor's rotor. The operations can be performed in the order shown, or in a different order. Further, two more of the operations may be performed concurrently rather than sequentially. At 102, the method includes measuring the voltage and current at the surface. In some embodiments, the electrical power to operate the downhole motor and pump is a 3-phase supply and thus, at 102, the voltage and current of each of the three phases is measured. For example, the output voltage and current of the VSD 90 is measured and digitized by the digital acquisition system 95. A low resistance resistor may be provided on each of the three phase conductors and the voltage across the resistor is monitored and used as a proxy for the current of that phase. The digitized measurements of current and voltage may be provided to the motor monitor processing system 100 which performs some or all of the rest of the operations of Fig. 3.

[0032] At 104, the method includes estimating the motor's terminal voltage, that is, the voltage at the input terminals of the motor itself, which may be connected through lengthy (dozens, hundreds or thousands of feet) cables to the VSD 90. The estimate of motor terminal voltage may be based on the surface measured voltage as well as the surface measured current. As the

motor may be located hundreds or thousands of feet downhole, due to the impedance of the electrical cables themselves that transfer power to the motor, the voltage at the motor will generally be less than the voltage at the surface. Using, for example, a simplified power frequency cable model, the motor terminal voltages for all three phases may be determined as:

$$v_{m,x}(t) = v_{s,x}(t) - (R_{cable,x})i_x(t) - (L_{cable,x})\frac{di_x(t)}{dt} \quad (1)$$

where “m” refers to the motor, “x” refers to the phase (e.g., phase a, phase b, phase c), “s” refers to the surface (i.e., $v_{s,x}(t)$ is the voltage measured at the surface for each phase with respect to time), $R_{cable,x}$ and $L_{cable,x}$ refer to the resistance and inductance of a cable of each phase from the surface to the motor, and $\frac{di_x(t)}{dt}$ is the derivative of current of each phase with respect to time. One implementation of equation (1) above is provided below:

$$v_{m,x}(k) = v_{s,x}(k) - (R_{cable,x})i_x(k) - (L_{cable,x})\frac{i_x(k) - i_x(k-1)}{T_s} \quad (2)$$

where “k” is an index value to a given voltage sample and T_s refers to the sampling interval.

[0033] The estimated voltage at the motor’s terminal as well as the currents may be unbalanced due to electrical asymmetry in the system such as cable asymmetry, motor lead extension (MLE) asymmetry, etc. As such, the illustrative embodiment of Fig. 3 for estimating rotor temperature may be performed by extracting the positive sequence voltage and positive sequence current (operation 106 in Fig. 3). Considering a three-phase system, symmetrical components (positive sequence, negative sequence, and zero sequence) permit analysis of power system operations during unbalanced conditions such as those caused by faults between phases and/or ground, open phases, unbalanced impedances, and so on. The positive sequence set includes the balanced three-phase currents and line-to-neutral voltages provided by the VSD 90. The positive sequence set is equal in magnitude and phase displaced by 120 degrees rotating at

the system frequency with a phase sequence of normally a, b, c. The negative sequence set is also balanced with three equal magnitude quantities at 120 degrees apart but with the phase rotation or sequence reversed, or a, c, b. The members of the zero-sequence set of rotating phasors are equal in magnitude and are in phase.

[0034] Any suitable technique to extract the positive sequence component can be performed by the motor monitor processing system 100 in operation 106. For example, in some embodiments, the positive sequence component can be extracted as follows. The estimated/calculated three phase motor terminal voltages and currents can be processed by a narrow bandpass filter to recover the content at the fundamental frequency. The narrow bandpass filter may be tuned to the fundamental frequency detected in the estimated motor terminal voltage and current. The narrow bandpass filter may be tuned to the fundamental frequency through a feedback signal generated by the combination of a zero crossing detector and adaptive tuner. Additionally or alternatively, a phase-lock loop (PLL) may be used to provide an estimate of the fundamental frequency.

[0035] The motor monitor processing system 100 then extracts the positive sequence components from the filtered motor terminal voltages and currents. The motor monitor processing system 100 also may extract the negative and/or zero sequence components. Any of a variety of techniques can be employed to extract the sequence components. For example, the sequence components of voltages and currents can be estimated using Fortescue's method. Per that method,

$$x_{aP}(t) = \frac{1}{3} [x_a(t) + S(120^\circ)x_b(t) + S(-120^\circ)x_c(t)] \quad (3)$$

$$x_{aN}(t) = \frac{1}{3} [x_a(t) + S(-120^\circ)x_b(t) + S(120^\circ)x_c(t)] \quad (4)$$

$$x_{a0}(t) = \frac{1}{3} [x_a(t) + x_b(t) + x_c(t)] \quad (5)$$

where “S” is a phase shifter operator (e.g., $S(120^0)x(t)$ refers to shifting the phase of $x(t)$ by 120 degrees in a positive direction and $S(-120^0)x(t)$ refers to shifting the phase of $x(t)$ by 120 degrees in a negative direction). The variable “x” in the above three equations refers to motor voltage or current. Thus, “ $x_{aP}(t)$ ” refers to the positive sequence component for current/voltage for phase a. Similarly, “ $x_{aN}(t)$ ” refers to the negative sequence component for current/voltage for phase a and “ $x_{a0}(t)$ ” refers to the zero sequence component for current/voltage for phase a.

[0036] Many filtering techniques can be used to perform operations of equations (3)-(5). One such example is to use a phase shifting all-pass filter such as:

$$H_{APF}(s) = \frac{1-(T\sqrt{3})s}{1+(T\sqrt{3})s} \quad (6)$$

$$H_{APF}(j\omega) = 1e^{-j2 \tan^{-1}(\omega T\sqrt{3})} \quad (7)$$

This type of filter introduces -120^0 phase shift at frequency $\omega = \frac{1}{T}$ rad/s, thereby implementing the $S(-120^0)$ operator. Thus, the phase shifting operators can be implemented using the following equations:

$$S(-120^0) \approx 1e^{-j2 \tan^{-1}(\omega T\sqrt{3})} \quad (8)$$

$$S(120^0) = -1-S(-120^0) \quad (9)$$

In real-time or near real-time, the implementation can be performed using the following digital equations:

$$y(k) = \frac{1}{1+\frac{T\sqrt{3}}{T_s}} \left[\left(1 - \frac{T\sqrt{3}}{T_s}\right) x(k) + \frac{T\sqrt{3}}{T_s} x(k-1) + \frac{T\sqrt{3}}{T_s} y(k-1) \right] \quad (10)$$

Once the phase “a” positive sequence component for voltage and current is computed, the corresponding positive sequence voltages and currents can be calculated by shifting the phase “a” sequence components $\pm 120^\circ$.

[0037] At 108 in the example of Fig. 3, the method includes estimating the resistance of the rotor based on the extracted positive sequence voltage and current. Various techniques can be employed by the motor monitor processing system 100 to estimate rotor resistance (designated as r_r). At least some of these techniques may be based on the approximate steady state equivalent circuit of the motor 26 as shown in the example of Fig. 4. The resistance R_M represents the coreloss resistance. The resistance r_s represents the stator resistance and is in series with the mutual inductance l_h multiplied by a stator stray factor σ_s , as well as l_h multiplied by a rotor stray factor σ_r and the rotor resistance r_r divided by the rotor slip, S . The mutual inductance l_h is also provided as shown. These values can be computed through known techniques such as through use of an analytical, semi-empirical motor model, which uses as inputs motor winding code information, stator temperature information, and operating condition information (e.g., root mean square voltage and approximate horsepower). The model outputs the various inductances, resistances, and factors. Two other inductance values not shown in Fig. 4 are used below—stator inductance and rotor inductance. The stator inductance l_s and rotor inductance l_r may be computed based on the mutual inductance l_h and the stator and rotor stray factors σ_s and σ_r as:

$$l_s = (1 + \sigma_s) l_h \quad (11)$$

$$l_r = (1 + \sigma_r) l_h \quad (12)$$

[0038] Fig. 5 shows an example of a technique for estimating (108) rotor resistance based on extracted positive sequence voltage and current. The blocks in Fig. 5 represent operations that may be performed by the motor monitor processing system 100. The positive sequence motor

voltages estimated for each phase a, b, and c (i.e., V_{maP} , V_{mbP} , V_{mcP}) are provided as inputs to an abc-to-alpha beta transformation operation 120. The abc-to-alpha beta transformation 120 may be implemented using the following equation:

