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Published:

— *with international search report (Art. 21(3))*

SUBMERSIBLE MULTIPHASE ELECTRIC MOTOR SYSTEMS

BACKGROUND

[0001] As an example, artificial lift equipment such as an electric submersible pump (ESP) can include a multiphase electric motor. In such an example, submersible may refer to an arrangement of components of the ESP that allow it to operate while disposed at a position in a geologic formation such as a position within a fluid reservoir. For example, a submersible multiphase electric motor may be a sealed motor (e.g., hermetically sealed, etc.) where one or more seals (e.g., mechanical, fluidic, etc.) act to preserve integrity of the motor when disposed in an environment. As an example, a system that is at least in part submersible may include a submersible multiphase electric motor, which may operatively drive a pump and/or other equipment.

SUMMARY

[0002] A system can include a current controller that includes state-space based control logic that outputs three voltage values based at least in part on two current values and values of asymmetric state-space system parameters associated with an electric submersible pump system that includes a power supply cable and an motor electrically coupled to the power supply cable. A system can include a three phase motor and a switch assembly that includes an electrical connection to a wye point of the motor where the switch assembly selectively switches the motor from a three phase operational mode to a two phase operational mode. Various other apparatuses, systems, methods, etc., are also disclosed.

[0003] 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

[0004] Features and advantages of the described implementations can be more readily understood by reference to the following description taken in conjunction with the accompanying drawings.

[0005] Fig. 1 illustrates examples of equipment in geologic environments;

- [0006]** Fig. 2 illustrates an example of an electric submersible pump system;
- [0007]** Fig. 3 illustrates examples of equipment;
- [0008]** Fig. 4 illustrates examples of equipment;
- [0009]** Fig. 5 illustrates an example of a system;
- [0010]** Fig. 6 illustrates an example of a system;
- [0011]** Fig. 7 illustrates an example of a system;
- [0012]** Fig. 8 illustrates an example of a system;
- [0013]** Fig. 9 illustrates an example of a system and an example of a circuitry schematic;
- [0014]** Fig. 10 illustrates an example of a current controller;
- [0015]** Fig. 11 illustrates an example of a rotor flux estimator;
- [0016]** Fig. 12 illustrates an example of a system;
- [0017]** Fig. 13 illustrates an example of a system;
- [0018]** Fig. 14 illustrates an example of a system;
- [0019]** Fig. 15 illustrates an example of a system;
- [0020]** Fig. 16 illustrates an example of a system;
- [0021]** Fig. 17 illustrates an example of a system and an example of a circuitry schematic;
- [0022]** Fig. 18 illustrates an example of a rotor position estimator;
- [0023]** Fig. 19 illustrates an example of a system;
- [0024]** Fig. 20 illustrates an example of a rotor position estimator;
- [0025]** Fig. 21 illustrates an example of a motor and an example of a vector diagram;
- [0026]** Fig. 22 illustrates an example of a motor and an example of a vector diagram;
- [0027]** Fig. 23 illustrates an example of a system that includes an example of a switch assembly;
- [0028]** Fig. 24 illustrates an example of a system and an example of a circuitry schematic;
- [0029]** Fig. 25 illustrates two cable configurations and example data presented in a table; and
- [0030]** Fig. 26 illustrates example components of a system and a networked system.

DETAILED DESCRIPTION

[0031] The following description includes the best mode presently contemplated for practicing the described implementations. This description is not to be taken in a limiting sense, but rather is made merely for the purpose of describing the general principles of the implementations. The scope of the described implementations should be ascertained with reference to the issued claims.

[0032] Fig. 1 shows examples of geologic environments 120 and 140. In Fig. 1, the geologic environment 120 may be a sedimentary basin that includes layers (e.g., stratification) that include a reservoir 121 and that may be, for example, intersected by a fault 123 (e.g., or faults). As an example, the geologic environment 120 may be outfitted with any of a variety of sensors, detectors, actuators, etc. For example, equipment 122 may include communication circuitry to receive and to transmit information with respect to one or more networks 125. Such information may include information associated with downhole equipment 124, which may be equipment to acquire information, to assist with resource recovery, etc. Other equipment 126 may be located remote from a well site and include sensing, detecting, emitting or other circuitry. Such equipment may include storage and communication circuitry to store and to communicate data, instructions, etc. As an example, one or more satellites may be provided for purposes of communications, data acquisition, etc. For example, Fig. 1 shows a satellite in communication with the network 125 that may be configured for communications, noting that the satellite may additionally or alternatively include circuitry for imagery (e.g., spatial, spectral, temporal, radiometric, etc.).

[0033] Fig. 1 also shows the geologic environment 120 as optionally including equipment 127 and 128 associated with a well that includes a substantially horizontal portion that may intersect with one or more fractures 129. For example, consider a well in a shale formation that may include natural fractures, artificial fractures (e.g., hydraulic fractures) or a combination of natural and artificial fractures. As an example, a well may be drilled for a reservoir that is laterally extensive. In such an example, lateral variations in properties, stresses, etc. may exist where an assessment of such variations may assist with planning, operations, etc. to develop the reservoir (e.g., via fracturing, injecting, extracting, etc.). As an example, the equipment 127 and/or 128 may include components, a system, systems, etc. for

fracturing, seismic sensing, analysis of seismic data, assessment of one or more fractures, etc.

[0034] As to the geologic environment 140, as shown in Fig. 1, it includes two wells 141 and 143 (e.g., bores), which may be, for example, disposed at least partially in a layer such as a sand layer disposed between caprock and shale. As an example, the geologic environment 140 may be outfitted with equipment 145, which may be, for example, steam assisted gravity drainage (SAGD) equipment for injecting steam for enhancing extraction of a resource from a reservoir. SAGD is a technique that involves subterranean delivery of steam to enhance flow of heavy oil, bitumen, etc. SAGD can be applied for Enhanced Oil Recovery (EOR), which is also known as tertiary recovery because it changes properties of oil *in situ*.

[0035] As an example, a SAGD operation in the geologic environment 140 may use the well 141 for steam-injection and the well 143 for resource production. In such an example, the equipment 145 may be a downhole steam generator and the equipment 147 may be an electric submersible pump (e.g., an ESP).

[0036] As illustrated in a cross-sectional view of Fig. 1, steam injected via the well 141 may rise in a subterranean portion of the geologic environment and transfer heat to a desirable resource such as heavy oil. In turn, as the resource is heated, its viscosity decreases, allowing it to flow more readily to the well 143 (e.g., a resource production well). In such an example, equipment 147 (e.g., an ESP) may then assist with lifting the resource in the well 143 to, for example, a surface facility (e.g., via a wellhead, etc.). As an example, where a production well includes artificial lift equipment such as an ESP, operation of such equipment may be impacted by the presence of condensed steam (e.g., water in addition to a desired resource). In such an example, an ESP may experience conditions that may depend in part on operation of other equipment (e.g., steam injection, operation of another ESP, etc.).

[0037] Conditions in a geologic environment may be transient and/or persistent. Where equipment is placed within a geologic environment, longevity of the equipment can depend on characteristics of the environment and, for example, duration of use of the equipment as well as function of the equipment. Where equipment is to endure in an environment over an extended period of time, uncertainty may arise in one or more factors that could impact integrity or expected lifetime of the equipment. As an example, where a period of time may be of the order of decades, equipment that is intended to last for such a period of time may be

constructed to endure conditions imposed thereon, whether imposed by an environment or environments and/or one or more functions of the equipment itself.

[0038] Fig. 2 shows an example of an ESP system 200 that includes an ESP 210 as an example of equipment that may be placed in a geologic environment. As an example, an ESP may be expected to function in an environment over an extended period of time (e.g., optionally of the order of years). As an example, commercially available ESPs (such as the REDATM ESPs marketed by Schlumberger Limited, Houston, Texas) may find use in various applications.

[0039] In the example of Fig. 2, the ESP system 200 may be coupled to a network 201 and various components may be disposed in a well 203 in a geologic environment (e.g., with surface equipment, etc.). As shown, the ESP system can include a power supply 205, the ESP 210, a controller 230, a motor controller 250 and a variable speed drive (VSD) unit 270. The power supply 205 may receive power from a power grid, an onsite generator (e.g., natural gas driven turbine), and/or other source. The power supply 205 may supply a voltage, for example, of about 4.16 kV.

[0040] As shown, the well 203 includes a wellhead that may include equipment such as a choke (e.g., a choke valve), etc. For example, the well 203 can include a choke valve to control various operations such as to reduce pressure of a fluid from high pressure in a closed wellbore to atmospheric pressure. Adjustable choke valves can include valves constructed to resist wear due to high-velocity, solids-laden fluid flowing by restricting or sealing elements. A wellhead may include one or more sensors such as a temperature sensor, a pressure sensor, a solids sensor, etc.

[0041] As to the ESP 210, it is shown as including cables 211 (e.g., or a cable), a pump 212, gas handling features 213, a pump intake 214, a motor 215, one or more sensors 216 (e.g., temperature, pressure, strain, current leakage, vibration, etc.) and optionally a protector 217.

[0042] As an example, an ESP may include a REDATM HOTLINETM high-temperature ESP motor. Such a motor may be suitable for implementation in a thermal recovery heavy oil production system, such as, for example, SAGD system or other steam-flooding system.

[0043] As an example, an ESP motor can include a three-phase squirrel cage with two-pole induction. As an example, an ESP motor may include steel stator

laminations that can help focus magnetic forces on rotors, for example, to help reduce energy loss. As an example, stator windings can include copper and insulation. As an example, an ESP motor can include one or more permanent magnets.

[0044] In the example of Fig. 2, the well 203 may include one or more well sensors 220, for example, such as the commercially available OPTICLINE™ sensors or WELLWATCHER BRITEBLUE™ sensors marketed by Schlumberger Limited (Houston, Texas). Such sensors are fiber-optic based and can provide for real time sensing of temperature, for example, in SAGD or other operations. As an example, such information may be received by one or more of the controller 230, the ESP motor controller 250, the VSD unit 270, etc. As shown in the example of Fig. 1, a well can include a relatively horizontal portion. Such a portion may collect heated heavy oil responsive to steam injection. Measurements of temperature along the length of the well can provide for feedback, for example, to understand conditions downhole of an ESP, along an ESP and/or uphole of ESP. Well sensors may extend thousands of feet into a well (e.g., consider distances of about 4,000 feet or 1,220 m or more) and optionally beyond a position of an ESP.

[0045] In the example of Fig. 2, the controller 230 can include one or more interfaces, for example, for receipt, transmission or receipt and transmission of information with the motor controller 250, a VSD unit 270, the power supply 205 (e.g., a gas fueled turbine generator, a power company, etc.), the network 201, equipment in the well 203, equipment in another well, etc.

[0046] As shown in Fig. 2, the controller 230 may include or provide access to one or more modules or frameworks. Further, the controller 230 may include features of an ESP motor controller and optionally supplant the ESP motor controller 250. For example, the controller 230 may include the UNICONN™ motor controller 282 marketed by Schlumberger Limited (Houston, Texas). In the example of Fig. 2, the controller 230 may access one or more of the PIPESIM™ framework 284, the ECLIPSE™ framework 286 marketed by Schlumberger Limited (Houston, Texas) and the PETREL™ framework 288 marketed by Schlumberger Limited (Houston, Texas) (e.g., and optionally the OCEAN™ framework marketed by Schlumberger Limited (Houston, Texas)).

[0047] As an example, the one or more sensors 216 of the ESP 210 may be part of a digital downhole monitoring system. For example, consider the

commercially available PHOENIX™ MULTISENSOR XT150™ system marketed by Schlumberger Limited (Houston, Texas). A monitoring system may include a base unit that operatively couples to an ESP motor (see, e.g., the motor 215), for example, directly, via a motor-base crossover, etc. As an example, such a base unit (e.g., base gauge) may measure intake pressure, intake temperature, motor oil temperature, motor winding temperature, vibration, currently leakage, etc. As explained with respect to Fig. 4, a base unit may transmit information via a power cable that provides power to an ESP motor and may receive power via such a cable as well.

[0048] As an example, a remote unit may be provided that may be located at a pump discharge (e.g., located at an end opposite the pump intake 214). As an example, a base unit and a remote unit may, in combination, measure intake and discharge pressures across a pump (see, e.g., the pump 212), for example, for analysis of a pump curve. As an example, alarms may be set for one or more parameters (e.g., measurements, parameters based on measurements, etc.).

[0049] Where a system includes a base unit and a remote unit, such as those of the PHOENIX™ MULTISENSOR X150™ system, the units may be linked via wires. Such an arrangement provide power from the base unit to the remote unit and allows for communication between the base unit and the remote unit (e.g., at least transmission of information from the remote unit to the base unit). As an example, a remote unit is powered via a wired interface to a base unit such that one or more sensors of the remote unit can sense physical phenomena. In such an example, the remote unit can then transmit sensed information to the base unit, which, in turn, may transmit such information to a surface unit via a power cable configured to provide power to an ESP motor.

[0050] In the example of Fig. 2, the motor controller 250 may be a commercially available motor controller such as the UNICONN™ motor controller. The UNICONN™ motor controller can connect to a SCADA system, the ESPWATCHER™ surveillance system, etc. The UNICONN™ motor controller can perform some control and data acquisition tasks for ESPs, surface pumps or other monitored wells. The UNICONN™ motor controller can interface with the PHOENIX™ monitoring system, for example, to access pressure, temperature and vibration data and various protection parameters as well as to provide direct current power to downhole sensors (e.g., the sensors 216). The UNICONN™ motor

controller can interface with fixed speed drive (FSD) controllers or a VSD unit, for example, such as the VSD unit 270.

[0051] For FSD controllers, the UNICONN™ motor controller can monitor ESP system three-phase currents, three-phase surface voltage, supply voltage and frequency, ESP spinning frequency and leg ground, power factor and motor load.

[0052] For VSD units, the UNICONN™ motor controller can monitor VSD output current, ESP running current, VSD output voltage, supply voltage, VSD input and VSD output power, VSD output frequency, drive loading, motor load, three-phase ESP running current, three-phase VSD input or output voltage, ESP spinning frequency, and leg-ground.

[0053] In the example of Fig. 2, the ESP motor controller 250 includes various modules to handle, for example, backspin of an ESP, sanding of an ESP, flux of an ESP and gas lock of an ESP. The motor controller 250 may include any of a variety of features, additionally, alternatively, etc.

[0054] In the example of Fig. 2, the VSD unit 270 may be a low voltage drive (LVD) unit, a medium voltage drive (MVD) unit or other type of unit (e.g., a high voltage drive, which may provide a voltage in excess of about 4.16 kV). As an example, the VSD unit 270 may receive power with a voltage of about 4.16 kV and control a motor as a load with a voltage from about 0 V to about 4.16 kV. The VSD unit 270 may include commercially available control circuitry such as the SPEEDSTAR™ MVD control circuitry marketed by Schlumberger Limited (Houston, Texas).

[0055] Fig. 3 shows cut-away views of examples of equipment such as, for example, a portion of a pump 320, a protector 370 and a motor 350 of an ESP. The pump 320, the protector 370 and the motor 350 are shown with respect to cylindrical coordinate systems (e.g., r , z , Θ). Various features of equipment may be described, defined, etc. with respect to a cylindrical coordinate system. As an example, a lower end of the pump 320 may be coupled to an upper end of the protector 370 and a lower end of the protector 370 may be coupled to an upper end of the motor 350. As shown in Fig. 3, a shaft segment of the pump 320 may be coupled via a connector to a shaft segment of the protector 370 and the shaft segment of the protector 370 may be coupled via a connector to a shaft segment of the motor 350. As an example, an

ESP may be oriented in a desired direction, which may be vertical, horizontal or other angle.

[0056] Fig. 4 shows a block diagram of an example of a system 400 that includes a power source 401 as well as data 402. The power source 401 provides power to a VSD block 470 while the data 402 may be provided to a communication block 430. The data 402 may include instructions, for example, to instruct circuitry of the circuitry block 450, one or more sensors of the sensor block 460, etc. The data 402 may be or include data communicated, for example, from the circuitry block 450, the sensor block 460, etc. In the example of Fig. 4, a choke block 440 can provide for transmission of data signals via a power cable 411 (e.g., including motor lead extensions “MLEs”). A power cable may be provided in a format such as a round format or a flat format with multiple conductors. MLEs may be spliced onto a power cable to allow each of the conductors to physically connect to an appropriate corresponding connector of an electric motor.

[0057] As shown, the power cable 411 connects to a motor block 415, which may be a motor (or motors) of an ESP and be controllable via the VSD block 470. In the example of Fig. 4, the conductors of the power cable 411 electrically connect at a wye point 425. The circuitry block 450 may derive power via the wye point 425 and may optionally transmit, receive or transmit and receive data via the wye point 425. As shown, the circuitry block 450 may be grounded. While the wye point 425 is shown with three connections, which may correspond to three phases, a multiphase wye point may, as an example, include more than three phases.

[0058] As an example, power cables and MLEs that can resist damaging forces, whether mechanical, electrical or chemical, may help ensure proper operation of a motor, circuitry, sensors, etc.; noting that a faulty power cable (or MLE) can potentially damage a motor, circuitry, sensors, etc. Further, as mentioned, an ESP may be located several kilometers into a wellbore. Accordingly, time and cost to replace a faulty ESP, power cable, MLE, etc., can be substantial (e.g., time to withdraw, downtime for fluid pumping, time to insert, etc.).

[0059] Commercially available power cables include the REDAMAX™ HOTLINE™ ESP power cables (e.g., as well as motor lead extensions “MLEs”), which are marketed by Schlumberger Limited (Houston, Texas). As an example, a REDAMAX™ HOTLINE™ ESP power cable can include combinations of one or more of polyimide tape, lead (Pb), EPDM, and PEEK, for example, to provide

insulation and a jacket. As an example, lead (Pb) walls can provide for compatibility with high gas/oil ratio (GOR) and highly corrosive conditions. Armor can mechanically protect the cable and may be galvanized steel, heavy galvanized steel, stainless steel, or MONEL™ alloy. As an example, a pothead can be an electrical connector between a cable and an ESP motor that may be, for example, constructed with metal-to-metal seals. As an example, a pothead can provide a mechanical barrier to fluid entry in high-temperature applications.