$$\vec{F}_{sv} = \frac{2}{3} [F_a e^{j0} + F_b e^{j\frac{2\pi}{3}} + F_c e^{-j\frac{2\pi}{3}}] \quad (13)$$

where “F” represents the variable being transformed (i.e., current or voltage, and voltage in the case of operation 120). The positive sequence current values (i_{a1P} , i_{b1P} , i_{c1P}) also are transformed through an abc-to-alpha beta transformation (122). The result of the transformations 120 and 122 are a voltage space vector $\vec{v}_s^s$ and a current space vector $\vec{i}_s^s$, respectively. These space vectors are computed with respect to the stator reference frame and both are provided as inputs to operation 124 at which the stator flux $\vec{\Psi}_s^s$ is calculated. The stator flux may be calculated with the following equation:

$$\vec{\Psi}_s^s = \int (\vec{v}_s^s - r_s \vec{i}_s^s) dt \quad (14)$$

The stator resistance r_s is estimated based on stator temperature, which may be obtained from a temperature sensor (e.g., a thermocouple) placed on the stator itself. The stator temperature measurement may be transmitted to the motor monitor processing system 100 through known data transfer techniques. The stator resistance may be computed from stator temperature through use, for example, of the equation (15) below:

$$r_s = r_{s0} + \frac{r_{s0}}{T_0} \left[T - \frac{1}{\alpha} \right] \quad (15)$$

where T is the stator's temperature, α is the thermal coefficient of resistance of the stator (a known value), and r_{s0} and T_0 is a predetermined stator resistance at a known temperature, respectively. A resetting DC term also is provided as an input to operation 124 to subtract out

any DC value present when computing the integral of Eq. (14). The stator flux $\vec{\psi}_s^s$ is then used to at 126 to calculate the rotor flux $\vec{\psi}_r^s$ with respect to the stator reference frame. The rotor flux may be calculated with the following equation:

$$\vec{\psi}_r^s = \left(\frac{l_r}{l_h}\right) \vec{\psi}_s^s + \left(l_h - \frac{l_r l_s}{l_h}\right) \vec{i}_s^s \quad (16)$$

[0039] At 128, the rotor flux angle θ_r is extracted from rotor flux $\vec{\psi}_r^s$. The rotor flux angle is then provided to another transformation at 130. This transformation may be an alpha beta-to-dq transformation which transforms the current space vector $\vec{i}_s^s$ to non-rotating current values i_{sq} and i_{sd} using the rotor flux angle θ_r . These latter current values along with an estimate of the fundamental frequency f_{fund} (determined at 132 and discussed above) and an estimate of the rotor speed f_r (determined at 134 using, for example, motor current signature analysis (“MCSA”)) are provided as inputs to operation 136 at which the rotor resistance r_r is computed. The computation of rotor resistance may be computed as the slip frequency ω_{sl} (difference between fundamental frequency and rotor speed in units of radians per unit time) times the ratio of i_{sd} to i_{sq} . That is,

$$r_r = \omega_{sl} \times \frac{i_{sd}}{i_{sq}} \quad (17)$$

[0040] Fig. 6 illustrates another example of a technique for estimating rotor resistance r_r . Operations 120 and 122 are the same as described above to transform the voltage and currents to space vectors with respect to the stator reference plane. The current space vector $\vec{i}_s^s$ is provided as input to operation 140 during which the magnitude I_{sd} and angle θ_{r1} of that vector is computed. Angle θ_{r1} is provided as an input to an alpha beta-to-dq transformation operation 142 along with the voltage space vector $\vec{v}_s^s$. The result of the transformation 142 are stationary voltages v_{sd} and v_{sq} which are inputs to operation 144 along with the fundamental frequency and rotor speed

estimates. Operation 144 calculates an estimate of rotor resistance and may be performed using the following equation:

$$r_r = \omega_{sl} \chi \sqrt{\frac{2\pi f_{und} l_h^2 l_r}{2\pi f_{und} l_s \frac{v_{sq}}{I_{sd}}} - l_r^2} \quad (18)$$

[0041] Referring back to Fig. 3, at 110 the method includes estimating rotor temperature based on the estimated rotor resistance. An example of an equation to estimate rotor temperature is:

$$T = \frac{1}{\alpha} + \left[\frac{r_r}{r_{r0}} - 1 \right] T_0 \quad (19)$$

where T is the estimate of rotor temperature, α is the thermal coefficient of resistance of the rotor (a known value), and r_{r0} and T_0 is a predetermined rotor resistance at a known temperature,.

[0042] At 112, once the rotor temperature is estimated, the motor monitor processing system 100 may compare the rotor temperature estimate T to a threshold value. If the rotor temperature is greater than the threshold (e.g., indicative of a problem), the motor monitor processing system 100 may take or at least initiate a corrective action at 114. Examples of corrective actions may include providing a feedback signal 103 to the VSD 90 to cause the VSD 90 to shut power off to motor 26 or reduce the voltage provided to the motor. Different or other corrective actions may be performed as well such as generating an alert 101 (e.g., text message, audible alarm, visual alarm, email, etc.).

[0043] In some embodiments, the downhole motor 26 includes multiple motors connected in series. Fig. 7 shows an example of three sub-motors connected in series and comprising an upper tandem (UT) motor 152, a center tandem (CT) motor 154, and a lower tandem (LT) motor 156. The above discussed technique for estimating rotor temperature can be extended to estimating the temperature of the rotors of the individual motors 152-156. Assuming that the motor has ‘n’

rotors, the voltage across each sub-motor is V_{1mP} , V_{2mP} , ..., V_{nmP} , where 1, 2, ..., n identifies the sub-motor, “m” refers to the voltage estimated at the motor itself (as opposed to the surface measurement of voltage) and “P” refers to positive sequence voltages.

[0044] Fig. 8 shows an example of an embodiment of a method for estimating the temperature of individual rotors in a multi-rotor motor configuration. The operations shown in Fig. 8 can be performed in the order shown or in a different order, and two or more of the operations may be performed concurrently. The motor monitor processing system 100 may perform some or all of the operations shown.

[0045] At 202, the method includes measuring the surface voltages and currents of the various phases as explained above. At 204, the method includes estimating the voltage and current at the downhole motor, again as explained above. Operation 206 includes obtaining the temperatures of the individual stators across the various sub-motors. As noted above, a temperature sensor may be provided on or near each stator or for a corresponding rotor (i.e., each stator may be instrumented with a separate temperature sensor) and the stator temperature readings can be transmitted to the surface and received by the motor monitor processing system 100. At 208, the motor monitor processing system 100 calculates the mean stator temperature (T_{mean}), for example, by dividing the sum of the individual stator temperatures by the number of stators.

[0046] At 210, the motor monitor processing system 100 extracts the positive sequence currents and voltages of the phases as explained above. These positive sequence currents and voltages are the voltages and currents of the collective series of connected sub-motors, not the voltages of the individual sub-motors. At 212, the motor monitor processing system 100 calculates the mean positive sequence voltage of the sub-motors as the total positive sequence

voltage for all sub-motors combined divided by the number of sub-motors. The resulting mean is designated as V_{mean} .

[0047] At 214, the method includes calculating the positive sequence voltage of each individual sub-motor (sub-motors 152, 154, and 156 in the example of Fig. 7). The difference between the positive sequence voltage of a given sub-motor (V_{xmP}) and the voltage mean for a given phase is given by:

$$\Delta V_x = V_{xmP} - V_{mean} = \alpha(T_{sx} - T_{mean}) \times I_p \quad (20)$$

where the subscript x identifies the individual sub-motor, α is the thermal coefficient of resistance of the motor's corresponding rotor, T_{sx} is the temperature of the stator of that sub-motor, and I_p is the positive sequence current of the corresponding phase. Solving for the individual sub-motor voltage, V_{xmP} , provides:

$$V_{xmP} = \alpha(T_{sx} - T_{mean}) \times I_p + V_{mean} \quad (21)$$

Equation (21) thus is solved by the monitor processing system 100 to compute the positive sequence voltage for each rotor and for each phase. Now that the individual rotor positive sequence voltages are determined, the resistance of the rotor can be determined (216) in much the same way as described with respect to, for example, Figs. 5 and 6. Equation (19) then can be used to estimate the temperature of the corresponding rotor (218). A thermal profile of the various rotors in the motor 26 can be determined. A thermal event assessment can be determined for each individual rotor by comparing its temperature to a threshold as explained previously. A corrective action can be initiated, for example, by the monitor processing system 100 if a given rotor temperature exceeds a threshold.

[0048] Fig. 9 shows an example of an embodiment of a method for estimating the flow rate of the downhole pump. The operations shown in Fig. 9 can be performed in the order shown or in a different order, and two or more of the operations may be performed concurrently. The motor monitor processing system 100 may perform some or all of the operations shown.

[0049] At 252, the method includes measuring the surface voltages and currents of the various phases as explained above. At 254, the method includes estimating the voltage and current at the downhole motor for each phase, again as explained above. Positive and negative voltage and current sequences are computed at 256.

[0050] The method includes computing (258) the electromagnetic DC torque for the positive voltage and current sequence and separately (260) for the negative voltage and current sequence. Fig. 10 illustrates an example of this computation. To compute the DC torque for the positive voltage sequence $\vec{V}_{fP}$ and current sequence $\vec{I}_{fP}$, a motor stator induced electromotive force (emf) vector $\vec{E}_{sP}$ is calculated at 280 based on the positive voltage and current sequence (at the fundamental frequency), as well as the motor per phase core-loss resistance (R_M) and the motor per phase stator resistance (r_s). The emf vector $\vec{E}_{sP}$ may be computed as:

$$\vec{E}_{sP} = \vec{V}_{fP} - \left[r_s * \left(\vec{I}_{fP} - \frac{\vec{V}_{fP}}{R_m} \right) \right] \quad (22)$$

At 282, the dot product of $\vec{E}_{sP}$ and an interim current vector $\vec{I1}$ is computed. The interim current vector $\vec{I1}$ may be computed as:

$$\vec{I1} = \vec{I}_{fP} - \frac{\vec{V}_{fP}}{R_m} \quad (23)$$

The dot vector operation is computed by multiplying corresponding elements of the $\vec{E}_{sP}$ and the $\vec{I1}$ vectors and summing the products together to generate an electromagnetic DC torque value

for the positive sequence current and voltage. Similar calculations are performed for the negative current and voltage sequences at 290 and 292 to generate an electromagnetic DC torque value for the negative sequence current and voltage. The two electromagnetic DC torques (for the positive and negative voltage and current sequences) are then added together at 262 in Fig. 9 (as also illustrated at 295 in Fig. 10) to compute the total electromagnetic DC torque.

[0051] At 264 in Fig. 9, the method may comprise subtracting a viscosity drag force from the total electromagnetic DC torque to compute the DC torque generated by the motor. Any of a variety of techniques can be employed to determine a viscosity drag force. In one example, an oil drag force /viscosity model may be generated apriori for the particular motor being used, such as through empirical analysis. This model may also factor in a friction load value from the bearings. Inputs to such a model may include motor speed as determined by, for example, MCSA, oil temperature, and oil pressure.

[0052] At 266, the motor speed is estimated (and may have been estimated and used in operation 264 to compute a viscosity drag force) and used at 268 to compute the output power from the motor. The motor's output power may be computed as the total electromagnetic DC torque computed at 264 multiplied by the motor speed.

[0053] At 270, the method includes determining the flow rate produced by the pump. In accordance with various embodiments, the motor's output power (which also represents the input power to the pump 30) and the motor speed (which also represents the pump's speed) are used, at least in part, to determine flow rate. In some examples, empirical studies can be performed on the pump (with a known number of pump stages) to measure flow rates for a known liquid (i.e., a liquid (e.g., water) with a known specific gravity), at a fixed reference speed, but at varying power levels for the pump. From such data, coefficients of a polynomial can be generated, and

will be application specific based on the particular pump being tested. The variable in the polynomial may itself be a function of pump input power, pump speed, and the specific gravity of whatever fluid is being pumped. In one example, the variable (X) to be input into the polynomial can be calculated as:

$$X = \frac{\text{power}}{(0.746)(\text{num})(SPG)\left(\frac{\omega}{\omega_{ref}}\right)^3} \quad (24)$$

where “power” is the output power from the motor as calculated above based on DC torque (and thus the input power to the pump), “num” is the number of stages of the pump, “SPG” is the specific gravity of the particular fluid being pumped, “ ω ” is the estimated motor (and thus pump) speed as determined by, for example, MSCA, and “ ω_{ref} ” is the reference speed of the motor during the empirical analysis explained above. The polynomial then is evaluated based on the calculated value of X to produce an estimate of the flow rate of the fluid being pumped.

[0054] At 272, the motor monitor processing system 100 determines whether the estimated flow rate is less than a particular threshold (which may be indicative of the lower range of a normal flow rate). If the flow rate is determined to be below the threshold, then a correct action may be initiated at 274 by the motor monitor processing system 100 as explained above. Otherwise, the process repeats.

[0055] Fig. 11 provides a system schematic of the motor monitor processing system 100 in accordance with an embodiment. The system 100 includes a processing resource 302 coupled to a non-transitory storage device 304. The processing resource 302 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 304 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 304 may be a single device or collection of multiple devices, and be either stand-alone storage devices or storage devices contained within the processing resource 302.

[0056] The non-transitory storage device 304 contains motor assessment software 306 that, when executed by the processing resource 302, cause the processing resource to perform some or all of the functionality described herein. The processing resource 302 can estimate, for example, rotor temperature and pump flow rate based on various inputs such as surface measured voltages and currents, stator temperatures, and other values as described herein. Alerts also can be generated or caused to be generated by the processing resource 302 as described above.

[0057] The techniques described herein permit the computation of the variables at each sampling instant without storing a long length value of current and voltage as well as statistical data. Use of statistical data is negligible. As such, the computation of temperature and flowrate can be computed quickly and efficiently.

[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:

measuring voltage and current of a power output of a multi-phase power drive configured to power a downhole motor to thereby produce measured voltage and current values;

based on the measured voltage and current values, estimating the voltage of the downhole motor for each of multiple phases;

extracting positive sequence voltage and current from the estimated voltage of the downhole motor and from the measured current value;

estimating temperature of the downhole motor or a fluid flow rate of a downhole pump powered by the downhole motor based on the extracted positive sequence voltage and current; and

adjusting operation of the downhole motor based on the estimated temperature or fluid flow rate.

2. The method of claim 1, wherein estimating the temperature or the fluid flow rate

comprises estimating the temperature, and wherein estimating the temperature comprises

estimating resistance of a rotor of the motor based on the extracted positive sequence voltage and current.

3. The method of claim 2, wherein estimating the temperature comprises computing an estimate of temperature of the rotor based on the estimated resistance of the rotor and a predetermined rotor resistance at a known temperature.

4. The method of claim 1, wherein estimating the temperature or the fluid flow rate comprises estimating the temperature, and wherein estimating the temperature comprises:

computing rotating voltage and space vectors based on the extracted positive sequence voltage and current, respectively;

computing non-rotating current values based on the computed rotating voltage and current space vectors; and

computing an estimate of temperature of a rotor of the motor based on the non-rotating current values, a fundamental frequency of the estimated voltage of the downhole motor, and an estimate of a speed of the motor.

5. The method of claim 1, wherein estimating the temperature or the fluid flow rate comprises estimating the temperature, and wherein estimating the temperature comprises:

computing rotating voltage and space vectors based on the extracted positive sequence voltage and current, respectively;

computing non-rotating voltage values based on the computed rotating voltage and space vectors; and

computing an estimate of temperature of a rotor of the motor based on the non-rotating voltage values, a fundamental frequency of the estimated voltage of the downhole motor, and an estimate of a speed of the motor.

6. The method 1, wherein estimating the temperature or the fluid flow rate comprises estimating the temperature of each of a plurality of sub-motors, and wherein extracting the positive sequence voltage includes extracting a positive sequence voltage of each of the plurality of sub-motors, and wherein estimating the temperature of each of the plurality of sub-motors comprises:

- obtaining a temperature of a stator of the respective sub-motor;
- calculating a mean positive sequence voltage based on extracted positive sequence voltage of each of the plurality of sub-motors; and
- estimating the resistance of the sub-motor's rotor based on the temperature of the stator of the respective sub-motor, the calculated mean positive sequence voltage, and an extracted positive sequence current.

7. The method of claim 1, wherein estimating the temperature or the fluid flow rate comprises estimating the fluid flow rate, and wherein estimating the fluid flow rate comprises:

- extracting negative sequence voltage and current;
- computing a torque value based on the extracted positive and negative sequence voltage and current; and
- determining an estimate of the fluid flow rate based on the computed torque, a specific gravity of pumped fluid, and an estimate of motor speed.