[0060] As an example of a REDAMAX™ HOTLINE™ ESP power cable, a 5 kV round ELBE G5R can include solid conductor sizes of 1 AWG/1, 2 AWG/1 and 4 AWG/1. As another example, a 5 kV flat EHLTB G5F can include a solid conductor size of 4 AWG/1. As to some examples, dimensions may be, for round configurations, about 1 inch to about 2 inches (e.g., about 25 mm to about 50 mm) in diameter and, for flat configurations, about half an inch (e.g., about 12 mm) by about 1 inch to about 2 inches (e.g., about 25 mm to about 50 mm).

[0061] Fig. 5 shows an example of a system 500 that includes a drive 510, a cable 540 and an ESP system 580. As an example, the cable 540 may be a single cable or multiply strung cables. As an example, a cable or cables may have a length of the order of hundreds or thousands of meters. As to the drive 510, it may include, for example, neutral-clamped PWM circuitry, cascade circuitry, etc.

[0062] As an example, the drive 510 may include a rectifier 512, a DC link 514, a controller 515 and an inverter 516, which may include insulated-gate bipolar transistors (IGBTs). As indicated in the example of Fig. 5, an optional load filter 518 may be operatively coupled to output from the inverter 516, for example, to help protect equipment such as a motor 584 of the ESP system 580. As shown in the example of Fig. 5, a drive may include a front end diode rectifier (e.g., AC power source to DC) 512 and a back end PWM controlled IGBT inverter (e.g., DC to "AC") 516, where the load filter 518 connects to the output of the back end PWM controlled IGBT inverter 516 to damp harmonics that can result from switching of the IGBTs.

[0063] As power disturbances may affect run life of a system (e.g., mean time between failure "MTBF"), as an example, a load filter may be applied to provide a clean (e.g., "smooth") harmonics-mitigated sine wave that, in turn, can lessen system stress.

[0064] Fig. 6 shows an example of a system 600 that includes a controller 610, an inverter 630 and an ESP cable and ESP system 650. In such an example,

the ESP system 650 may include an induction motor. As an example, the controller 610 of the system 600 may be a variable speed drive (VSD) controller where, for example, voltage (v_s^*) and/or frequency (ω_s^*) may be controlled (e.g., to control operation of a motor of the ESP system 650). For example, the controller 610 may be a volts-per-Hertz (V/f) controller. As shown in the example of Fig. 6, the inverter 630 of the system 600 may be a voltage controlled voltage source inverter (VC VSI). Such an inverter 630 may be operatively coupled to conductors of the ESP cable of the ESP cable and ESP system 650, for example, to supply voltages (v_{sa} , v_{sb} , v_{sc}) to multiple phases (a, b and c) of an electric motor of the ESP system 650.

[0065] Fig. 7 shows an example of a system 700 that may be a current controlled voltage source inverter system. As an example, the system 700 may be a vector control system (e.g., a system that can implement vector control).

[0066] Vector control may also be referred to as field-oriented control (FOC). Vector control can be variable-frequency drive control scheme where, for example, stator currents of a three-phase AC electric motor may be identified as two orthogonal components that can be represented as a vector. In such a scheme, one component can define magnetic flux of a motor and another component can define torque of the motor.

[0067] A vector control system may include circuitry that calculate, via flux and torque references of a drive's speed control, corresponding current component references. As an example, a control scheme may implement proportional-integral (PI) control, for example, in an effort to maintain measured current components at their reference values (e.g., using pulse-width modulation (PWM) of a variable-frequency drive).

[0068] As an example, vector control may include generating a three-phase PWM motor voltage output derived from a complex voltage vector to control a complex current vector derived from a motor's three-phase motor stator current input, for example, through projections and/or rotations (e.g., back and forth between three-phase speed and time dependent system and vectors rotating reference-frame two-coordinate time invariant system).

[0069] As an example, a complex stator motor current space vector can be defined in a (d , q) coordinate system with orthogonal components along d (direct) and q (quadrature) axes such that a field flux linkage component of current is aligned along the d -axis and a torque component of current is aligned along the q -axis. In

such an example, an induction motor's (d, q) coordinate system may be superimposed to the induction motor's instantaneous (a, b, c) three-phase sinusoidal system.

[0070] As an example, projections associated with a (d, q) coordinate system may include forward projection from instantaneous currents to an (a, b, c) complex stator current space vector representation of a three-phase sinusoidal system; forward three-to-two phase, (a, b, c)-to- (α, β) projection using the Clarke transformation, noting that backward two-to-three phase projection may use space vector pulse-width modulation (PWM) modulator or inverse Clarke transformation and one of the other PWM modulators; and forward and backward two-to-two phase, (α, β) -to- (d, q) and (d, q) -to- (α, β) projections using the Park and inverse Park transformations, respectively.

[0071] In comparing vector control to V/f control, vector control may exhibit an increase in efficiency, reduction of startup current trip, a widened stable speed range operation, etc.

[0072] Referring again to Fig. 7, the system 700 can include a current controller 710, a transform circuitry 730, a voltage source inverter 750, a rotor flux estimator 760 (e.g., rotor flux estimation circuitry), transform circuitry 770 and an induction motor 790.

[0073] In a vector control scheme, motor stator currents, i_a, i_b, i_c may be controlled from a rotor flux reference frame by splitting the current into a d -axis component, i_{sd} and a q -axis component, i_{sq} . As an example, one or more control algorithms may be implemented to derive reference values of the d -axis component, i_{sd}^* and the q -axis component, i_{sq}^* . For example, consider a Field Oriented Control (FOC) algorithm, a Maximum Torque Per Ampere (MTPA) control algorithm, etc.

[0074] In a steady state scenario, rotor flux may be proportional to i_{sd} and motor torque may be proportional to i_{sd} and i_{sq} . In such a scenario, an appropriate speed regulation loop as well as flux regulation loop may be controlled using independent control of i_{sd} and i_{sq} , for example, as shown in Fig. 7.

[0075] As an example, a control scheme can include estimating rotor flux angle, θ_r to transform stator currents into a rotor flux reference frame. For example, consider the rotor flux estimator 760 of the system 700 of Fig. 7, which may receive inputs as to motor stator currents, i_a, i_b, i_c as well as motor terminal phase to neutral voltages, $V_{saN}, V_{sbN}, V_{scN}$ (e.g., as fed back information). For the surface motor

system 700, the surface induction motor 790 may be readily accessible and, for example, physically proximate to its corresponding drive, operatively coupled by a relatively short cable (e.g., of the order of tens of meters). In such an example, voltage sensors may be included for sensing voltage and providing feedback, for example, as input to a rotor flux estimator.

[0076] As explained, an electric submersible pump (ESP) may be disposed in a bore, which may be, for example, of the order of hundreds meters or a thousand meters or more in distance (e.g., depth, whether vertical, deviated, etc.). In such a scenario, a cable or cables spanning the distance between the ESP and a surface drive may likewise be of the order of hundreds of meters or a thousand meters or more in length.

[0077] In various ESP applications that include an induction motor, a cable or cables may contribute considerably to resistance and inductance in phase circuit parameters of a motor drive system. A cable or cables may result in circuit parameters of a multiphase system being unbalance (e.g., asymmetrical with respect to the multiple phases).

[0078] The system 700 of Fig. 7 may be suitable for “symmetrical” phases, for example, where a cable does not contribute considerably to resistance and inductance in a manner that may cause differences between individual phase circuits of multiple phases (e.g., differences that result in asymmetry). For a system such as the system 700, various blocks may not adequately handle or account for asymmetry. For example, assumed conditions of vector control to control the stator currents after abc/dq may no longer be valid due to asymmetry.

[0079] As an example, asymmetry may be handled using a dual rotating abc/dq frame based control algorithm. Such an approach involves increasing the number of current control loops with additional computations making the control loops interdependent, which may complicate implementation. As an example, asymmetry may be handled using a hysteresis controller to control currents of motor phases. Such an approach may involve varying switching frequency of switching devices, which may be unacceptable for various ESP applications due to magnitude of motor voltages. Also, as mentioned, for various applications, sensing motor terminal phase to neutral voltages may not be practical or possible via standard voltage sensors and, likewise, sending such information reliably back to a surface

drive for feedback operation may be problematic (e.g., fraught with noise, signal separation issues, etc.).

[0080] Fig. 8 shows an example of a current controlled voltage source inverter system 800 (CC VSI). As shown in the example of Fig. 8, the system 800 can include transform circuitry 830 (e.g., for dq to abc transformation), a current controller 830, a voltage source inverter, LC filter and transformer block 850, a rotor flux estimator 860 (e.g., rotor flux estimation circuitry) and an ESP cable and ESP induction motor 890.

[0081] The system 800 may allow for control of induction motor stator currents directly in an abc frame, which may help to ensure proper vector control even in the case of substantial asymmetry in phase circuit parameters (e.g., due at least in part to cable length).

[0082] As an example, the system 800 can include circuitry for estimating motor terminal phase to neutral voltages using one or more cable parameters and/or sensing one or more of such parameters using the ESP system itself. As an example, a system can provide for real-time motor, cable electrical parameters estimations that operate in parallel, for example, to compensate for different parameter variation.

[0083] As an example, in the system 800, the abc frame current references may be estimated and the stator currents may be controlled directly in abc frame by the current controller 830. The rotor flux estimator 860 can receive motor currents, i_a , i_b , i_c as well as estimated or sensed motor terminal phase to neutral voltages, V_{saN} , V_{sbN} , V_{scN} . The current controller 830 as well as the rotor flux estimator 860 can receive updated motor/ cable electrical parameter information, which may enhance accuracy of operation.

[0084] Fig. 9 shows an example of a system 900 and an example of a circuitry schematic 905. The system 900 and circuitry schematic 905 include features for vector control of an induction motor such as an induction motor of an ESP system that is operatively coupled to a drive via a cable or cables, which may introduce asymmetry.

[0085] As shown in Fig. 9, the system 900 includes a VSD/LC filter 910, optionally a transformer 930, a motor power cable 970 (e.g., or chained cables) and an induction motor 990. The system 900 is a multiphase system where phases are represented as a, b and c, which are joined at a wye point "N" at or near the

induction motor 990. The schematic 905 of Fig. 9 may be considered to be an example of an electrical equivalent circuit for power frequency operation.

[0086] In the system 900, the transformer 930 may be optional, for example, present in a system where a low voltage drive (LVD) is used. As an example, the VSD/LC filter 910 may output three-phase voltage, for example, with respect to DC link mid-point O , which may be referred to as v_{iaO} , v_{ibO} , v_{icO} . For power frequency operation, the transformer and the long cable resistance and inductance for each of the three phases may be referred as (R_{ta}, L_{ta}) , (R_{tb}, L_{tb}) , (R_{tc}, L_{tc}) . As an example, parameters may be assumed to be asymmetrical. Motor per phase resistance and self-inductance may be referred as R and L , respectively. Back emf induced in each of the stator phases may be referred as e_{aN} , e_{bN} , e_{cN} , where N is the neutral of the motor stator phases (e.g., wye point). The points O and N may be considered as being electrically isolated. Combining motor as well as cable and transformer, the individual phase resistance and inductances may be referred as (R_a, L_a) , (R_b, L_b) and (R_c, L_c) .

[0087] Given the foregoing example nomenclature, a system may be described using the following equations:

$$\begin{aligned} L_a \frac{di_a}{dt} + R_a i_a &= v_{iaN} - e_{aN} \\ L_b \frac{di_b}{dt} + R_b i_b &= v_{ibN} - e_{bN} \\ L_c \frac{di_c}{dt} + R_c i_c &= v_{icN} - e_{cN} \\ i_a + i_b + i_c &= 0 \end{aligned}$$

[0088] With replacement and rearrangement, the foregoing electrical system equations can be transformed to as:

$$\begin{aligned} v_{iac} - e_{ac} &= (L_a + L_c) \frac{di_a}{dt} + L_c \frac{di_b}{dt} + (R_a + R_c) i_a + R_c i_b \\ v_{ibc} - e_{bc} &= (L_b + L_c) \frac{di_b}{dt} + L_c \frac{di_a}{dt} + (R_b + R_c) i_b + R_c i_a \end{aligned}$$

where, v_{iac} and v_{ibc} are the inverter/LC filter two line to line output voltages (phase ac and bc respectively) and e_{ac} and e_{bc} are two line to line motor back electromotive force, emf (phase ac and bc respectively).

[0089] Defining state variables as: $x_1=i_a$ and $x_2=i_b$, state-space equations may be described as:

$$\begin{aligned}\frac{dx_1}{dt} &= a_{11}x_1 + a_{12}x_2 + u_1 + d_1 \\ \frac{dx_2}{dt} &= a_{21}x_1 + a_{22}x_2 + u_2 + d_2\end{aligned}$$

where, the inputs are related with inverter line voltages as:

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} v_{iac} \\ v_{ibc} \end{bmatrix}$$

[0090] Various parameters may be related to the circuit elements as:

$$\begin{aligned}a_{11} &= -\frac{R_a L_b + R_c L_b + R_a L_c}{L_a L_b + L_b L_c + L_c L_a}, \quad a_{12} = -\frac{R_c L_b - R_b L_c}{L_a L_b + L_b L_c + L_c L_a}, \\ a_{21} &= -\frac{R_a L_c - R_c L_a}{L_a L_b + L_b L_c + L_c L_a}, \quad a_{22} = -\frac{R_b L_a + R_c L_a + R_b L_c}{L_a L_b + L_b L_c + L_c L_a} \\ b_{11} &= \frac{L_b + L_c}{L_a L_b + L_b L_c + L_c L_a}, \quad b_{12} = b_{21} = -\frac{L_c}{L_a L_b + L_b L_c + L_c L_a}, \\ b_{22} &= \frac{L_a + L_c}{L_a L_b + L_b L_c + L_c L_a}\end{aligned}$$

[0091] Disturbance terms may be related with the motor line to line back emfs as:

$$d_1 = -\frac{(L_b + L_c)e_{ac} - L_c e_{bc}}{L_a L_b + L_b L_c + L_c L_a}, \quad d_2 = -\frac{-L_c e_{ac} + (L_a + L_c)e_{bc}}{L_a L_b + L_b L_c + L_c L_a}$$

[0092] As an example, state-space equations may be implemented to design a controller to control the power frequency motor currents while operating an inverter at a relatively constant switching frequency. Such an approach may consider unbalance in phase circuit parameters (e.g., compare to dq transformation based current control). As an example, a state-space can be a vector space. In such an example, internal states of a system may be represented in a vector space and, hence, in a state-space. As an example, a state-space may be a space with axes

that represent state variables, for example, where a particular state of a system may be represented as a vector within the state-space.

[0093] As an example, a system can include current tracking control circuitry. As an example, a controller may be designed based on system state-space equations, for example, to control currents in an *abc* frame. For example, a controller may implement a method that includes using state-space equations (e.g., included in a system via hardware, software, hardware and software, etc.).

[0094] As an example, where a state-space approach is implemented, state error may be defined as:

$$e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} x_1^* - x_1 \\ x_2^* - x_2 \end{bmatrix}$$

where, x_1^* and x_2^* are the reference values of states. As an example, reference values may be calculated by knowing i_{sd}^* and i_{sq}^* (see, e.g., the system 800 of Fig. 8).

[0095] As an example, a control scheme may include use of one or more Lyapunov functions. For example, consider a positive definite Lyapunov function that is defined as:

$$V = \frac{1}{2} e^T e$$

[0096] In such an example, control action may be defined as:

$$u_1 = \frac{dx_1^*}{dt} - \hat{a}_{11}x_1 - \hat{a}_{12}x_2 + \lambda_1 e_1$$

$$u_2 = \frac{dx_2^*}{dt} - \hat{a}_{21}x_1 - \hat{a}_{22}x_2 + \lambda_2 e_2$$

where, $\hat{a}_{11}$, $\hat{a}_{12}$, $\hat{a}_{21}$, $\hat{a}_{22}$ are the state-space system parameters based on estimated values of cable/motor resistance and inductances (e.g., considered collectively, etc.); and where λ_1 , λ_2 are controller parameters.

[0097] As an example, the first time derivative of the Lyapunov function can be expressed as:

$$\begin{aligned}\frac{dV}{dt} &= e^T \frac{de}{dt} = -e^T \Gamma e + e^T \begin{bmatrix} (\hat{a}_{11} - a_{11})x_1 + (\hat{a}_{12} - a_{12})x_2 - d_1 \\ (\hat{a}_{21} - a_{21})x_1 + (\hat{a}_{22} - a_{22})x_2 - d_2 \end{bmatrix} \\ &= (-\lambda_1 e_1^2 + e_1 D_1(.)) + (-\lambda_2 e_2^2 + e_2 D_2(.))\end{aligned}$$

where, $\Gamma = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$.

[0098] In such an example, designing the maximum value of $D_1(.)$ and $D_2(.)$ as $|D_1(.)|_{max}$ and $|D_2(.)|_{max}$, the controller parameters may be chosen as:

$$\begin{aligned}\lambda_1 &> \frac{|D_1(.)|_{max}}{e_b} \\ \lambda_2 &> \frac{|D_2(.)|_{max}}{e_b}\end{aligned}$$

[0099] Such an approach can help to ensure that $\frac{dV}{dt}$ is to be negative definite as long as $e_1, e_2 \leq e_b$, which can help to ensure error converging to a designated error bound e_b .

[00100] A lower value of controller parameters, λ_1, λ_2 may be used, for example, where an estimator or controller is implemented to estimate disturbance terms d_1 and d_2 in parallel to current tracking control.

[00101] As an example, a system may provide for translating controller output to inverter voltage. As an example, a control scheme may implement control for two inverter line voltages, v_{iac} and v_{ibc} . In such an example, there may be no direct constraint on inverter pole voltages, v_{iao} , v_{ibo} , v_{ico} . As an example, voltage stress optimization may be performed to distribute voltage stress on each leg of inverters. Such a process may be used for different inverter topologies. As an example, to distribute voltage stress on each leg in an equitable manner, consider the following equations:

$$v_{iao} + v_{ibo} + v_{ico} = 0$$

where individual pole voltages can be solved in terms of v_{iac} and v_{ibc} as:

$$\begin{aligned}v_{iao} &= \frac{1}{3}(2v_{iac} - v_{ibc}) \\ v_{ibo} &= \frac{1}{3}(2v_{ibc} - v_{iac})\end{aligned}$$

$$v_{ic0} = -\frac{1}{3}(v_{iac} + v_{ibc})$$

[00102] As an example, the foregoing inverter pole voltages may be transferred to individual leg pulse-width modulation (PWM) control signals based on the DC link voltage. As an example, for a 2-level three-phase inverter, sine PWM can be one of a plurality of options that may be used.

[00103] Fig. 10 shows an example of the current controller 830 of the system 800 of Fig. 8 that may be suitable for a 2-level three-phase inverter. Fig. 10 includes various equations, as explained above, along with inputs and outputs to the current controller 830.

[00104] Fig. 11 shows an example of the rotor flux estimator 860 of the system 800 of Fig. 8 where, for example, rotor flux may be estimated based at least in part on motor stator variables.

[00105] As shown in Fig. 11, motor terminal phase to neutral voltages, v_{saN} , v_{sbN} , v_{scN} are fed to the estimator 860 and converted to stator voltage space vector, $\vec{v}_s^s$ by $abc/\alpha\beta$ transformation. As shown, stator current space vector, $\vec{i}_s^s$ may be calculated using motor terminal three phase power frequency currents, i_a , i_b , i_c .

[00106] As also shown in Fig. 11, rotor flux vector, $\vec{\psi}_r^s$ may be estimated via appropriate inputs as:

$$\begin{aligned}\vec{\psi}_s^s &= \int (\vec{v}_s^s - r_s \vec{i}_s^s) dt \\ \vec{\psi}_r^s &= \left(\frac{l_r}{l_h}\right) \vec{\psi}_s^s + \left(l_h - \frac{l_r l_s}{l_h}\right) \vec{i}_s^s \\ \vec{\psi}_r^s &= \psi_r e^{j\theta_r}\end{aligned}$$

where, $\vec{\psi}_s^s$ is the stator flux, l_s is the stator per phase self-inductance (see, e.g., Fig. 9, $l_s = L$), r_s is the stator resistance (see, e.g., Fig. 9, $r_s = R$), l_r is the rotor per phase self-inductance referred to stator, l_h is the per-phase magnetizing inductance referred to stator. The magnitude of rotor flux, $\vec{\psi}_r^s$ is referred as ψ_r and its angle with respect to a stator is referred as θ_r . As an example, rotor slip speed, ω_{r-slip} may be estimated as:

$$\omega_{r-slip} = \left(\frac{r_r l_h}{l_r}\right) \cdot \left(\frac{i_{sq}}{\psi_r}\right)$$

where, r_r is per-phase rotor resistance referred to stator.

[00107] As an example, a system can include features to estimate motor phase to neutral voltages (e.g., via hardware, software, hardware and software, etc.). One or more techniques may be implemented to estimate motor terminal phase to neutral voltages, V_{saN} , V_{sbN} , V_{scN} .

[00108] Fig. 12 shows an example of a system 1200 for estimating motor terminal phase to neutral voltages, V_{saN} , V_{sbN} , V_{scN} . The system 1200 can assume a cable model, for example, a model where voltages may be estimated by subtracting drops in a cable per phase via phase circuit parameters. For example, the system 1200 may provide for estimation of motor terminal phase to neutral voltage using a power frequency model of one or more cables.

[00109] In the example of Fig. 12, inverter pole voltages and motor currents can be inputs and, as the inverter DC link mid-point O and motor neutral N may be electrically isolated, the zero sequence component of voltage may be subtracted.

[00110] As an example, a gauge may be operatively coupled to a wye point of an induction motor of an ESP system. In such an example, the gauge may include one or more motor terminal phase to neutral voltage sensors where output from such sensors may be transmitted remotely (e.g., to surface circuitry), analyzed locally (e.g., via downhole circuitry), etc. As an example, a system may implement one or more approaches for voltage estimation. As mentioned, one or more sensed and/or one or more estimated voltages may be used in a control scheme.

[00111] As an example, a system may include features to estimate motor and/or cable electrical parameters (e.g., via hardware, software, hardware and software, etc.). As an example, one or more electrical power frequency parameters of one or more cables as well as one or more motors may be estimated in real-time for a current controller, a rotor flux estimator and/or a motor terminal phase to neutral voltage estimator.

[00112] As an example, a current controller such as the current controller 830 of Fig. 8 may operate robustly enough to cater to parameter variation. As an example, a current controller may receive one or more values of one or more real-time parameters, which may, for example, enhance transient performance. As an example, one or more types of parameter tracking approaches may be used, for

example, consider approaches based on adaptive algorithms, artificial intelligence, etc.

[00113] Fig. 13 shows an example of a system 1300 that may be implemented for tracking one or more parameter values. The system 1300 includes a model block 1310 (e.g., for a model of a cable and motor), an adjustor 1320, an identification algorithm block 1330 and a parameter variation block 1340.

[00114] The system 1300 may implement a method, for example, where the model block 1310 receives inverter voltages and where the adjustor receives calculated stator currents, which may be compared to the actual stator currents. In such an example, the adjustor 1320 may calculate and output one or more current errors based at least in part on its inputs (e.g., calculate variation of each parameter at required sampling instants). In the example of Fig. 13, the identification algorithm block 1330 may include an adaptive learning algorithm. The identification algorithm block 1330 may output information to the parameter variation block 1340 that may be indicative of one or more variations germane to the model of the model block 1310. As an example, a model of the model block 1310 may be an analytical model, a numerical model, etc. (e.g., implemented via hardware, software, hardware and software).

[00115] Fig. 14 shows an example of a system 1400, which includes a model block 1410 (e.g., for a model of a cable and motor), an adjustor 1420, an identification algorithm block 1430 and a parameter variation block 1440, for example, as in the system 1300 of Fig. 13. In the example of Fig. 14, the parameter variation block 1440 (e.g., or one or more other blocks) may receive information associated with operation of a system that includes at least one ESP motor. For example, the parameter variation block 1440 may include receiving information such as one or more of downhole temperature and motor speed, which may be considered feedback. Such feedback may be used in an effort to reduce error and enhance control. As an example, a model of the model block 1410 may be an analytical model, a numerical model, etc. (e.g., implemented via hardware, software, hardware and software).

[00116] As an example, parameter variation may depend on downhole temperature and motor speed feedback. In such an example, downhole temperature at one or more sections of a cable, cables, a motor and/or motors may be measured, for example, using a distributed temperature sensing system (e.g., fiber optic based,

etc.), using a downhole gauge, etc. Such information may be acquired, sampled, transmitted, etc. at appropriate times (e.g., periodic frequency, etc.) for purposes of a system such as the system 1400 of Fig. 14. As an example, a sampling frequency can be lower to cater data flow from a gauge to surface circuitry. As an example, motor speed feedback may be performed at a lower sampling frequency (e.g., optionally at regular intervals).

[00117] As an example, an ESP system may include one or more types of electric motors that include permanent magnets. For example, consider an ESP system that includes a permanent magnet synchronous motor (PMM). In such an example, vector control may be implemented, considering that V/f control of such a motor may involve over drive being operated without rotor position.

[00118] As an example, vector control of a PMM may be performed using motor stator current control in a dq domain. Such an approach may perform satisfactorily where circuit parameters of each of three phases are balanced and symmetrical. A vector control approach applied to a PMM may involve receipt of rotor position information, for example, as may be derived utilizing motor phase currents as well as motor terminal phase to neutral voltages.

[00119] As explained, an ESP system may be disposed in a bore at a distance from a drive, which may be located at a surface (e.g., a surface adjacent an opening to the bore). As mentioned, one or more cables can contribute to resistance and inductance in phase circuit parameters of a motor drive system in case of ESP system, for example, to impart circuit parameters of the drive system that can be unbalanced/ asymmetrical.

[00120] As an example, a method can include controlling PMM stator currents directly in an abc frame in an effort to ensure proper vector control, for example, where considerable asymmetry may exist in phase circuit parameters. Such a method may include estimating motor terminal phase to neutral voltages using one or more cable parameters and/or sensing values for such one or more parameters using one or more ESP components. As an example, a method may use real-time motor and cable electrical parameter estimation, which may operate in parallel to compensate for different parameter variation(s). As an example, a PMM may be a cylindrical-rotor type PMM, a salient-pole type PMM or another type of PMM.

[00121] Fig. 15 shows an example of a current controlled voltage source inverter system 1500 (CC VSI). As shown in the example of Fig. 15, the system

1500 can include transform circuitry 1530 (e.g., for dq to abc transformation), a current controller 1530, a voltage source inverter, LC filter and transformer block 1550, a rotor flux estimator 1560 (e.g., rotor flux estimation circuitry), a position to speed conversion block 1565 and an ESP cable and ESP permanent magnet motor (PMM) 1590.

[00122] In the system 1500, abc frame current references, i_a^* , i_b^* , i_c^* may be estimated from a d -axis component, i_{sd}^* and a q -axis component, i_{sq}^* and stator currents, i_a , i_b , i_c may be controlled directly in the abc frame by the current controller 1530. As shown, the rotor flux estimator 1560 receives motor currents, i_a , i_b , i_c (e.g., motor current values) and estimated and/or sensed motor terminal phase to neutral voltages, v_{saN} , v_{sbN} , v_{scN} . As an example, the current controller 1530 and the rotor flux estimator 1560 may receive updated motor/cable electrical parameter information (e.g., to enhance accuracy of operation).

[00123] In the example of Fig. 15, the d -axis component, i_{sd}^* and the q -axis component, i_{sq}^* may be estimated via a speed control block. For example, Fig. 16 shows an example of a system 1600 that includes a speed control block 1610 and a torque to current conversion block 1630. The system 1600 may form at least a portion of a speed control loop. For example, a speed controller may estimate the reference torque, T^* , based on an error of the reference speed, ω_r^* , and estimated rotor speed, ω_r (e.g., the reference torque T^* may be based at least in part on one or more errors, speeds, etc.) As an example, torque to current conversion may be performed using one or more algorithms (e.g., consider a Field Oriented Control (FOC) algorithm, a Maximum Torque Per Ampere (MTPA) algorithm, etc.).

[00124] Fig. 17 shows an example of a system 1700 and an example of a circuitry schematic 1705. The system 1700 and circuitry schematic 1705 include features for vector control of PMM such as a PMM of an ESP system that is operatively coupled to a drive via a cable or cables, which may introduce asymmetry.

[00125] As shown in Fig. 17, the system 1700 includes a VSD/LC filter 1710, optionally a transformer 1730, a motor power cable 1770 (e.g., or chained cables) and a permanent magnet motor (PMM) 1790. The system 1700 is a multiphase system where phases are represented as a, b and c, which are joined at a wye point "N" (e.g., intended to be neutral) at or near the PMM 1790. The schematic 1705 of Fig. 17 may be considered to be an example of an electrical equivalent circuit for power frequency operation.

[00126] The schematic 1705 shows the presence of the VSD/LC filter 1710, the transformer 1730, the long cable 1770 and the PMM 1790 (e.g., as may drive a pump of an ESP system). The transformer 1730 may be optional, for example, provided where the drive is a low voltage drive (LVD).

[00127] As shown in Fig. 17, the VSD/LC filter 1710 outputs three-phase voltage output with respect to a DC link mid-point O such that the voltages may be referred to as v_{iaO} , v_{ibO} , v_{icO} . For power frequency operation, transformer and cable resistance and inductance for each of the three phases may be referred as (R_{ta}, L_{ta}) , (R_{tb}, L_{tb}) , (R_{tc}, L_{tc}) . As an example, parameters of the system 1700 may be assumed to be asymmetrical. As shown, motor per phase resistance and self-inductance may be referred as R and L , respectively. Back emf induced in each of the stator phases may be referred as e_{aN} , e_{bN} , e_{cN} , where N is the neutral of the motor stator phases (e.g., wye point). In the example of Fig. 17, the points O and N may be relatively electrically isolated. By combining the motor 1790 as well as the cable 1770 and transformer 1730, each phase resistance and inductances may be referred as (R_a, L_a) , (R_b, L_b) and (R_c, L_c) .

[00128] As an example, a system may be described using the following equations:

$$\begin{aligned} L_a \frac{di_a}{dt} + R_a i_a &= v_{iaN} - e_{aN} \\ L_b \frac{di_b}{dt} + R_b i_b &= v_{ibN} - e_{bN} \\ L_c \frac{di_c}{dt} + R_c i_c &= v_{icN} - e_{cN} \\ i_a + i_b + i_c &= 0 \end{aligned}$$

[00129] Such equations may follow the derivations presented above (see, e.g., the description of Fig. 9 for an induction motor, preceding introduction of Fig. 10).

[00130] Referring to the system 1500 of Fig. 15, the rotor position estimator 1560 may be configured for purposes of control of a PMM. As an example, the rotor position estimator 1560 may operate with initial rotor position information. For example, if the initial rotor position, θ_{r0} , is known at the starting of the motor, the initial stator flux magnitude, $\vec{\psi}_{s0}^s$ can be estimated (e.g., as the initial stator current may be considered to be zero) as:

$$\vec{\psi}_{s0}^s = \psi_r e^{j(\frac{3\pi}{2} + \theta_{r0})}$$

where, ψ_r is the d -axis rotor flux linkage of the permanent magnet (e.g., this can be known from the design value and initial magnetic test on the motor). Fig. 18 shows an example of the rotor position estimator 1560 where such an approach is implemented (e.g., an approach that includes receiving information indicative of initial position).

[00131] As shown in Fig. 18, motor terminal phase to neutral voltages, v_{saN} , v_{sbN} , v_{scN} are fed to the estimator 1560 and converted to stator voltage space vector, $\vec{v}_s^s$ by an $abc/\alpha\beta$ transformation. As an example, stator current space vector, $\vec{i}_s^s$ may be calculated using motor terminal three phase power frequency currents, i_a , i_b , i_c .

[00132] As an example, with the initial stator flux magnitude, $\vec{\psi}_{s0}^s$, the stator flux may be determined as follows:

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

[00133] From the foregoing equations, rotor flux vector, $\vec{\psi}_r^s$ may be estimated as follows:

$$\begin{aligned} \vec{\psi}_r^s &= \vec{\psi}_s^s - l_s \vec{i}_s^s \\ \vec{\psi}_r^s &= \psi_r e^{j(\frac{3\pi}{2} + \theta_r)} \end{aligned}$$

where, $\vec{\psi}_s^s$ is the stator flux, l_s is the stator per phase self-inductance (see, e.g., Fig. 17, $l_s = L$), r_s is the stator resistance (see, e.g., Fig. 17, $r_s = R$), l_r is the rotor per phase self-inductance referred to stator, l_h is the per-phase magnetizing inductance referred to stator.

[00134] As an example, from the angle of rotor flux, $\vec{\psi}_r^s$, the rotor position, θ_r may be estimated via one or more techniques. For example, the initial rotor position, θ_{r0} , may be estimated a MVD technique or via a LVD technique.

[00135] As to the MVD technique, where the motor is running with a Medium Voltage Drive (MVD), the position may be estimated by connecting a DC voltage to

two of the three phases, the permanent magnet rotor can be aligned to a pre-defined rotor position, which can be taken as initial rotor position. The DC voltage can be applied between any two phases by controlling the inverter voltages. After that the motor can be started as regular vector control using this estimator.

[00136] As to the LVD technique, where the motor is running with a Low Voltage Drive (LVD), applying DC voltage across the motor phases may be problematic due to the presence of transformer at the output of the inverter. Thus, for LVD, a scheme as illustrated by a system 1900 of Fig. 19 may be implemented, which includes applying DC voltage between two phases of PMM for LVD operation.

[00137] As shown in Fig. 19, the system 1900 can a surface portion 1901 and a downhole portion 1903 where a cable 1940 may extend from the surface portion 1901 to the downhole portion 1903. As shown, the system 1900 can include a magnetic coupling 1910, a secondary of a transformer 1920, a single phase rectifier 1930, the cable 1940 and a permanent magnet motor stator 1950 (e.g., of a permanent magnet motor).

[00138] In the system 1900 of Fig. 19, an assumption may be made that a DC voltage is applied between phases a and b of the PMM. However, such an arrangement may be performed with other phase combinations. As an example, the single phase rectifier 1930 may be introduced between phases a and b after the secondary of the transformer 1920. In such an example, when, initial position is to be fixed, switches S_1 , S_2 , S_3 may be opened and switches S_{a1} , S_{a2} , S_{b1} , S_{b2} may be closed. As a result, DC voltage is applied between phases a and b and the rotor of the permanent magnet motor can orient itself to a predefined initial position. As an example, inverter output voltages can be controlled to get suitable DC voltage at the rectifier output. Thereafter, switches S_{a1} , S_{a2} , S_{b1} , S_{b2} may be opened and switches S_1 , S_2 , S_3 may be closed to start operation of a drive with this predefined rotor position. As an example, interlocks may be included between different sets of the switches. As an example, the rectifier system may be removed from the installation after the motor has started its intended operation (e.g., to drive a pump to pump fluid). As an example, the system 1900 may be a "start-up" system, for example, where the single phase rectifier 1930 and optionally associated circuitry may be removed after a start-up phase (e.g., or a control initiation phase). As an example, such components may be pluggable, for example, to allow for a recalibration of a rotor position is desired, sharing of the components amongst various systems, etc.

[00139] As an example, a downhole gauge may be utilized additionally and/or alternatively to estimate an initial rotor position, for example, using one or more magnetic sensors. In such an example, information may be transmitted to surface circuitry and the motor can be started with vector control using this estimator.

[00140] Fig. 20 shows an example of the rotor position estimator 1562 of the system 1500 of Fig. 15. In such an example, the rotor position estimation 1562 may estimate rotor position after the PMM attains a certain speed. For example, the PMM can be started using low frequency sinusoidal current or V/f control without rotor position information and, when the rotor reaches a certain speed (e.g., about 10 percent), the drive can be switched to a vector control mode.

[00141] Referring again to the system 1500 of Fig. 15, utilizing the estimators 1560 and 1565, motor speed, ω_r , can be estimated. As an example, motor speed can be estimated from the position information.

[00142] As an example, a PMM vector control scheme may implement one or more of the approaches as illustrated in Figs. 12, 13 and 14. As illustrated, the system 1500 may provide for vector control based speed/ torque operation of a PMM as may be operatively coupled to one or more cables that introduce phase asymmetry into a multiphase system.

[00143] As an example, a multiphase system may experience asymmetry in the form of one phase becoming practically inoperable. In such an example, a three-phase system may become effectively a two-phase system.

[00144] As an example, a system may include circuitry that can operate a multiphase system with X phases as a multiphase system with X-1 phases. For example, consider circuitry that can operate a three phase system ($X = 3$) as a two phase system.

[00145] As an example, an ESP motor may operate with a three phase balanced supply in a stator to generate a gap rotating magnetic field (e.g., a field in a gap between components where the gap may include a fluid such as a dielectric fluid). In such an example, circuitry may be included in a system for controlling the three-phase motor where one of the phases is effectively unavailable or otherwise not practical for use, for example, to operate the motor using two of the phases for excitation.