8. The method of claim 7, further comprising computing an output power of the motor based on the computed torque value and the estimate of motor speed.

9. The method of claim 7, wherein computing the torque value comprises:
- computing a direct current (DC) torque based on the extracted positive sequence voltage and current;
 - computing a DC torque based on the extracted negative sequence voltage and current;
 - and
 - summing the computed DC torques based on the extracted positive and negative sequence voltage and currents to produce a total electromagnetic DC torque.
10. The method of claim 10, further comprising subtracting a viscosity drag force from the total electromagnetic DC torque to compute the torque value.
11. A non-transitory storage device containing software that, when executed by a processing resource, causes the processing resource to:
- estimate a voltage of a downhole motor for each of multiple phases based on measurements of voltage and current from a multi-phase power drive configured to power a downhole motor;
 - extract positive sequence voltage and current from the estimated voltage of the downhole motor and from the measured current;
 - estimate temperature of the downhole motor or a fluid flow rate of a downhole pump powered by the downhole motor based on the extracted positive sequence voltage and current; and

generate a signal to adjust operation of the downhole motor based on the estimated temperature or fluid flow rate.

12. The non-transitory storage device of claim 11, wherein the software causing the processing resource to estimate the temperature or fluid flow rate comprises the software, when executed, causing the processing resource to estimate the temperature by causing the processing resource to:

estimate resistance of a rotor of the motor based on the extracted positive sequence voltage and current; and
compute an estimate of the temperature of the rotor based on the estimated resistance of the rotor and a predetermined rotor resistance at a known temperature.

13. The non-transitory storage device of claim 11, wherein the software causing the processing resource to estimate the temperature or fluid flow rate comprises the software, when executed, causing the processing resource to estimate the temperature by causing the processing resource to:

compute rotating voltage and space vectors based on the extracted positive sequence voltage and current, respectively;
compute non-rotating current values based on the computed rotating voltage and current space vectors; and
compute an estimate of temperature of a rotor of the motor based on the non-rotating current values, a fundamental frequency of the estimated voltage of the downhole motor, and an estimate of a speed of the motor.

14. The non-transitory storage device of claim 11, wherein the software causing the processing resource to estimate the temperature or fluid flow rate comprises the software, when executed, causing the processing resource to estimate the temperature by causing the processing resource to:

compute rotating voltage and space vectors based on the extracted positive sequence voltage and current, respectively;

compute non-rotating voltage values based on the computed rotating voltage and space vectors; and

compute an estimate of temperature of a rotor of the motor based on the non-rotating voltage values, a fundamental frequency of the estimated voltage of the downhole motor, and an estimate of a speed of the motor.

15. The non-transitory storage device of claim 11, wherein the software causing the processing resource to estimate the temperature or fluid flow rate comprises the software, when executed, causing the processing resource to estimate the temperature of each of a plurality of sub-motors by causing the processing resource to:

extract a positive sequence voltage of each of the plurality of sub-motors;

calculate a mean positive sequence voltage based on extracted positive sequence voltage of each of the plurality of sub-motors; and

estimate the resistance of the sub-motor's rotor based on a temperature of a stator of the respective sub-motor, the calculated mean positive sequence voltage, and an extracted positive sequence current.

16. The non-transitory storage device of claim 11, wherein the software causing the processing resource to estimate the temperature or fluid flow rate comprises the software, when executed, causing the processing resource to estimate the fluid flow rate by causing the processing resource to:

extract negative sequence voltage and current;

compute a torque value based on the extracted positive and negative sequence voltage and current;

compute an output power of the motor based on the computed torque value and an estimate of motor speed; and

determine an estimate of the fluid flow rate based on the computed output power, a specific gravity of pumped fluid, and the estimate of motor speed.

17. The non-transitory storage device of claim 16, wherein the software, when executed, causes the processing resource to:

compute a direct current (DC) torque based on the extracted positive sequence voltage and current;

compute a DC torque based on the extracted negative sequence voltage and current;

sum the computed DC torques based on the extracted positive and negative sequence voltage and currents to produce a total electromagnetic DC torque; and

subtract a viscosity drag force from the total electromagnetic DC torque to compute the torque value.

18. A motor monitor processing system, comprising:
- a storage device storing executable code; and
 - a processing resource coupled to the storage device;
- wherein the processing resource, upon executing the executable code, is configured to:
- estimate a voltage of a downhole motor for each of multiple phases based on measurements of voltage and current from a multi-phase power drive configured to power a downhole motor;
 - extract positive sequence voltage and current from the estimated voltage of the downhole motor and from the measured current;
 - estimate temperature of the downhole motor based on the extracted positive sequence voltage and current; and
 - generate a signal to adjust operation of the downhole motor based on the estimated temperature or fluid flow rate.
19. The motor monitor processing system of claim 18, wherein the processing resource, upon executing the executable code, is configured to:
- estimate resistance of a rotor of the motor based on the extracted positive sequence voltage and current; and
 - compute an estimate of the temperature of the rotor based on the estimated resistance of the rotor and a predetermined rotor resistance at a known temperature.

20. The motor monitor processing system of claim 18, wherein the processing resource, upon executing the executable code, is configured to:

extract negative sequence voltage and current;

compute a torque value based on the extracted positive and negative sequence voltage and current;

compute an output power of the motor based on the computed torque value and an estimate of motor speed; and

determine an estimate of the fluid flow rate based on the computed output power, a specific gravity of pumped fluid, and the estimate of motor speed.

generate the signal to adjust operation of the downhole motor based on the determined estimate of the fluid flow rate.

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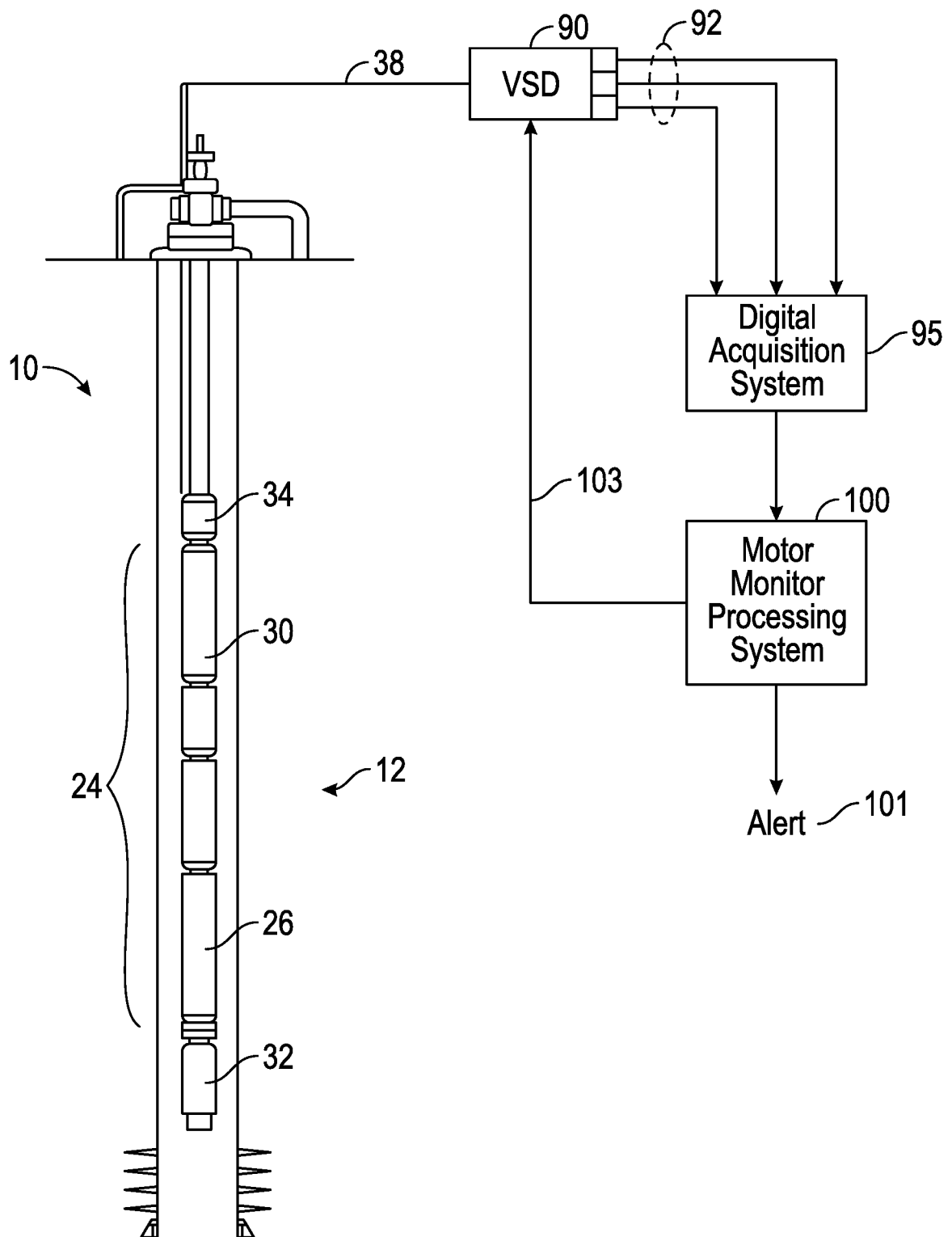