[00146] As an example, a system may include one or more cables that introduce phase asymmetry (e.g., circuit parameter asymmetry). In such an

example, a current control technique can include creating a rotating magnetic field when one of the phases is unavailable or otherwise not practical for use; effectively allowing a motor to operate using two of three phases. Such an approach may increase the operating regime of a three-phase motor and avoid costs associated with retrieving a cable and motor from a downhole location (e.g., for repair, replacement, etc.).

[00147] As an example, a method may include real-time motor and/or cable electrical parameter estimation operating in parallel, for example, to compensate for different parameter variation to control a motor. For example, consider the systems 1300 and 1400 of Figs. 13 and 14, respectively. As an example, one or more estimations of a parameter value or parameter values may be based at least in part on sensed information, for example, sensed during operation of a system, while a system is deployed, etc. As an example, sensed information may be acquired during a period of time where a rotor of an electric motor is not rotating and/or during a period of time where a rotor of an electric motor is rotating. As an example, sensed information may be acquired during a condition, which may correspond to an operational state, an error state, etc.

[00148] Fig. 21 shows an example of a motor 2115 that includes circuitry for three phases electrically coupled at a wye point 2125 and an example of a vector diagram 2130. As illustrated in Fig. 21, a three-phase motor stator is fed with three-phase balanced excitation to develop a rotating magnetic field in a gap (e.g., a gap between components where the gap may include a fluid such as a dielectric fluid).

[00149] As shown in the vector diagram 2130, the three phases of the motor stator are fed with voltages, so that the currents in the three phases, i_a , i_b , i_c are:

$$\begin{aligned} i_a &= I_m \cos(\theta) \\ i_b &= I_m \cos\left(\theta - \frac{2\pi}{3}\right) \\ i_c &= I_m \cos\left(\theta + \frac{2\pi}{3}\right) \\ \theta &= \int \omega dt \end{aligned}$$

where, I_m is the peak value of the current in each phase, θ is the electrical phase of currents and ω is the frequency of the currents.

[00150] By assuming that the number of turns of each phase of stator winding is N_s , the space vector of magnetic field, $\vec{F}_{SV}$, in a gap of the motor due to stator excitation can be expressed as follows (e.g., consider a rotating magnetic field in a gap, which may be a gap at least partially filled with a fluid such as a dielectric fluid):

$$\vec{F}_{SV} = \left(\frac{2}{3}\right) N_s \left(i_a e^{j0} + i_b e^{j\left(\frac{2\pi}{3}\right)} + i_c e^{-j\left(\frac{2\pi}{3}\right)} \right)$$

$$\vec{F}_{SV} = N_s I_m e^{j\theta}$$

[00151] In the following example equations, it is assumed that, phase c of the motor stator is disconnected or otherwise not practically usable; noting that the equations may be appropriately modified to account for one of phase a or phase b being disconnected or otherwise not practically usable.

[00152] The following equations assume that the current through phase c is approximately zero (e.g., mathematically, $i_c = 0$). Solving for i_a and i_b to get the space vector of the magnetic field provides:

$$\vec{F}_{SV} = \left(\frac{2}{3}\right) N_s \left(i_a e^{j0} + i_b e^{j\left(\frac{2\pi}{3}\right)} \right) = N_s I_m e^{j\theta}$$

[00153] Solving the real and imaginary terms separately, the following mathematical terms result:

$$i_a = \sqrt{3} I_m \sin\left(\theta + \frac{\pi}{3}\right)$$

$$i_b = \sqrt{3} I_m \sin(\theta)$$

$$i_c = 0$$

[00154] Fig. 22 shows an example of a motor 2215 that includes circuitry for three phases where one of the phases is not electrically coupled at a wye point 2225 (see, e.g., dashed lines) and an example of a vector diagram 2230. As illustrated in Fig. 22, a three-phase motor stator is fed with two-phase excitation to develop a rotating magnetic field in a gap (e.g., consider a gap between components where the gap may be at least partially filled with a fluid such as a dielectric fluid). For

example, the motor 2215 may be fed with current according to the equations for i_a and i_b , above.

[00155] The vector diagram 2230 illustrates a rotating magnetic field with two phases, noting that the third phase is assumed to have a current of approximately zero.

[00156] As an example, where one phase of a multiphase system is not usable, the current magnitude of other phases may increase approximately $\sqrt{3}$ times to develop an approximately equivalent magnitude rotating magnetic field. Also, the phase difference of the current excitations of the available phases may no longer be of about 120 degrees, but rather, it may be of about 60 degrees under such operational conditions.

[00157] Fig. 23 shows an example of a system 2300 that includes a motor 2315 with a wye point 2325 and a switch assembly 2335. As an example, such a downhole switch assembly may be positioned at or near a motor head end (e.g., a pot head of a motor assembly). Fig. 23 shows the switch assembly 2335 in a first state and in a second state where the first state may be considered a three phase operational state and where the second state may be considered a two phase operational state where phases a and b are used to excite a stator of the motor 2315. As shown, the switch assembly 2335 may include circuitry that allows for switching of one or more of the phases a, b or c to be electrically coupled to the wye point 2325 via a pathway that does not pass directly to a stator of the motor 2315.

[00158] As an example, a downhole switch assembly may be placed at or near a pot head of a motor assembly. As an example, three conductors of one or more cables may be connected to respective motor phases via the switch assembly. Where one of the phases is in operable or a decision is made to switch from three phase to two phase operation, the switch assembly may disconnect one of the three phases and connect that particular phase to the neutral, N (e.g., a wye point of the motor). In such an example, a diversion created by the switch assembly forms a path for current return. As an example, where a gauge is included in an ESP system, a gauge may include circuitry to implement a switch and/or to call for switching, optionally in a manner responsive to unbalance at the wye point of a motor (e.g., unbalance exceeding a level of unbalance indicative of an issue with one of a plurality of phases).

[00159] Fig. 24 shows an example of a system 2400 and an example of a circuitry schematic 2405. The system 2400 and circuitry schematic 2405 include features for switching of a phase to effectively change operation from three phase to two phase.

[00160] As shown in Fig. 24, the system 2400 includes a VSD/LC filter 2410, optionally a transformer 2430, a switch 2435 (e.g., a switch assembly), a motor power cable 2470 (e.g., or chained cables) and an induction motor (IM) 2490. The system 2400 is a multiphase system where phases are represented as a, b and c, which are joined at a wye point "N" (e.g., intended to be neutral) at or near the IM 2490. The schematic 2405 of Fig. 24 may be considered to be an example of an electrical equivalent circuit for operation of the induction motor 2490 using two of the three phases (e.g., per the switch 2435). As an example, the system 2400 may control current in terms of magnitude as well as phase angle of two available phases (e.g., or selected phases).

[00161] Fig. 24 shows the VSD/LC filter 2410, the transformer 2430, the cable 2470 and the induction motor 2490. The transformer 2430 is optional, for example, it may be included in a low voltage drive (LVD) scenario. As shown, the VSD/LC filter 2410 provides three-phase voltage output with respect to a DC link mid-point O such that voltages may be referred as v_{iaO} , v_{ibO} , v_{icO} . For power frequency operation, the transformer and the cable resistance and inductance for each of the three phases may be referred as (R_{ta}, L_{ta}) , (R_{tb}, L_{tb}) , (R_{tc}, L_{tc}) . Parameters may be assumed to be asymmetrical. Motor per phase resistance and self-inductance may be referred as R and L , respectively. Back emf induced in each of the available stator phases may be referred as e_{aN} , e_{bN} , where N is the neutral of the motor stator phases. The point O and N may be considered to be relatively electrically isolated. Due to asymmetrical operation, each available phase of the motor can include a mutual inductance, l_m .

[00162] The system 2400 may be (e.g., for three phase operation) described using the basic equations as:

$$\begin{aligned} (L + L_{ta}) \frac{di_a}{dt} - l_m \frac{di_b}{dt} + (R_{ta} + R)i_a &= v_{iaN} - e_{aN} \\ -l_m \frac{di_a}{dt} + (L + L_{tb}) \frac{di_b}{dt} + (R_{tb} + R)i_b &= v_{ibN} - e_{bN} \\ -L_{tc} \frac{di_a}{dt} - L_{tc} \frac{di_b}{dt} - R_{tc}i_a - R_{tc}i_b &= v_{icN} \end{aligned}$$

[00163] With replacement and rearrangement, the electrical system equations can be transformed to:

$$\begin{aligned} v_{iac} - e_{aN} &= L_a \frac{di_a}{dt} - L_m \frac{di_b}{dt} + R_a i_a + R_{tc} i_b \\ v_{ibc} - e_{bN} &= L_b \frac{di_b}{dt} - L_m \frac{di_a}{dt} + R_b i_b + R_{tc} i_a \end{aligned}$$

where, the modified circuit parameters may be expressed as:

$$\begin{aligned} L_a &= L + L_{ta} + L_{tc} \\ L_b &= L + L_{tb} + L_{tc} \\ L_m &= l_m - L_{tc} \\ R_a &= R + R_{ta} + R_{tc} \\ R_b &= R + R_{tb} + R_{tc} \end{aligned}$$

where, v_{iac} and v_{ibc} are the inverter/LC filter two line to line output voltages (phase ac and bc respectively) and e_{aN} and e_{bN} are two available phase back emfs of the motor.

[00164] Such equations may follow the derivations presented above (see, e.g., the description of Fig. 9 for an induction motor, preceding introduction of Fig. 10).

[00165] As an example, a control scheme may implement one or more of the approaches as illustrated in Figs. 12, 13 and 14.

[00166] Fig. 25 shows examples of cables 2510 and 2530 and example data in a table 2550. The cable 2510 may be considered to be a round cable while the cable 2530 may be considered to be a flat cable. A flat cable may exhibit asymmetry, for example, due to differences in conditions experienced by its conductors. For example, a middle conductor may be positioned in a cable casing such that it has less heat transfer area compared to end conductors. In such an example, the middle conductor (e.g., an interior conductor) may increase in temperature more than an end conductor. Properties of a conductor can be temperature dependent. Thus, where temperatures of conductors of a multiphase cable differ, asymmetries may be introduced as a result of such temperature differences. As an example, fields generated by cables while conducting current may also give rise to asymmetries (e.g., as to heat generation, stress, field

interactions, etc.). For example, a field about a middle conductor may differ from a field about an end conductor.

[00167] The table 2550 shows example data for an example system that includes an electric motor rated at about 75 HP (e.g., powered at about 1150V and about 40 A) operatively coupled to a pump section and operatively coupled to a “flat” power cable with a length of about 4000 feet (e.g., about 1200 meters). As an example, an electric motor suitable for use in one or more downhole environments may be supplied with power from an uphole power source (e.g., surface power source) via one or more power cables and, for example, may be rated in terms of HP (e.g., consider a motor rated at about a few HP to a motor rated at more than about 1000 HP). As an example, unbalance, for a given cable length, etc., may increase in a manner that corresponds to HP rating. For example, a motor rated at about 500 HP positioned at a depth may be expected to experience greater unbalance than a motor rated at about 50 HP positioned at the same depth. As an example, as depth may determine, at least in part, pressure head, a greater depth may correspond to greater HP (e.g., to pump fluid uphole).

[00168] As indicated in the table 2550, voltage unbalance at a motor of about 0.07 percent may correspond to a current unbalance of about 0.9 percent. Where a cable extends from a distance from a power supply to a motor, voltage unbalance may exist at the power supply (e.g., power supply end of the cable) and at the motor (e.g., motor end of the cable). In such an example, the voltage unbalance at the power supply end is less than at the motor end of the cable, as indicated by the data in the table 2550. In particular, a voltage unbalance of about 0.1 percent increases to about 0.7 percent, which, in turn, results in a current unbalance of about 3.6 percent. As an example, a given percent of voltage unbalance may cause a multiple thereof in terms of percent of current unbalance. For example, consider an increase of the order of about 5 times to about 10 times in terms of percent voltage unbalance to percent current unbalance. As an example, a current unbalance of the order of about 1 percent may be indicative of asymmetry in a system. As an example, where a phase of a multiphase electric motor becomes practically inoperable (e.g., grounded due to loss of insulation, etc.), unbalance may increase considerably (e.g., consider unbalance of about 50 percent as a result of a grounded phase).

[00169] As an example, asymmetry of a system may increase with cable length. As an example, asymmetry of a system may be temperature dependent. As

an example, asymmetry of a system may depend at least in part on configuration of a cable (e.g., flat, round, etc.). As an example, asymmetry of a system may depend on bore geometry (e.g., twists, turns, etc.). As an example, a cable may extend a distance of the order of hundreds of meters or a thousand meters or more. As an example, a system may be modeled to estimate a level of unbalance and, for example, implemented using vector control that can account for asymmetry.

[00170] As an example, introduction of a negative sequence voltage can act to apply force with a rotation opposite to that of a balanced system. As an example, unbalance can increase vibration, increase sound noise, increase temperature, reduce load carrying capacity, decrease torque, and/or reduce speed.

[00171] As explained, factors associated with a cable or cables may result in asymmetries with respect to individual phases of a multiphase system. As an example, vector control may be implemented in a manner that accounts for such asymmetries, for example, via inclusion of one or more parameters into control logic. As an example, values of one or more of such parameters may be measured and/or estimated, optionally in real-time (e.g., during operation of an ESP motor). In such an example, vector control may be adjusted in a manner responsive to changes in one or more parameter values. As mentioned, operational conditions can include, for example, temperature, which may depend on factors such as temperature of a geologic environment, status of an EOR operation (e.g., SAGD, etc.), temperature and flow rate of fluid being pumped by an ESP system or ESP systems.

[00172] As an example, unbalance in a cable/power supply components can introduce impedance unbalance resulting in current and voltage unbalance at motor terminals. Such unbalance can, in turn, contribute to torque vibration, reduction in torque, etc. As an example, a system can include circuitry that implements vector control that can help balance currents in motor phases, for example, such that a motor is able to develop flat, controlled torque even in the presence of unbalance in cable/ power supply circuit impedance. As an example, a vector control system may operate to balance phases of a multiphase system that includes a multiphase electric motor where the multiphase system includes asymmetries that cause impedance to differ between two or more of the phases. Such asymmetries may be due at least in part to properties of one or more cables that are operatively coupled to the multiphase electric motor where such properties may include, for example, electrical properties, mechanical properties, and/or heat transfer properties. An environment

may contribute at least in part to unbalance. For example, consider temperature of a bore in a geologic formation where equipment is disposed in the bore, flow of fluid in a bore where the fluid may contact equipment, and/or topology of a bore (e.g., bends, twists, etc.), which may orient equipment (e.g., bend a cable, cause a cable to contact a bore wall or other surface, etc.).

[00173] As an example, a system can include a current controller that includes state-space based control logic that outputs three voltage values based at least in part on two current values and values of asymmetric state-space system parameters associated with an electric submersible pump system that includes a power supply cable and an motor electrically coupled to the power supply cable. As an example, such control logic may output three voltage values based on three current values where one of the current values is approximately zero.

[00174] As an example, a system that includes a motor can include a rotor flux estimator that includes circuitry that outputs a rotor flux angle value based at least in part on three current values of current supplied to the motor. In such an example, the circuitry may output rotor flux angle values based at least in part on three voltage values of voltage supplied to the motor where the three voltage values of voltage supplied to the motor are based at least in part on three voltage values output by a current controller.

[00175] As an example, a system can include transform circuitry that transforms two current values from an d, q domain to two current values of an a, b, c domain. As an example, an d, q domain may be defined by a d -axis and a q -axis. As an example, a complex stator motor current space vector can be defined in a (d, q) coordinate system (e.g., a d, q domain) with orthogonal components along d (direct) and q (quadrature) axes such that a field flux linkage component of current is aligned along the d -axis and a torque component of current is aligned along the q -axis. In such an example, an induction motor's (d, q) coordinate system may be superimposed to the induction motor's instantaneous (a, b, c) three-phase sinusoidal system (e.g., an a, b, c domain). As an example, two current values of an a, b, c domain may be received as two current values of a current controller.

[00176] As an example, a system can include transform circuitry that may transform two current values from a d, q domain to two current values of an a, b, c domain based at least in part on a rotor flux angle value. In such an example, the system may include a rotor flux estimator that includes circuitry that outputs the rotor

flux angle value based at least in part on three current values of current supplied to a motor.

[00177] As an example, a system can include a voltage source inverter that outputs three current values based at least in part on reception of three voltage values output by a current controller.

[00178] As an example, a system can include a parameter estimator that estimates values for one or more of asymmetric state-space system parameters based at least in part on a model of at least one of the power supply cable and the motor. For example, such a model may depend at least in part on temperature and/or may depend at least in part on motor speed of a motor. As an example, a parameter estimator may operate to estimate values for one or more of asymmetric state-space system parameters in real-time (e.g., at particular times, etc.).

[00179] As an example, a system can include an induction motor. In such an example, the system may include circuitry that estimates terminal phase to neutral voltage values for three phase power supplied to the induction motor. In such an example, the system may include a rotor flux estimator that includes circuitry that outputs a rotor flux angle value based at least in part on estimated terminal phase to neutral voltage values.

[00180] As an example, a system may include a permanent magnet motor. In such an example, the system may include a position to speed converter that includes circuitry that outputs a position value based at least in part on an estimated rotor flux angle value.

[00181] As an example, a system may include a three phase motor and a switch assembly that selectively switches the motor from a three phase operational mode to a two phase operational mode. In such an example, the two phase operational mode may be a vector controlled mode controlled at least in part via a current controller.

[00182] As an example, a system can include a three phase motor; and a switch assembly that includes an electrical connection to a wye point of the motor where the switch assembly selectively switches the motor from a three phase operational mode to a two phase operational mode. As an example, the switch assembly may operate in response to unbalance of phases, for example, where one phase becomes grounded, the switch assembly may switch to the two phase operational mode where the two phases of the two phase operational mode do not

include the grounded phase (e.g., as associated with a phase of a multiphase power cable). As an example, a switch assembly may include an input for a control signal where receipt of a control signal by the input causes the switch assembly to switch from one operational mode to another operational mode.

[00183] As an example, a system may include a rectifier circuit that can be implemented to determine an initial position of a rotor of an electric motor. In such an example, the rectifier circuit may be removable, for example, after an initial position of the rotor has been determined. As an example, a controller may operate at least in part on an initial position value of a rotor. For example, control logic may depend at least in part on an initial position value of a rotor.

[00184] As an example, one or more control modules (e.g., for a controller such as the controller 230, the controller 250, etc.) may be configured to control an ESP (e.g., a motor, etc.). As an example, one or more control modules may include circuitry (e.g., hardware, software or hardware and software) that can implement vector control. As an example, a module may include an input, an output and control logic, for example, that receives input and that outputs one or more control signals (e.g., data, etc.) based at least in part on the input and the control logic.

[00185] As an example, circuitry can includes one or more levels of available integration, for example, from discrete logic circuits to VLSI. As an example, circuitry can include one or more programmable logic components programmed to perform one or more functions (e.g., of a system, a method, etc.). As an example, circuitry may include one or more general-purpose and/or special-purpose processors (e.g., programmed with instructions to perform one or more functions). As an example, circuitry may function according to one or more equations, which may include one or more state-space equations.

[00186] As an example, one or more methods described herein may include associated computer-readable storage media (CRM) blocks. Such blocks can include instructions suitable for execution by one or more processors (or cores) to instruct a computing device or system to perform one or more actions. As an example, equipment may include a processor (e.g., a microcontroller, etc.) and memory as a storage device for storing processor-executable instructions. In such an example, execution of the instructions may, in part, cause the equipment to perform one or more actions (e.g., for control, sensing, telemetry, etc.).

[00187] According to an embodiment, one or more computer-readable media may include computer-executable instructions to instruct a computing system to output information for controlling a process. For example, such instructions may provide for output to a sensing process, an injection process, a drilling process, an extraction process, an extrusion process, a pumping process, a heating process, etc.

[00188] Fig. 26 shows components of a computing system 2600 and a networked system 2610. The system 2600 includes one or more processors 2602, memory and/or storage components 2604, one or more input and/or output devices 2606 and a bus 2608. According to an embodiment, instructions may be stored in one or more computer-readable media (e.g., memory/storage components 2604). Such instructions may be read by one or more processors (e.g., the processor(s) 2602) via a communication bus (e.g., the bus 2608), which may be wired or wireless. The one or more processors may execute such instructions to implement (wholly or in part) one or more attributes (e.g., as part of a method). A user may view output from and interact with a process via an I/O device (e.g., the device 2606). According to an embodiment, a computer-readable medium may be a storage component such as a physical memory storage device, for example, a chip, a chip on a package, a memory card, etc.

[00189] According to an embodiment, components may be distributed, such as in the network system 2610. The network system 2610 includes components 2622-1, 2622-2, 2622-3, . . . 2622-N. For example, the components 2622-1 may include the processor(s) 2602 while the component(s) 2622-3 may include memory accessible by the processor(s) 2602. Further, the component(s) 2602-2 may include an I/O device for display and optionally interaction with a method. The network may be or include the Internet, an intranet, a cellular network, a satellite network, etc.

Conclusion

[00190] Although only a few examples have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the examples. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims. In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural

equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures. It is the express intention of the applicant not to invoke 35 U.S.C. § 112, paragraph 6 for any limitations of any of the claims herein, except for those in which the claim expressly uses the words “means for” together with an associated function.

CLAIMS

What is claimed is:

1. A system comprising:
a current controller that comprises state-space based control logic that outputs three voltage values based at least in part on two current values and values of asymmetric state-space system parameters associated with an electric submersible pump system that comprises a power supply cable and an motor electrically coupled to the power supply cable.
2. The system of claim 1 further comprising a rotor flux estimator that comprises circuitry that outputs a rotor flux angle value based at least in part on three current values of current supplied to the motor.
3. The system of claim 2 wherein the circuitry outputs rotor flux angle values based at least in part on three voltage values of voltage supplied to the motor wherein the three voltage values of voltage supplied to the motor are based at least in part on the three voltage values output by the current controller.
4. The system of claim 1 further comprising transform circuitry that transforms two current values from an d, q domain to two current values of an a, b, c domain.
5. The system of claim 4 wherein the two current values of the a, b, c domain are received as the two current values of the current controller.
6. The system of claim 4 wherein the transform circuitry transforms the two current values from the d, q domain to two current values of the a, b, c domain based at least in part on a rotor flux angle value.
7. The system of claim 6 further comprising a rotor flux estimator that comprises circuitry that outputs the rotor flux angle value based at least in part on three current values of current supplied to the motor.

8. The system of claim 1 further comprising a voltage source inverter that outputs three current values based at least in part on reception of the three voltage values output by the current controller.
9. The system of claim 1 further comprising a parameter estimator that estimates values for one or more of the asymmetric state-space system parameters based at least in part on a model of at least one of the power supply cable and the motor.
10. The system of claim 9 wherein the model depends at least in part on temperature.
11. The system of claim 9 wherein the model depends at least in part on motor speed of the motor.
12. The system of claim 9 wherein the parameter estimator operates to estimate the values in real-time.
13. The system of claim 1 wherein the motor is an induction motor.
14. The system of claim 13 further comprising circuitry that estimates terminal phase to neutral voltage values for three phase power supplied to the induction motor.
15. The system of claim 14 further comprising a rotor flux estimator that comprises circuitry that outputs a rotor flux angle value based at least in part on estimated terminal phase to neutral voltage values.
16. The system of claim 1 wherein the motor is a permanent magnet motor.
17. The system of claim 16 further comprising a position to speed converter that comprises circuitry that outputs a position value based at least in part on an estimated rotor flux angle value.

18. The system of claim 1 wherein the motor comprises a three phase motor and further comprising a switch assembly that selectively switches the motor from a three phase operational mode to a two phase operational mode.
19. The system of claim 18 wherein the two phase operational mode comprises a vector controlled mode controlled at least in part via the current controller.
20. A system comprising:
a three phase motor; and
a switch assembly that comprises an electrical connection to a wye point of the motor wherein the switch assembly selectively switches the motor from a three phase operational mode to a two phase operational mode.

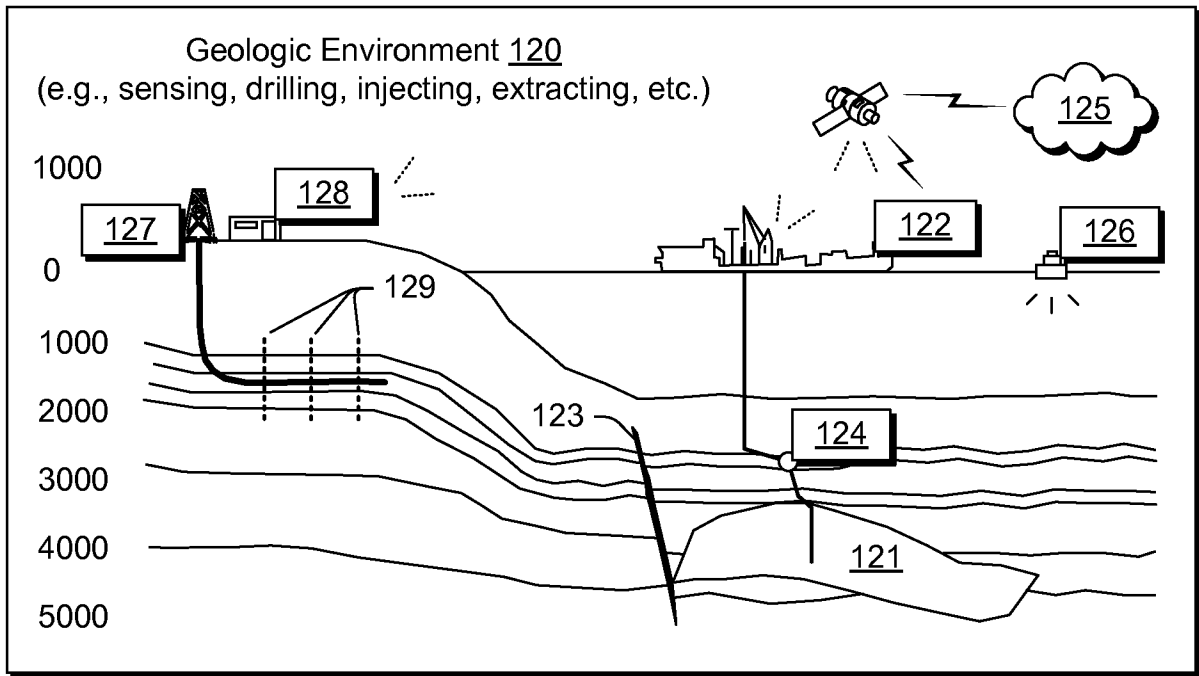
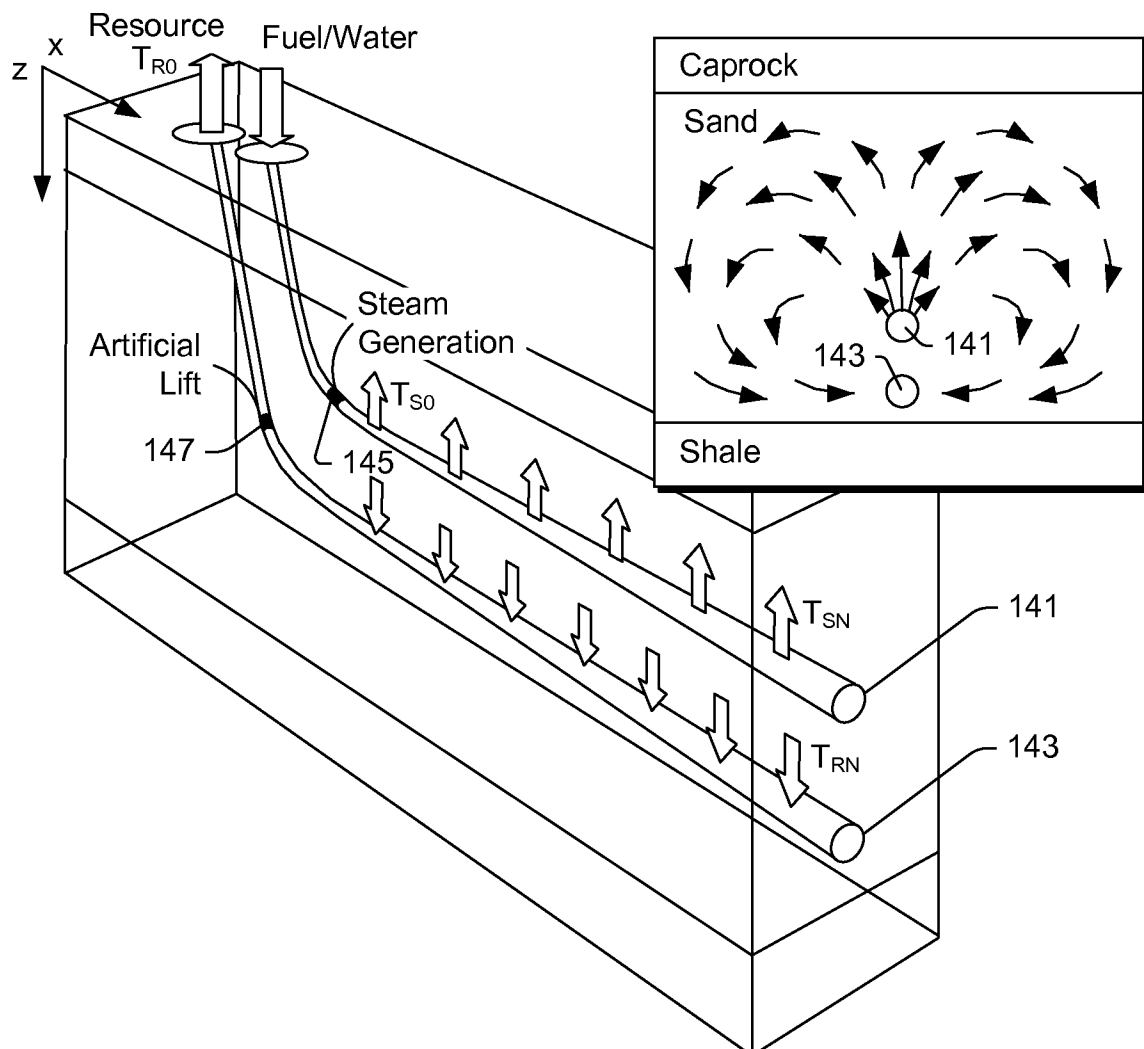
Geologic Environment 140