FIG. 1

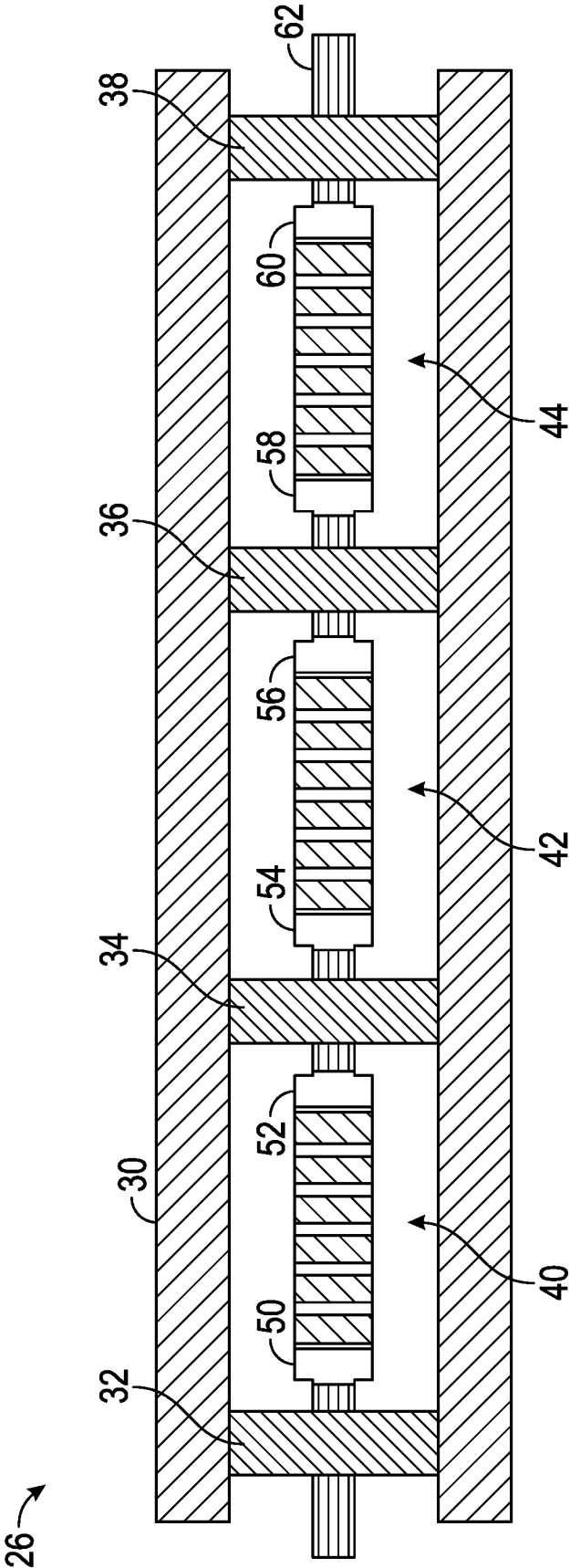


FIG. 2

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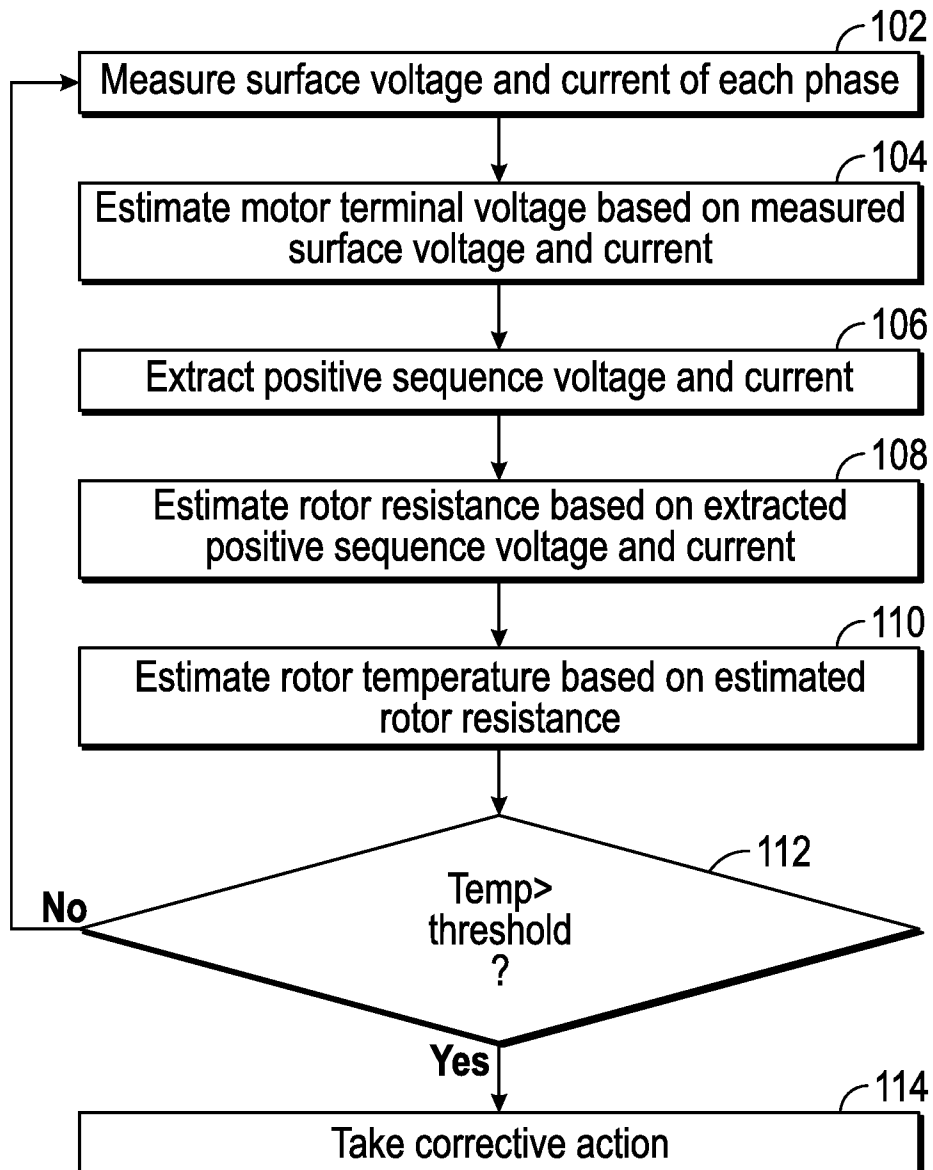