Fig. 1

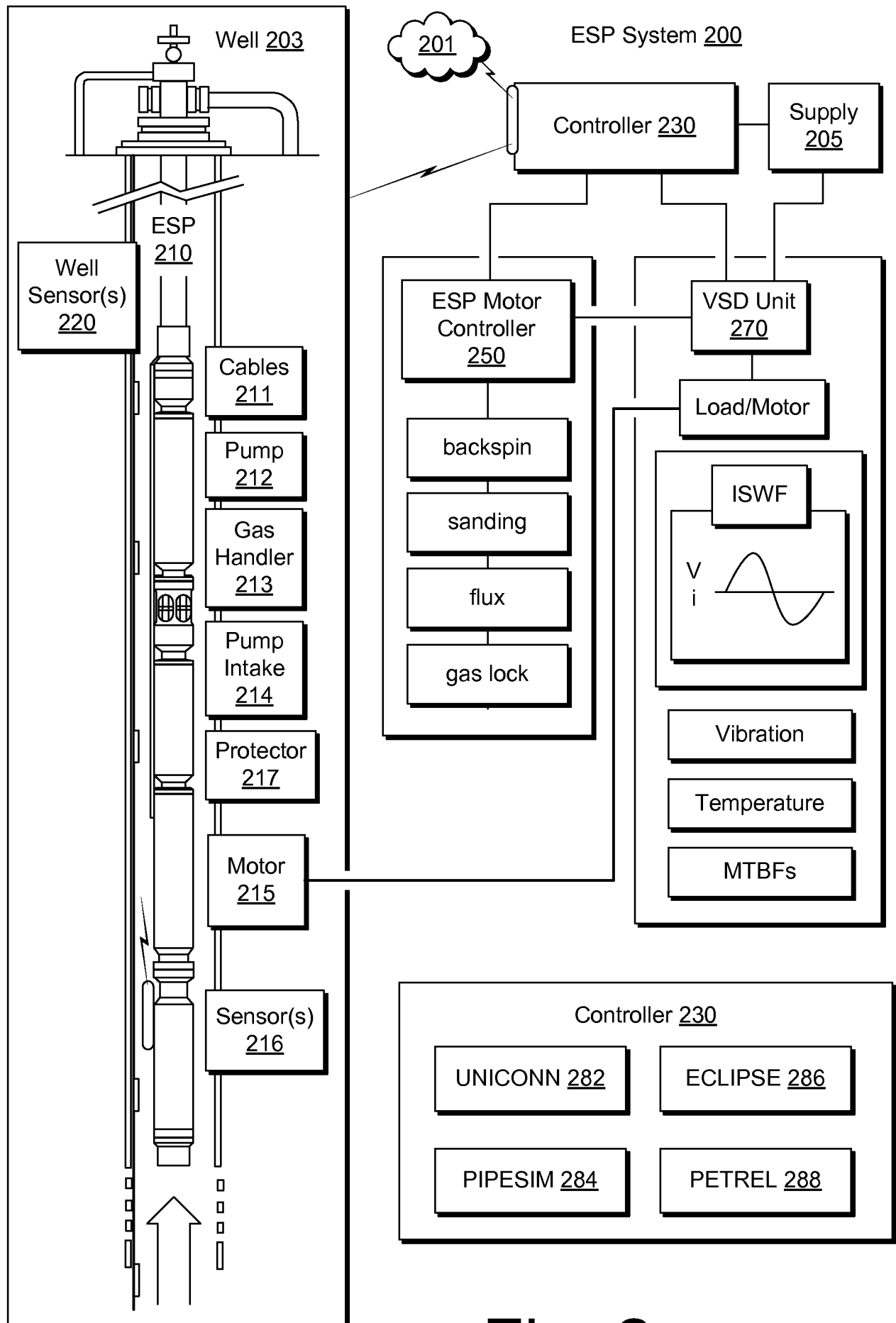


Fig. 2

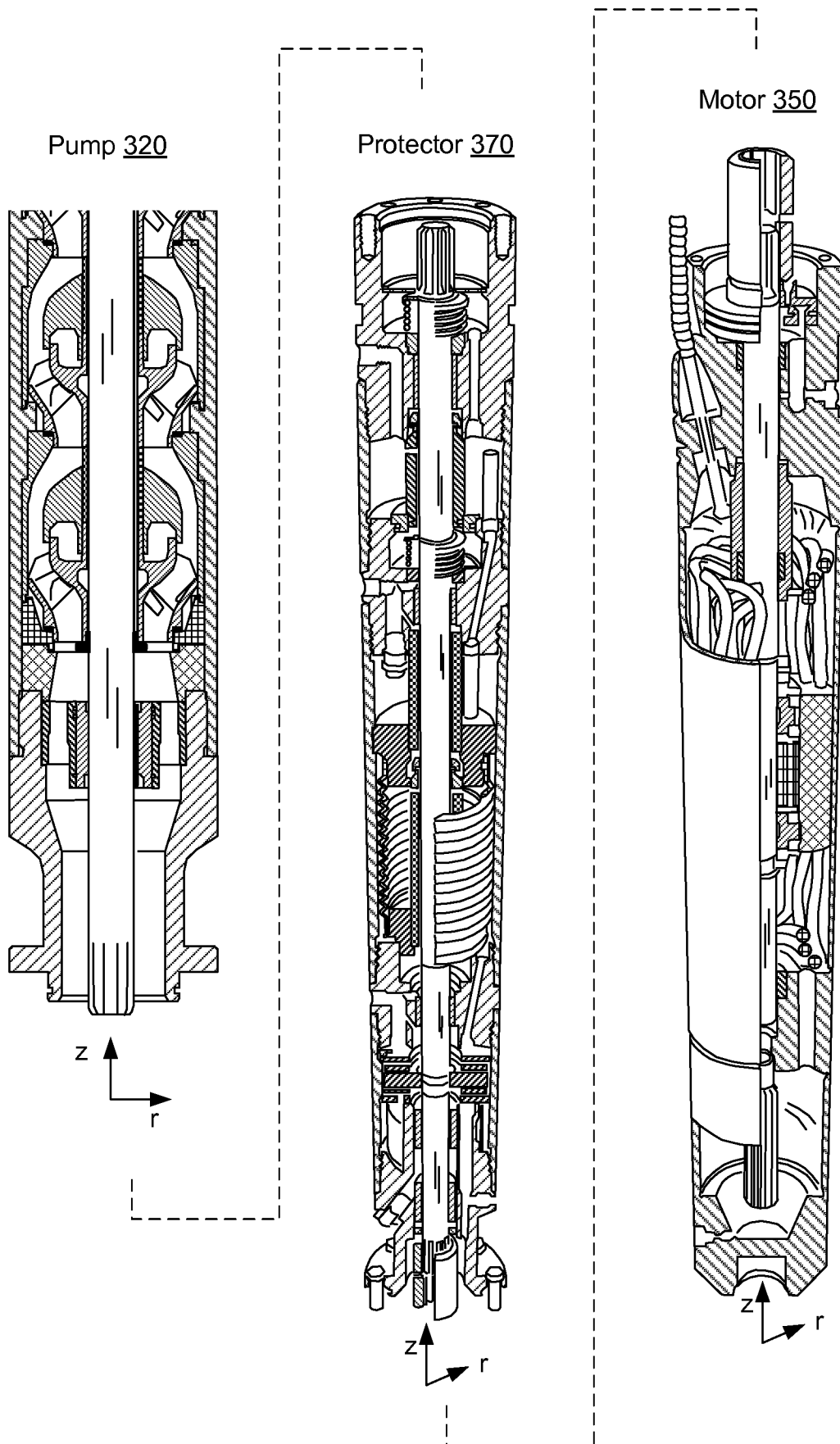


Fig. 3

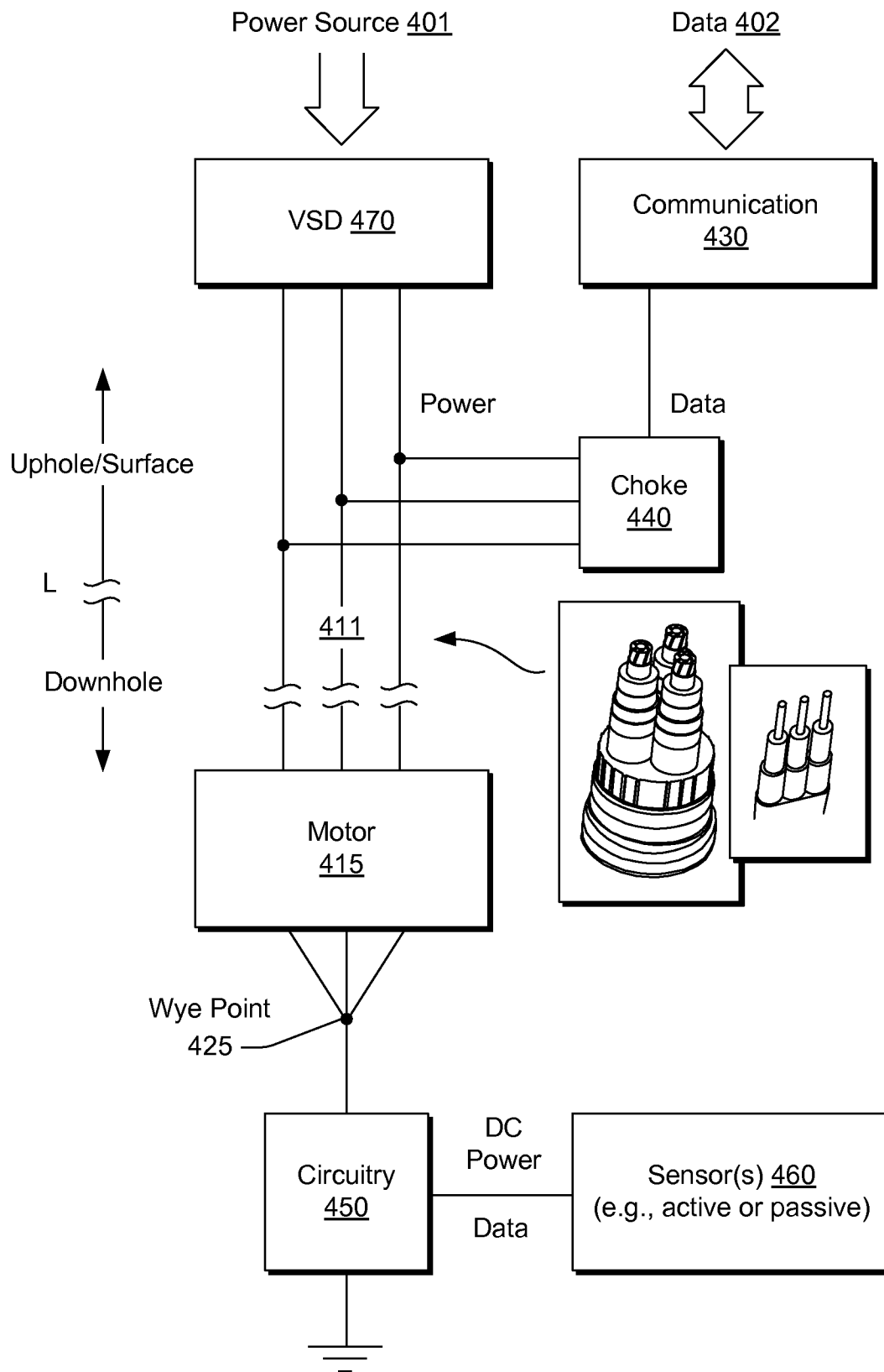
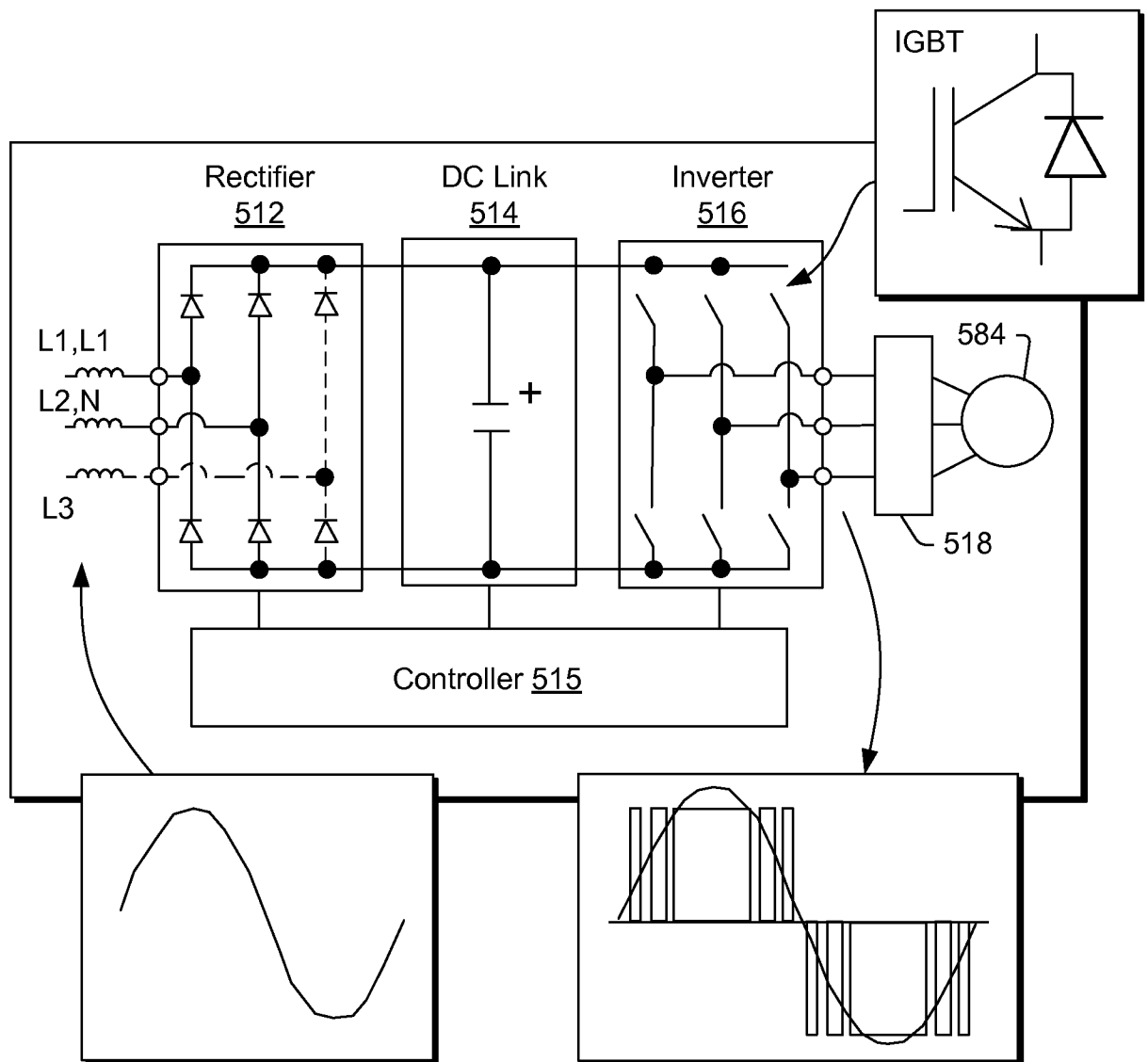
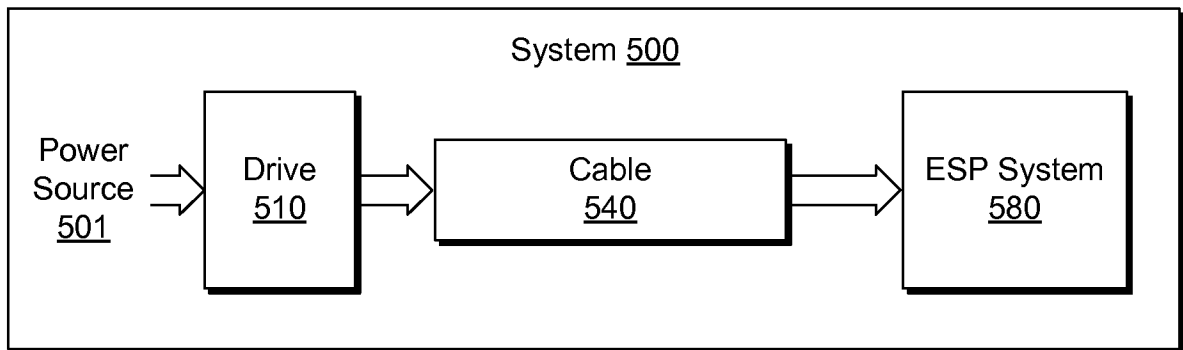