FIG. 3

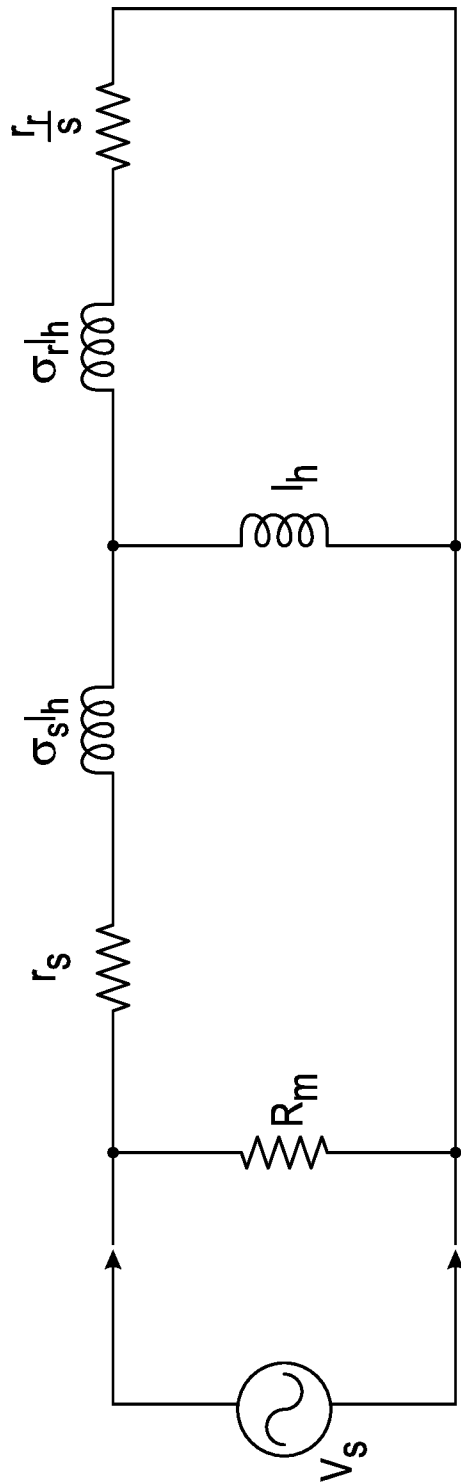


FIG. 4

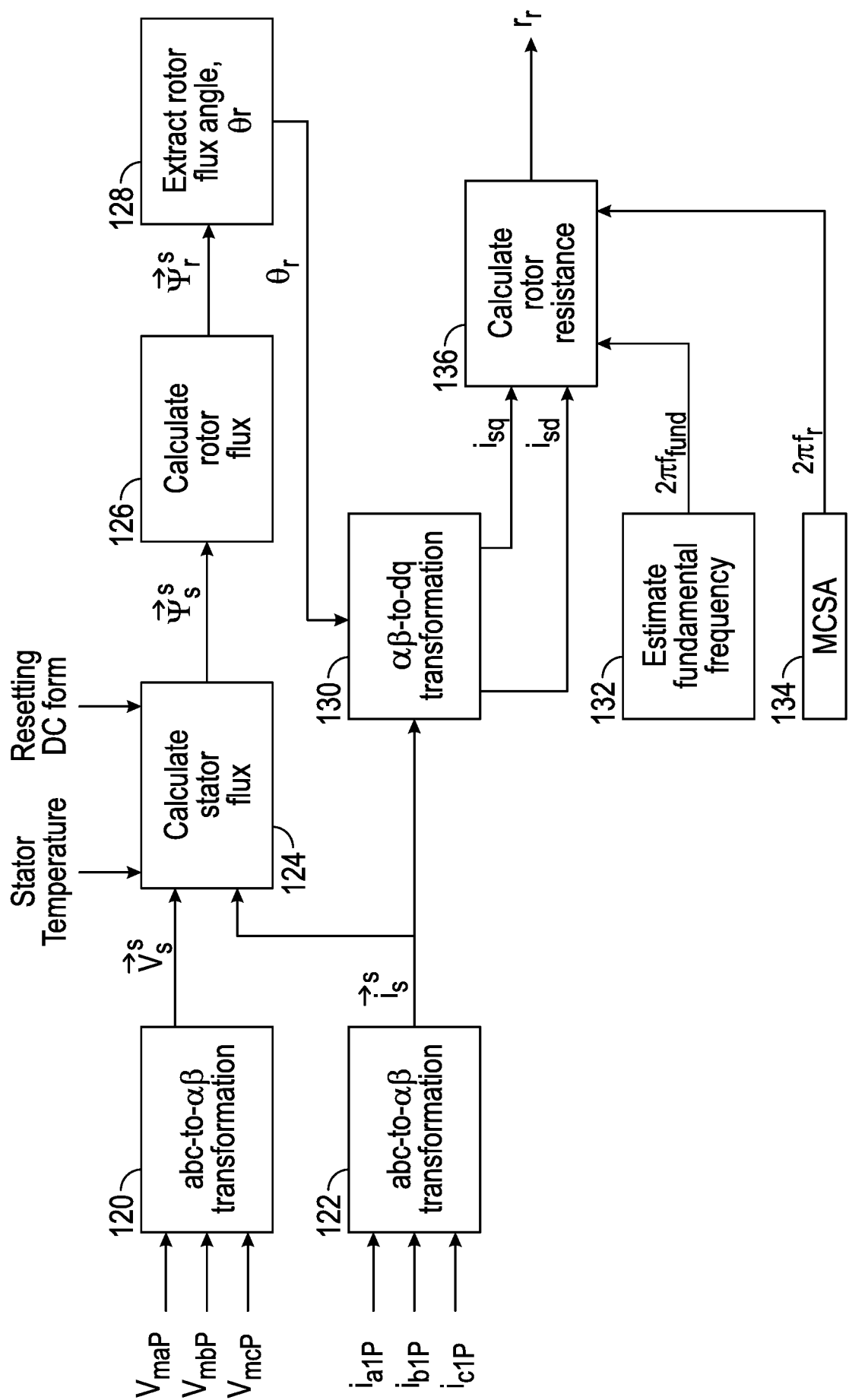


FIG. 5

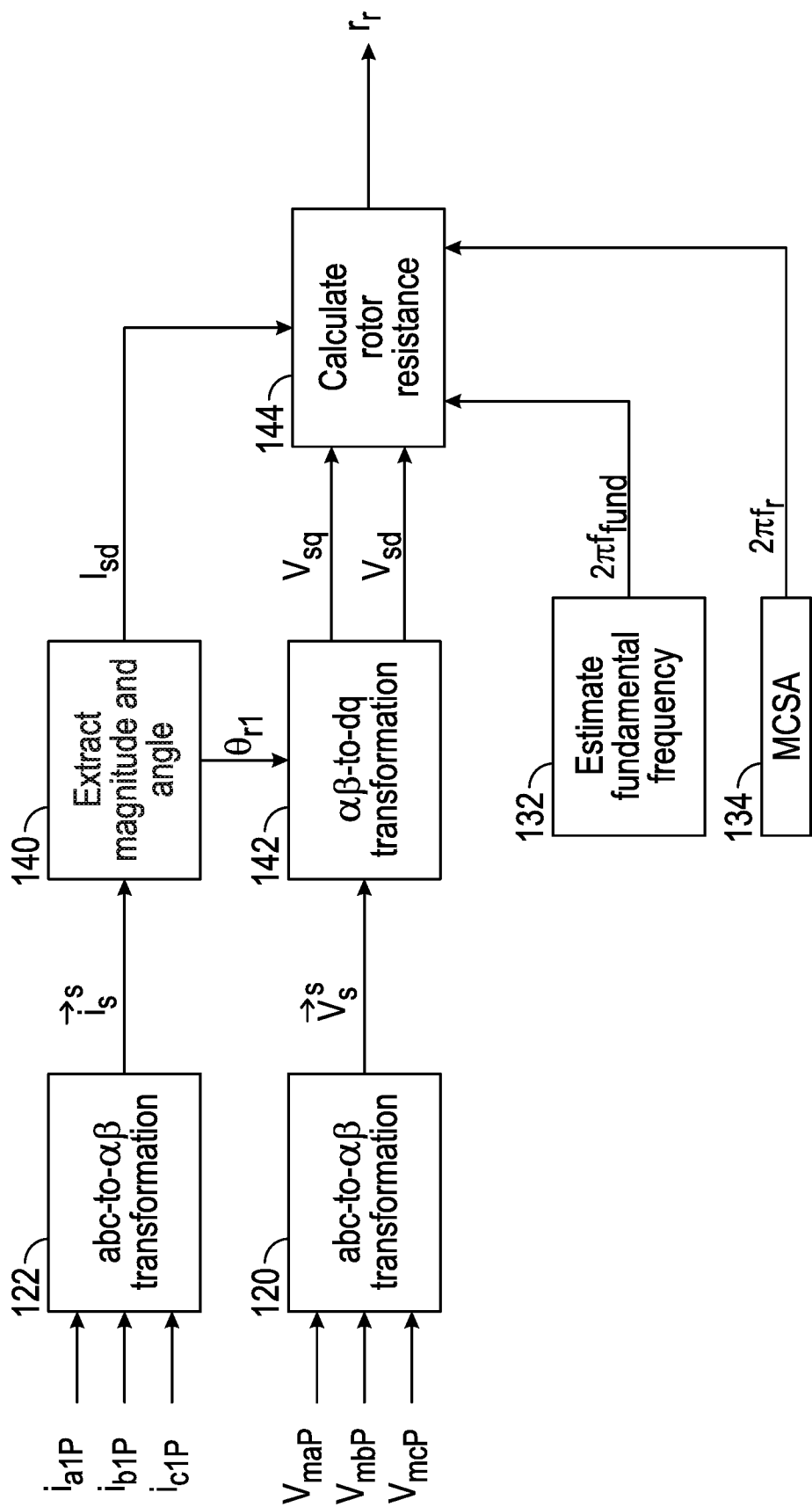


FIG. 6

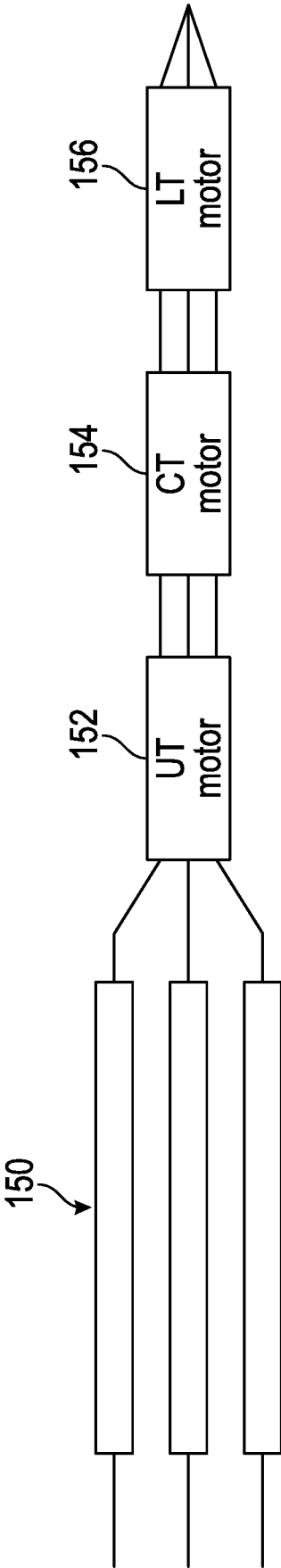


FIG. 7

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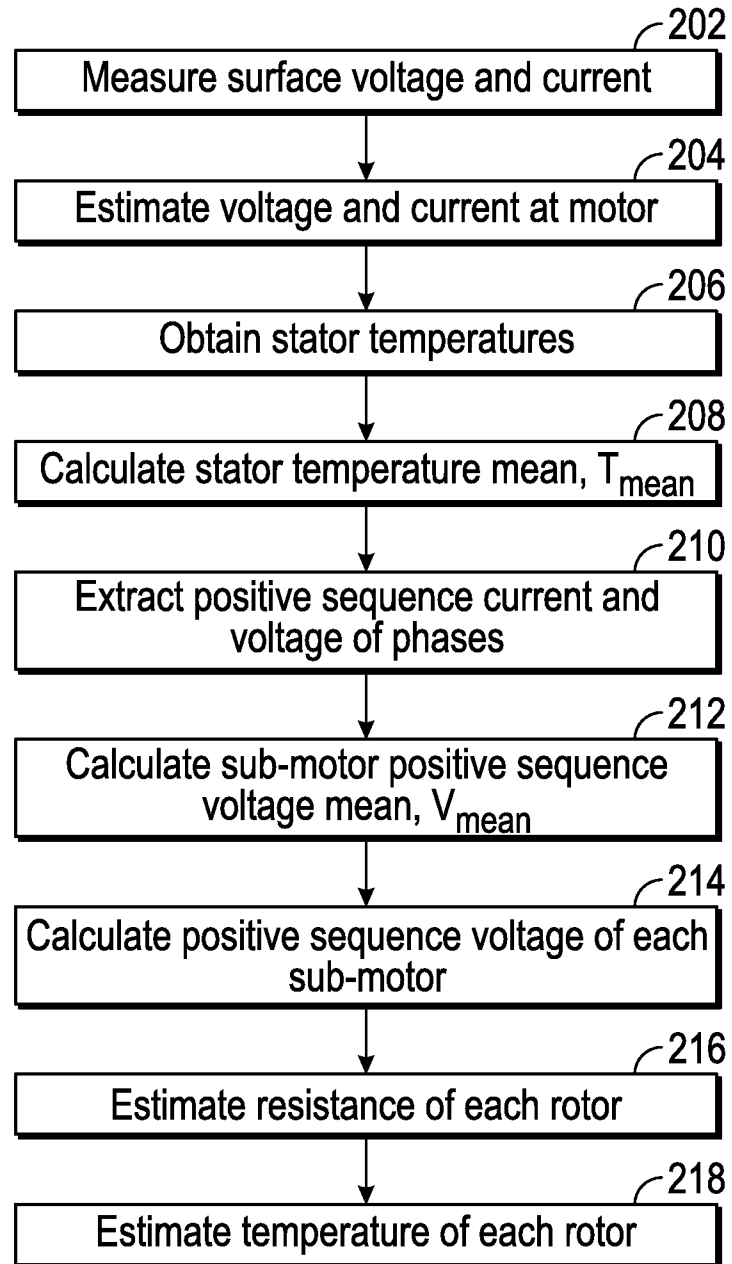


FIG. 8

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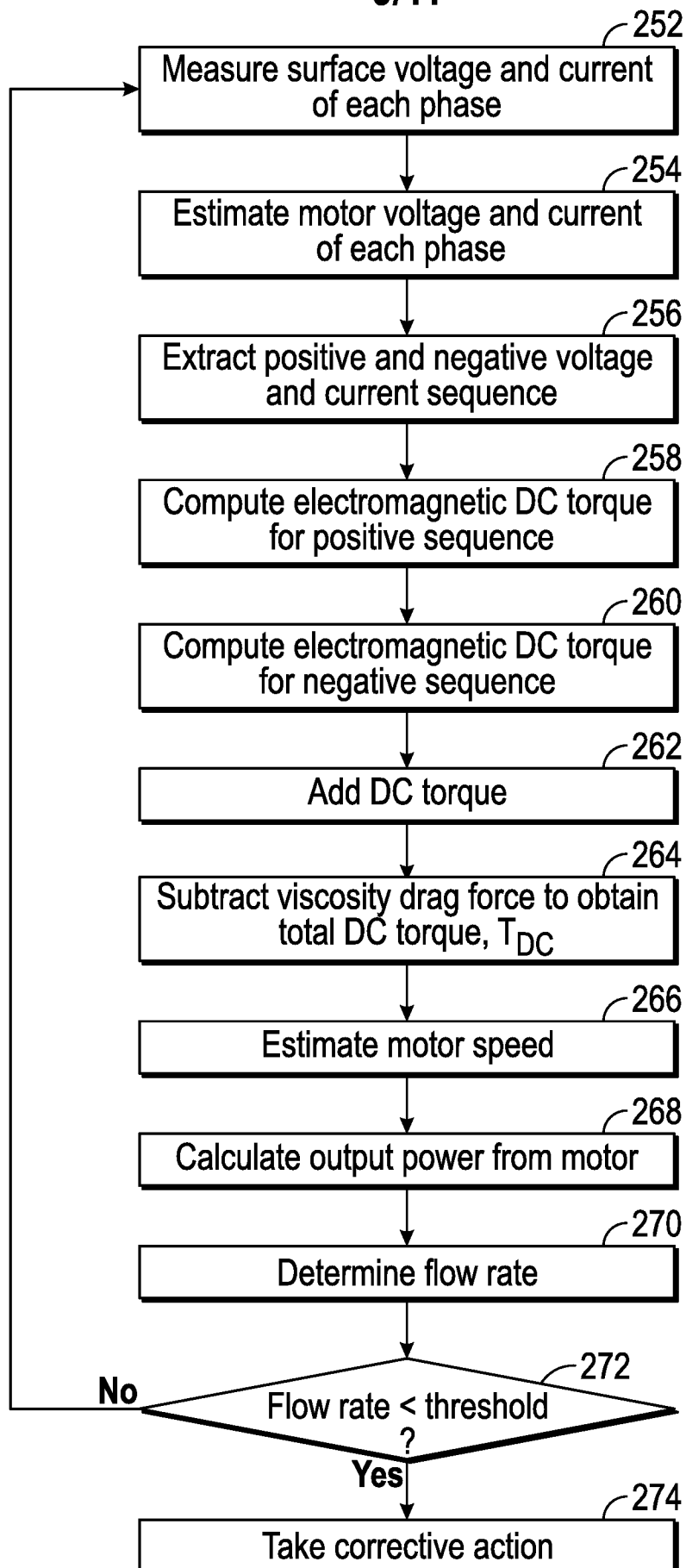