Fig. 4

**Fig. 5**

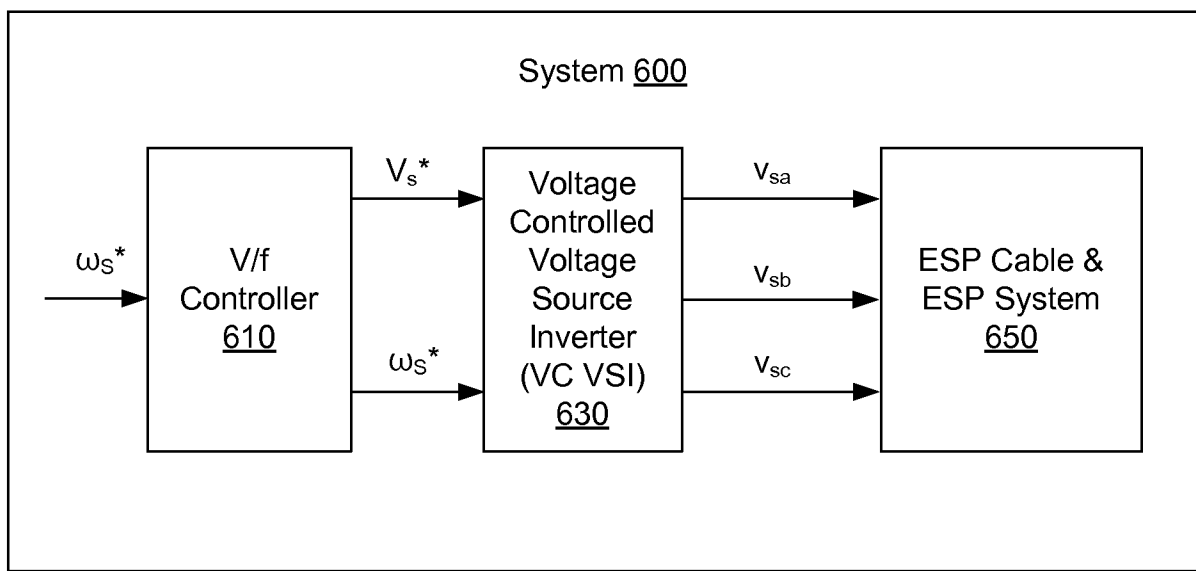


Fig. 6

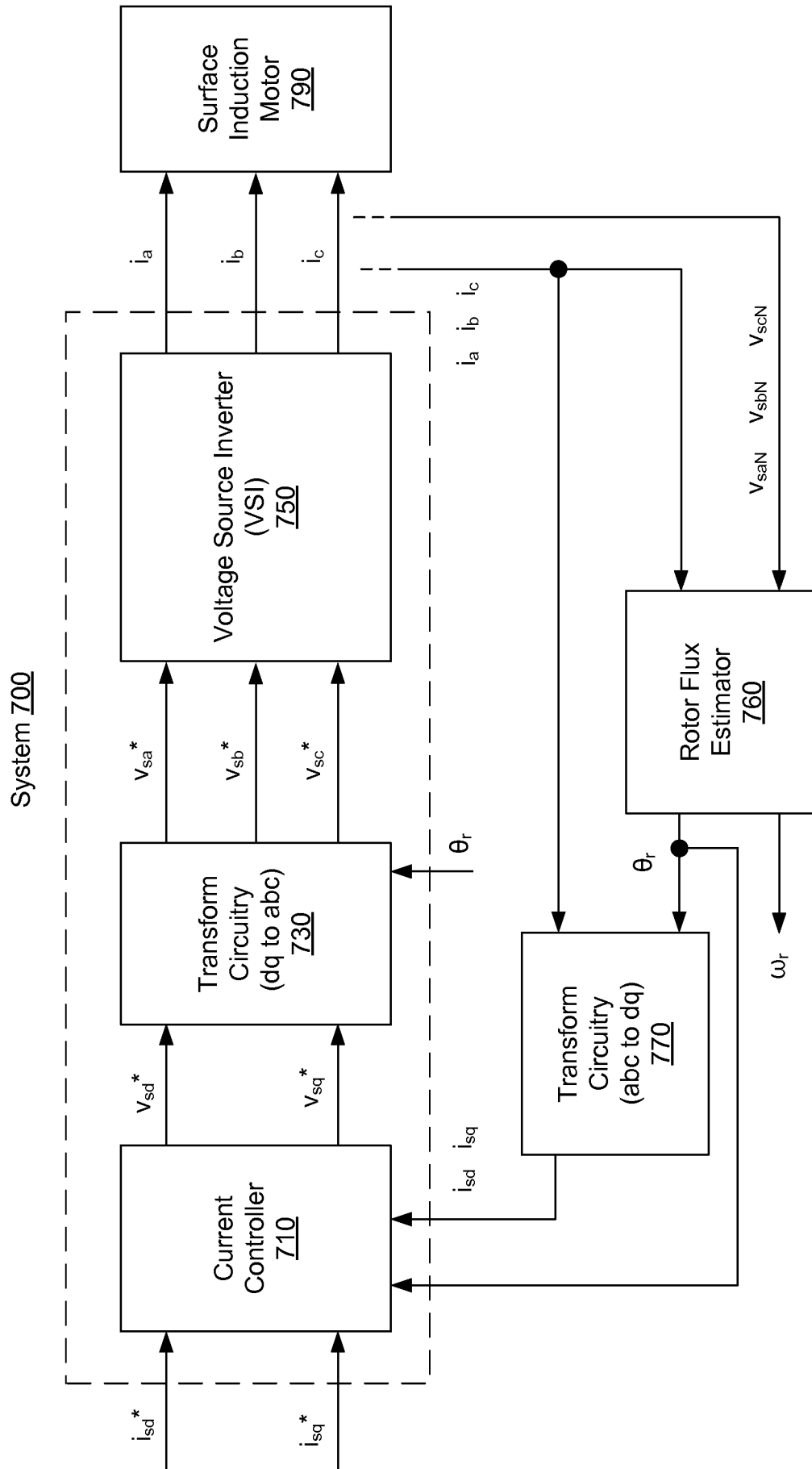


Fig. 7

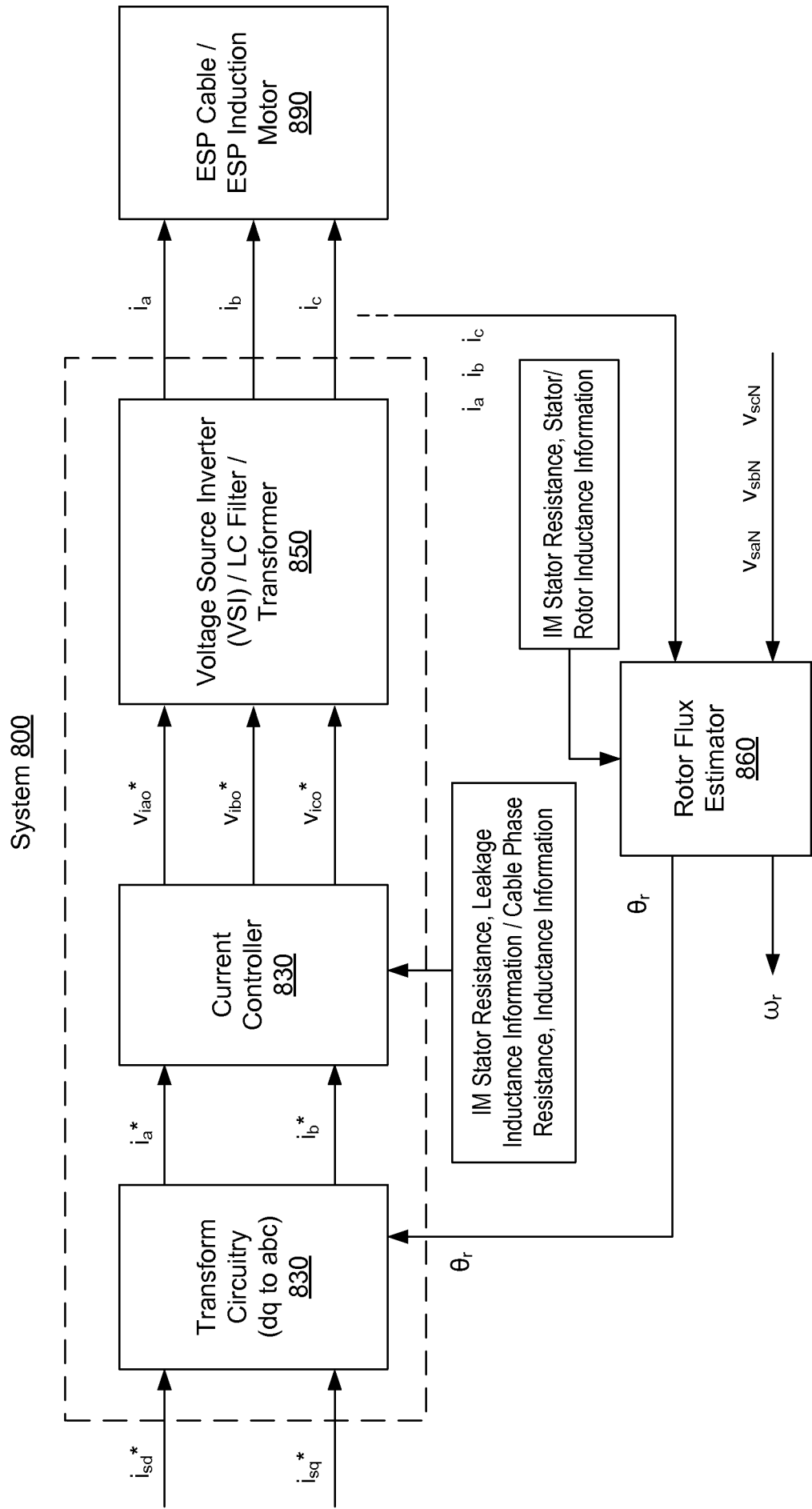


Fig. 8

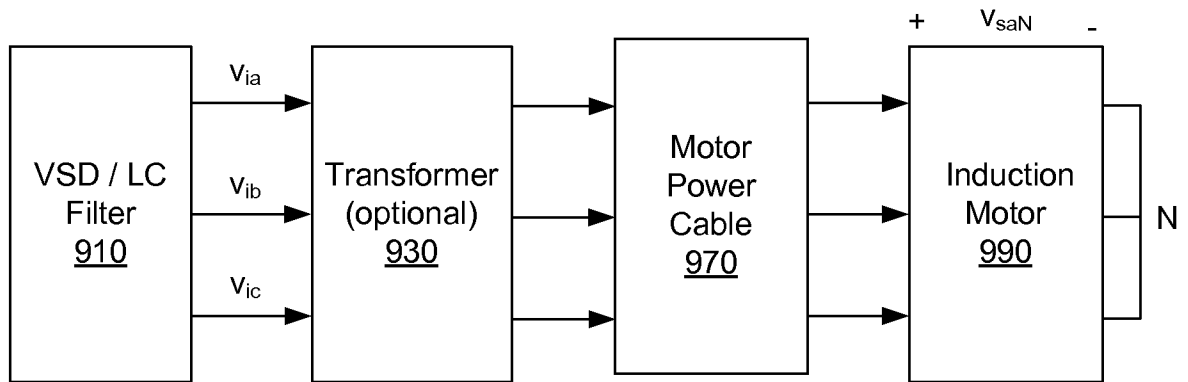
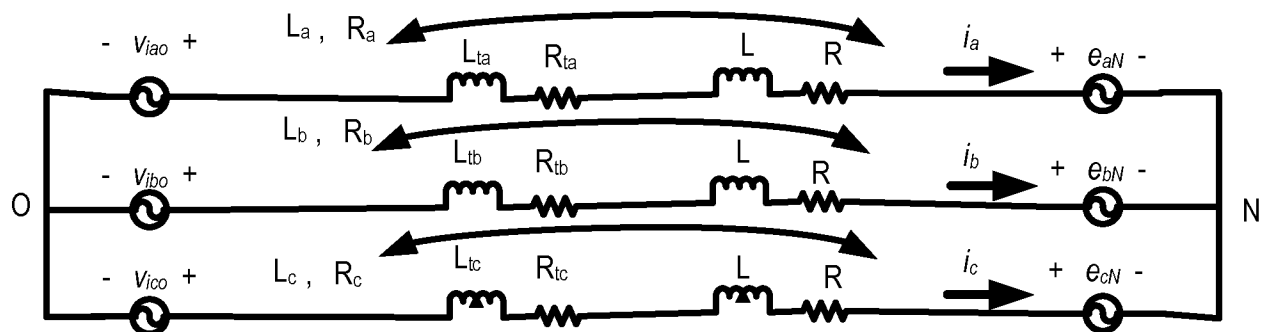
System 900Schematic 905