FIG. 9

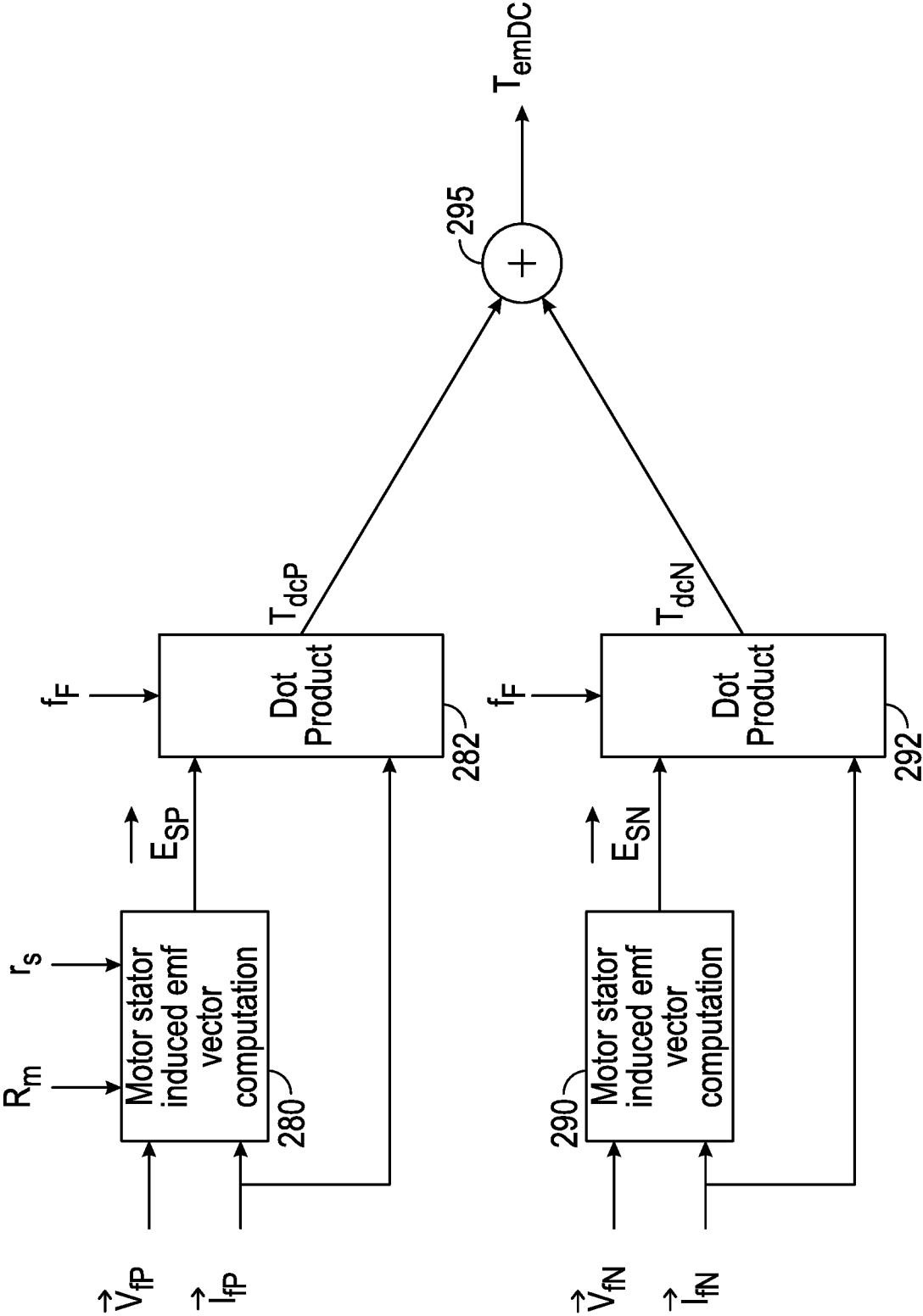


FIG. 10

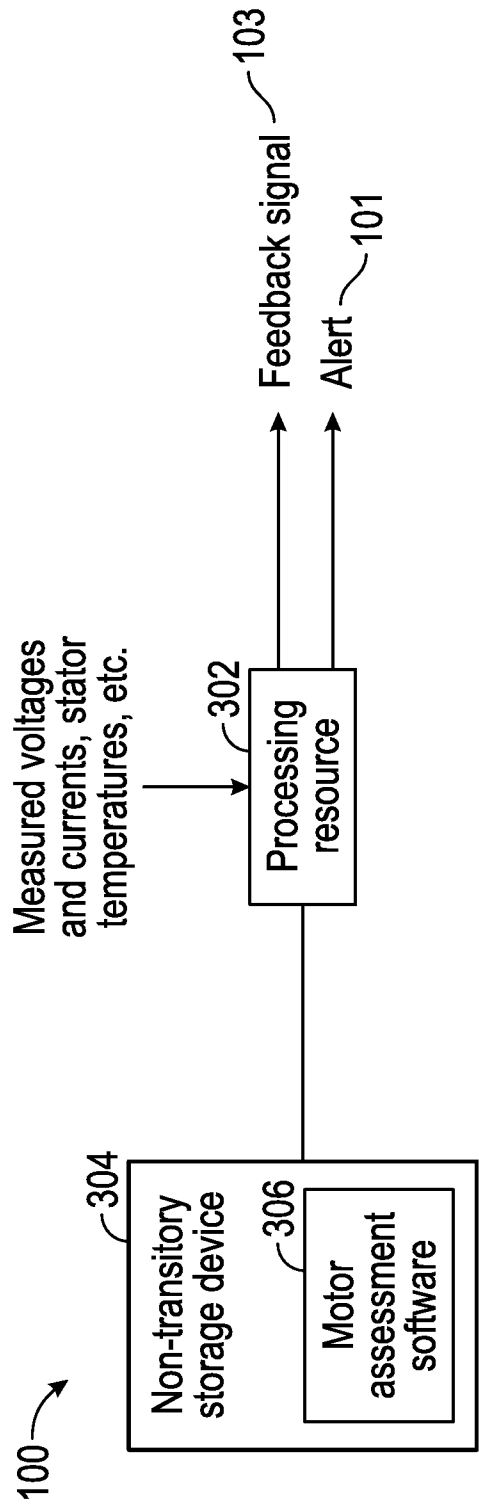


FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/012019**A. CLASSIFICATION OF SUBJECT MATTER****F04D 27/00(2006.01)i, F04D 13/10(2006.01)i, E21B 43/12(2006.01)i, G01F 1/56(2006.01)i**

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F04D 27/00; E21B 43/12; H02P 6/08; G01N 33/48; G05B 15/02; G01N 35/00; H02K 9/00; G01R 27/08; H02P 6/18; F04D 13/10; G01F 1/56

Documentation 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 models

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

eKOMPASS(KIPO internal) & Keywords: electric submersible pump, temperature, motor, flow rate, voltage, current, estimate, extract, and process**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007-0145835 A1 (YUKITAKE, YASUHIRO) 28 June 2007 See paragraph [0022], claim 1, and figures 1-5.	1-20
Y	US 2009-0284204 A1 (COLBY et al.) 19 November 2009 See paragraphs [0011], [0026], [0027], [0096] and figures 7A, 7B.	1-20
A	US 2011-0084638 A1 (PATEL et al.) 14 April 2011 See claim 1 and figure 1.	1-20
A	US 2015-0308244 A1 (MOOG INC.) 29 October 2015 See paragraph [0029], claim 1, and figures 1, 2.	1-20
A	US 2012-0270325 A1 (SPERRY et al.) 25 October 2012 See paragraphs [0021]-[0029] and figure 2.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

12 September 2016 (12.09.2016)

Date of mailing of the international search report

12 September 2016 (12.09.2016)

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/US2016/012019

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