Fig. 9

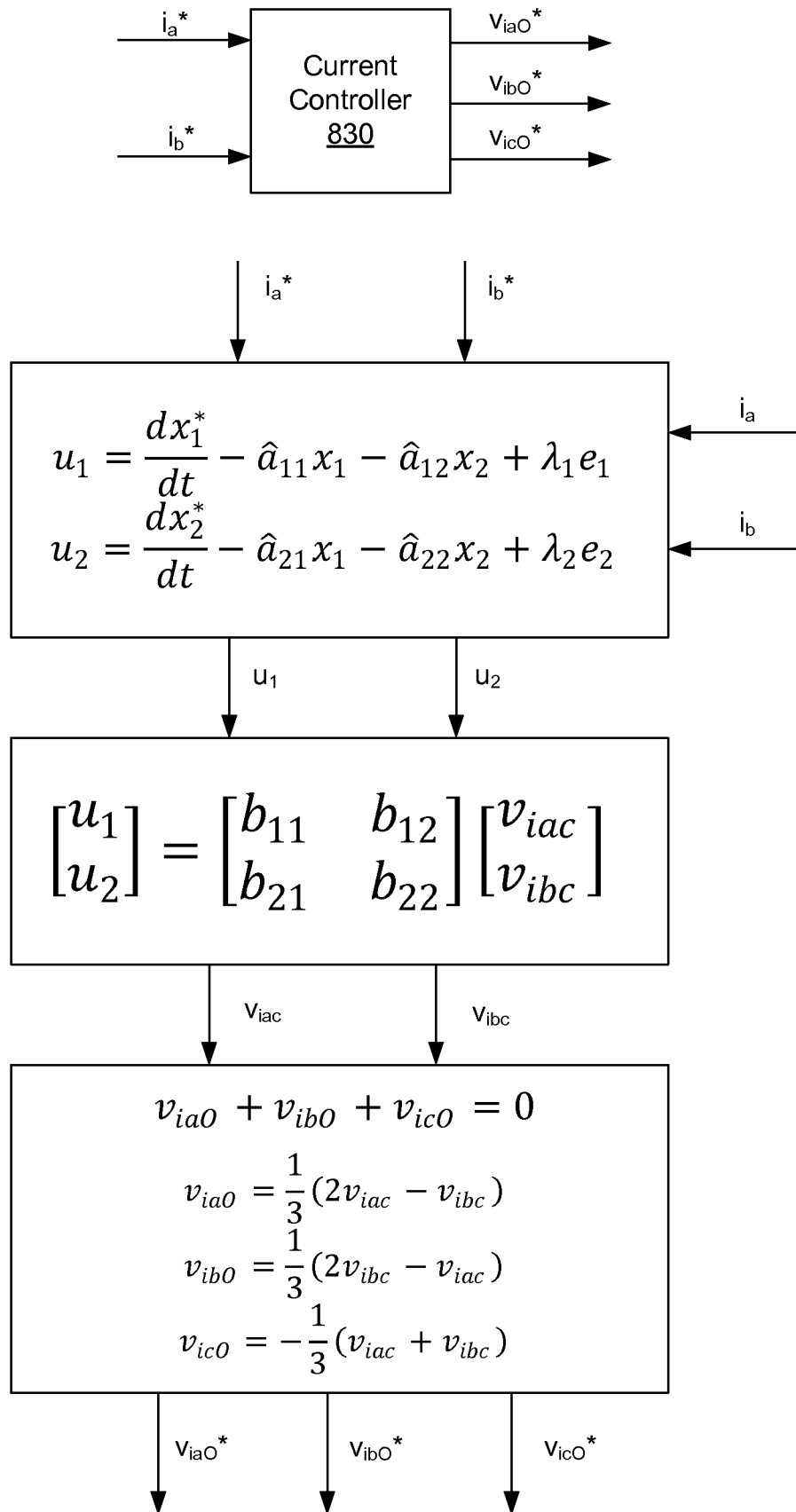


Fig. 10

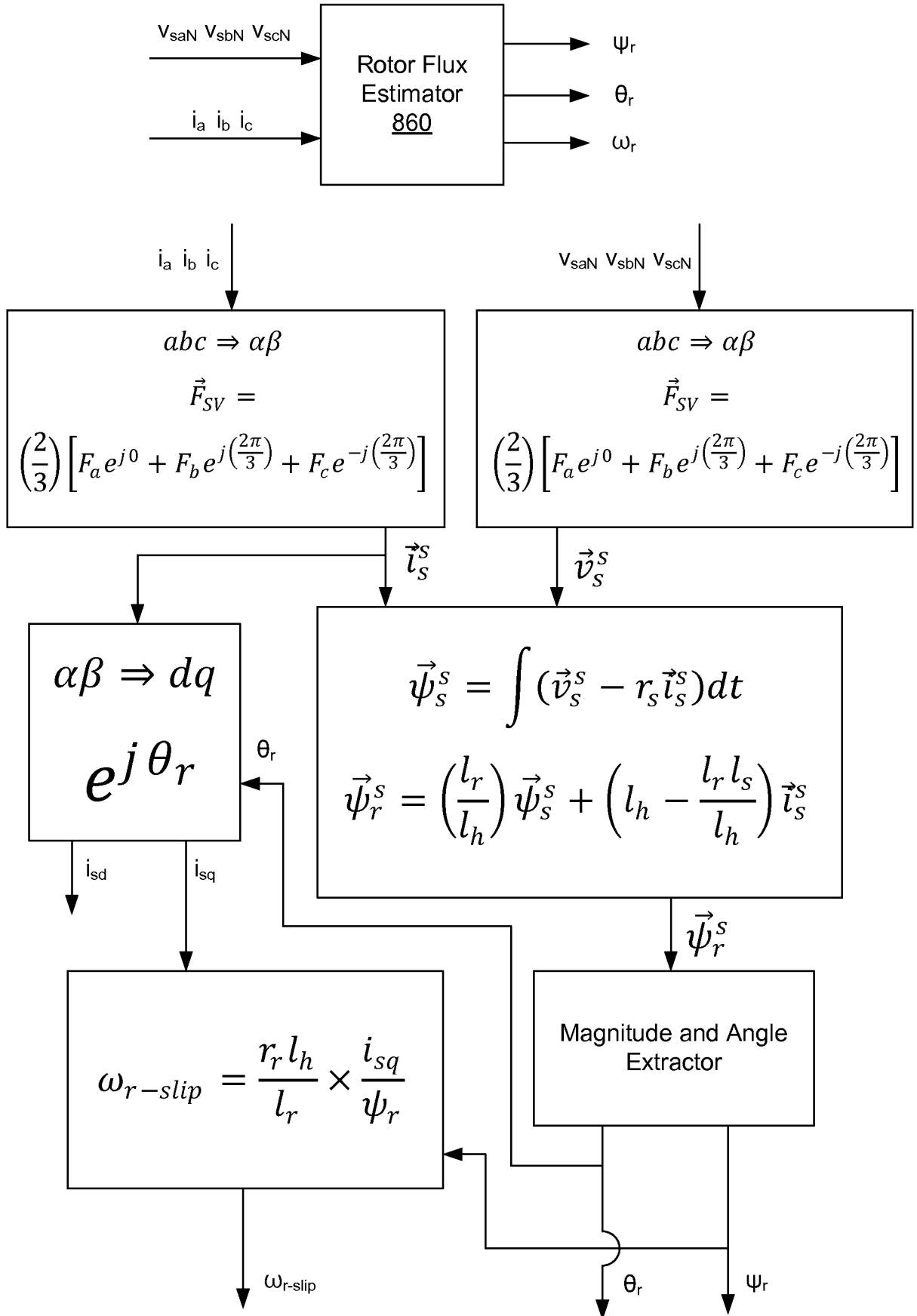


Fig. 11

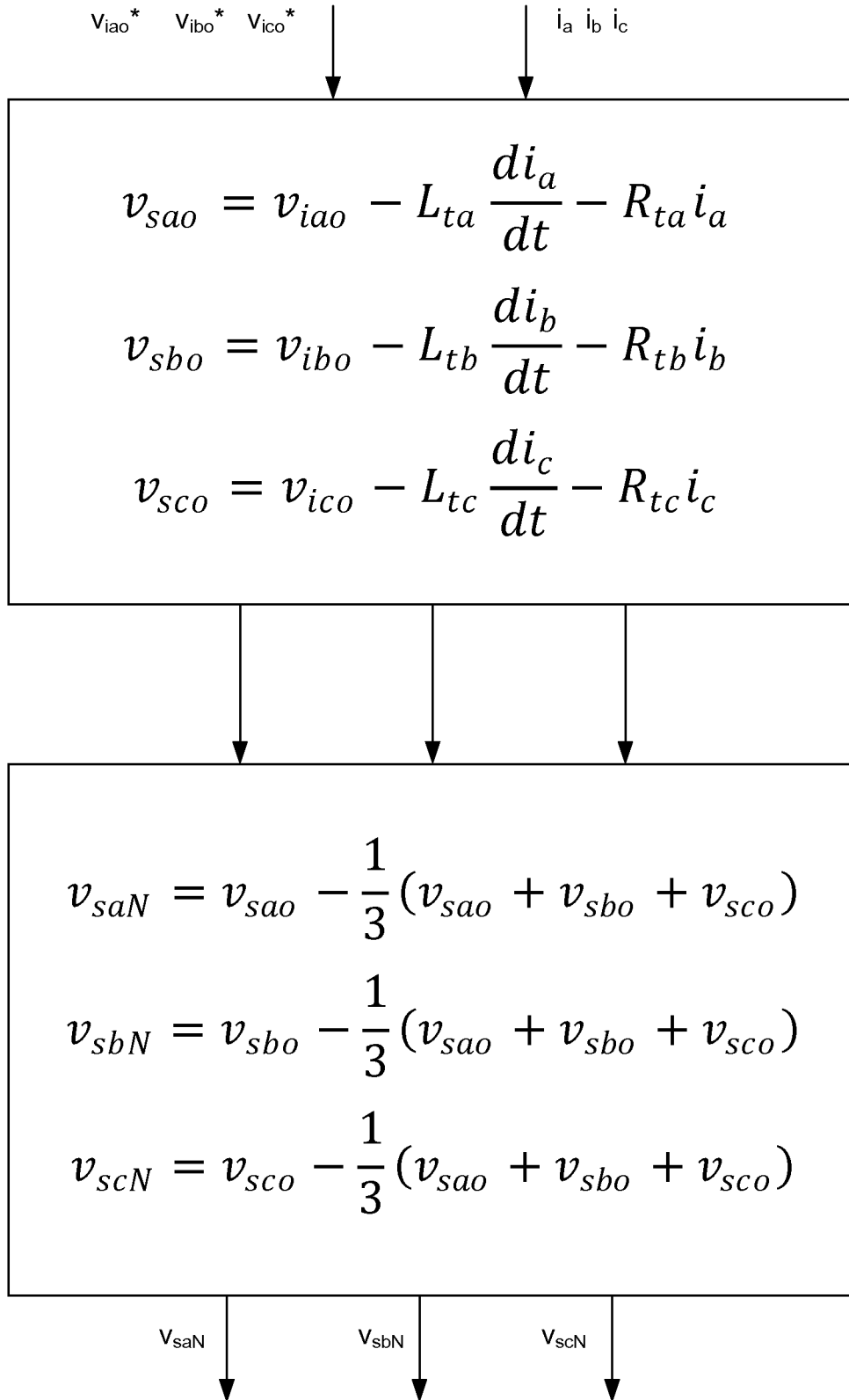
System 1200

Fig. 12

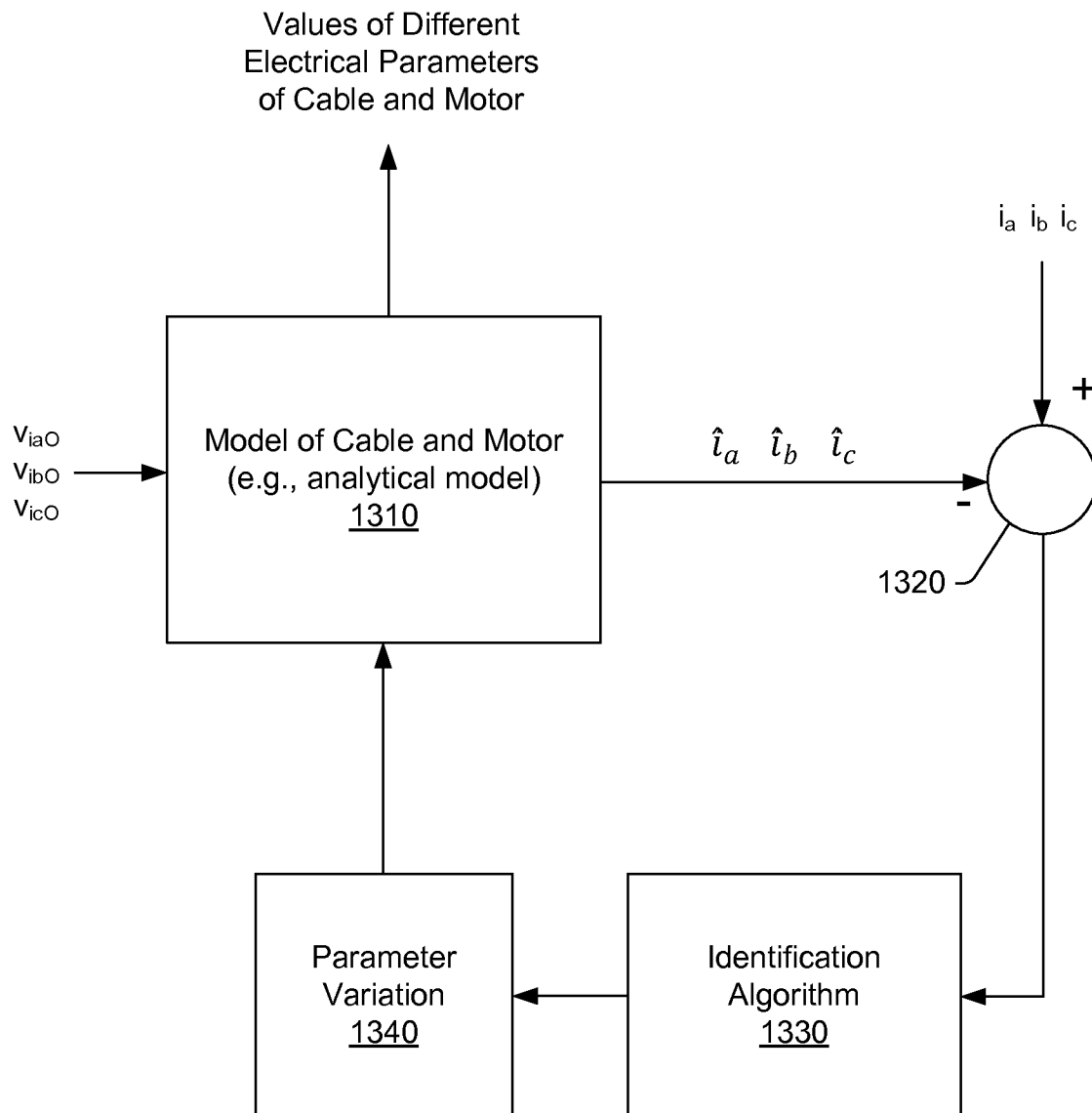
System 1300

Fig. 13

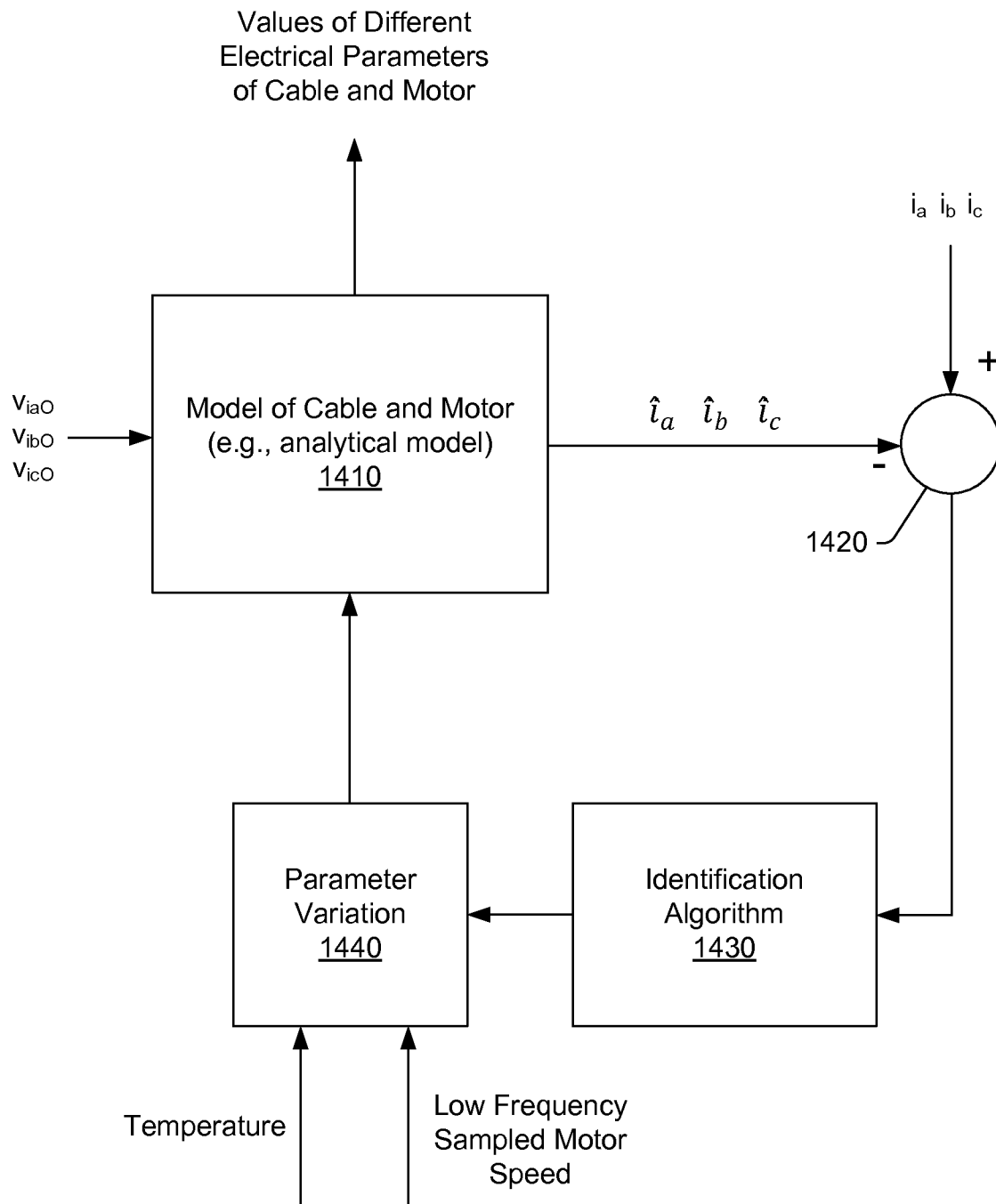
System 1400

Fig. 14

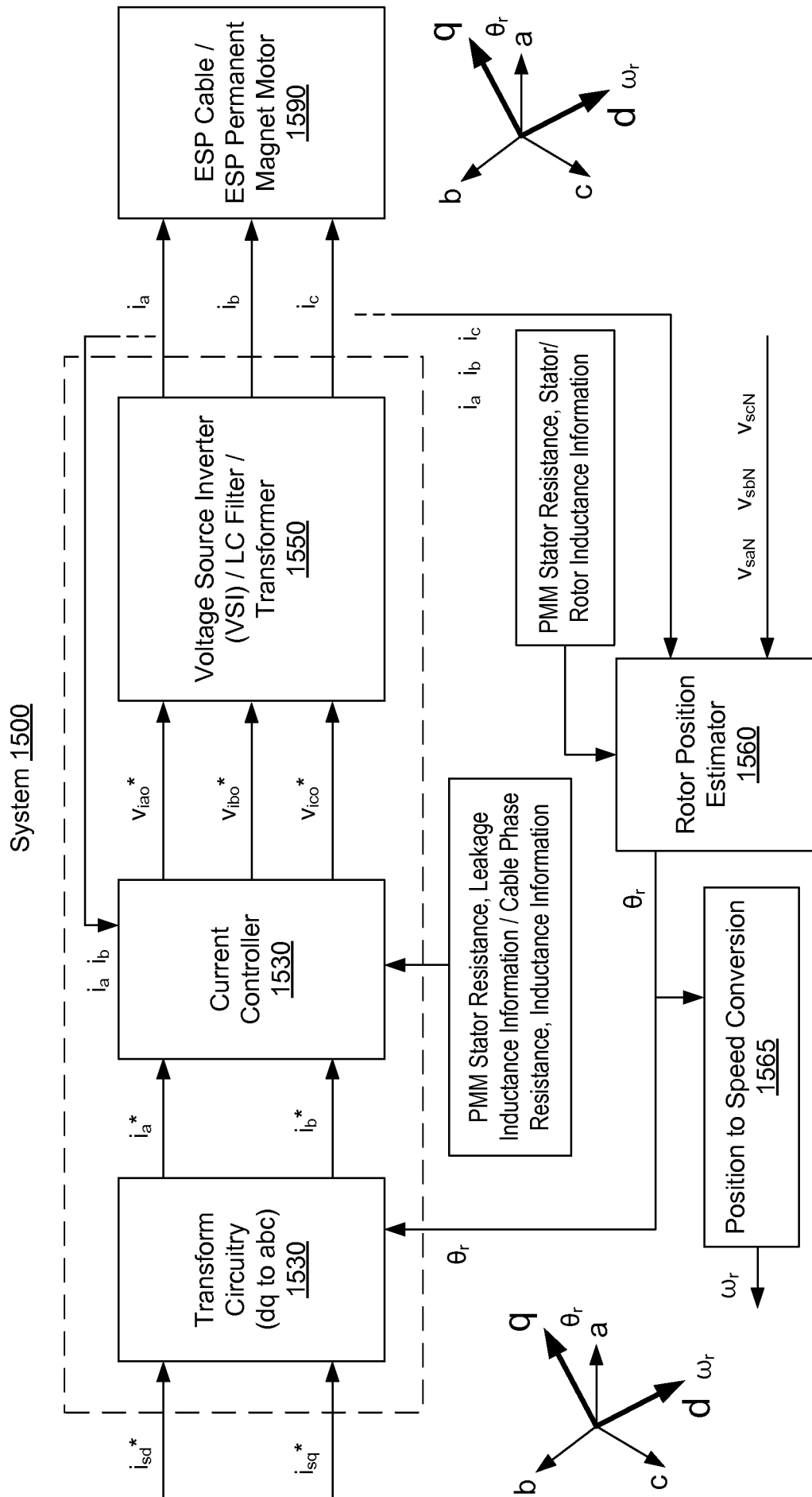
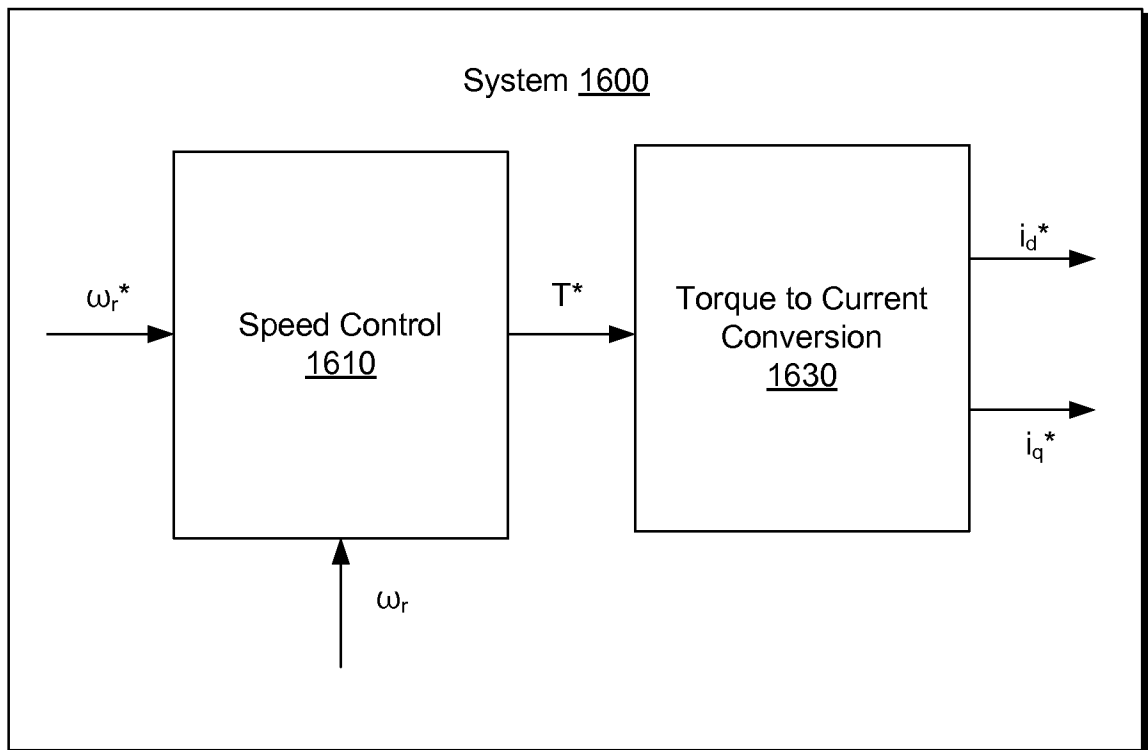


Fig. 15

**Fig. 16**

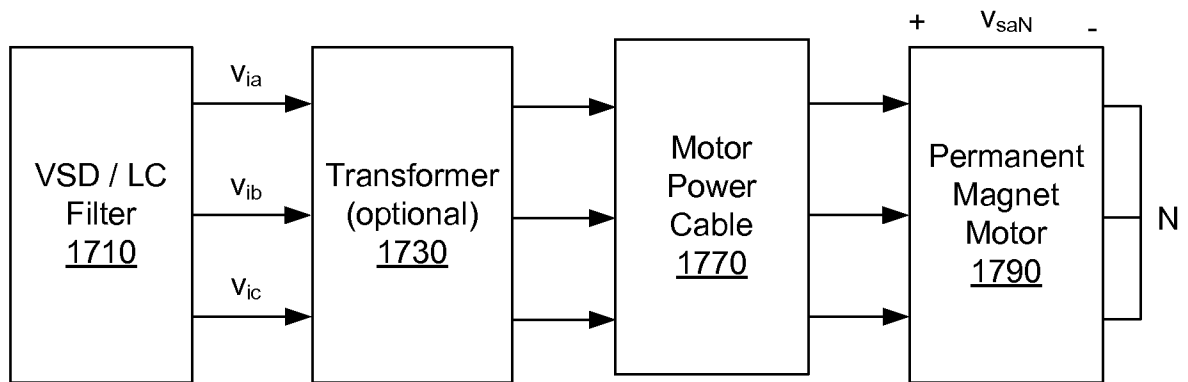
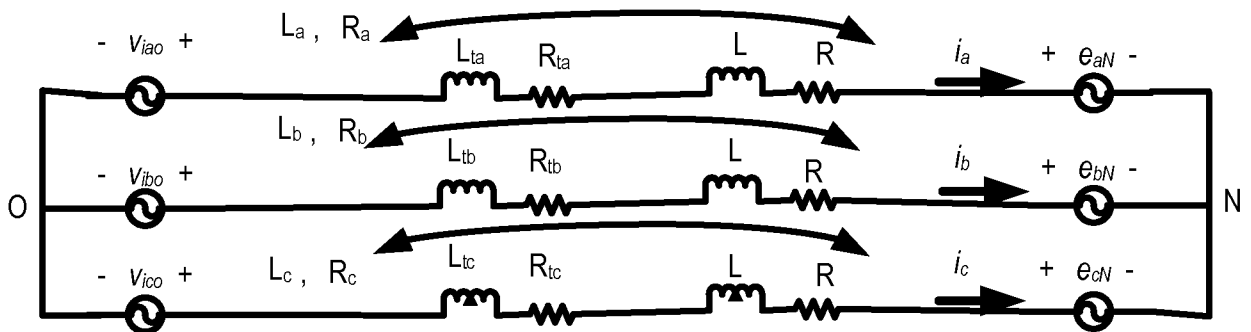
System 1700Schematic 1705

Fig. 17

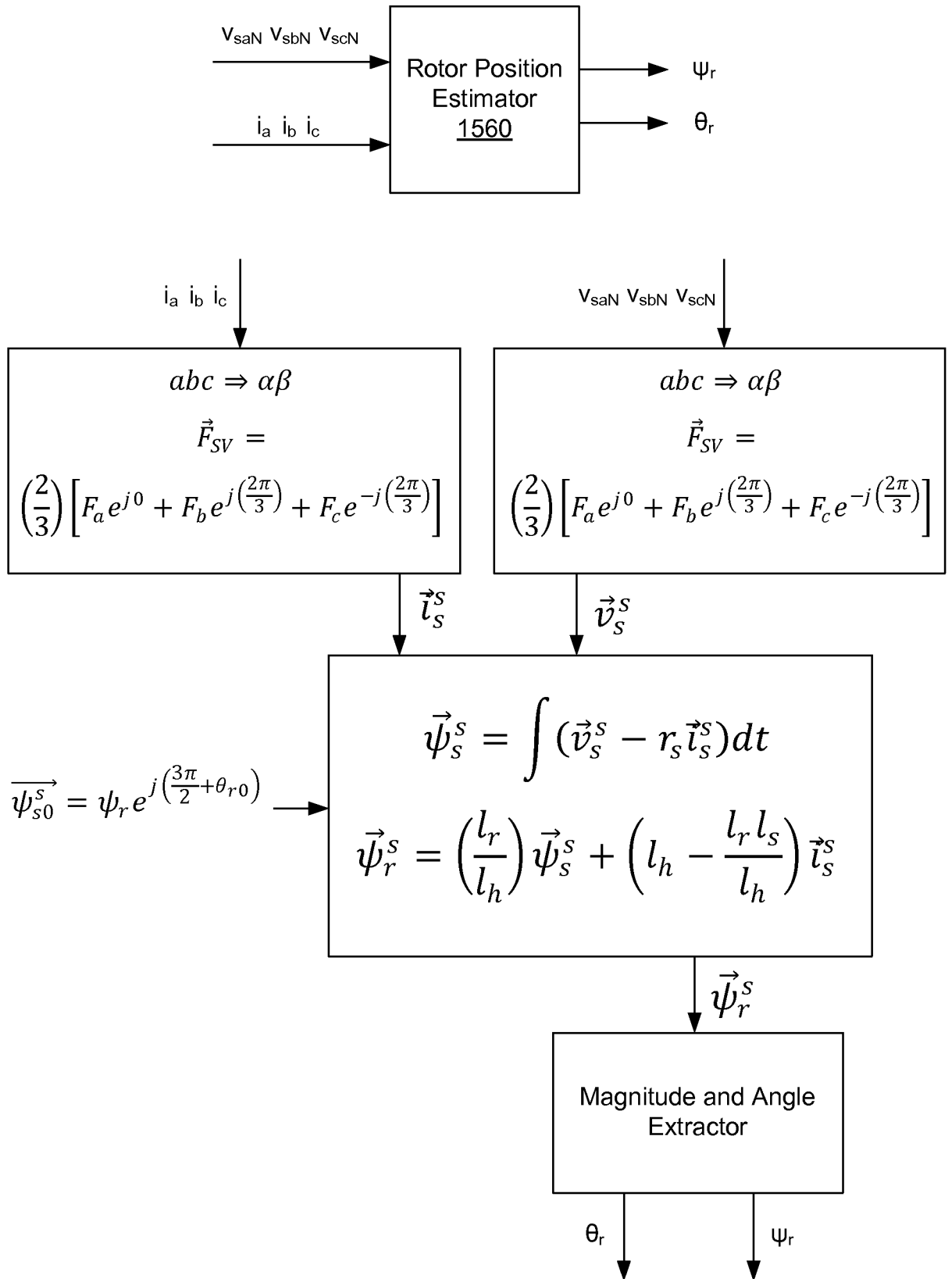


Fig. 18

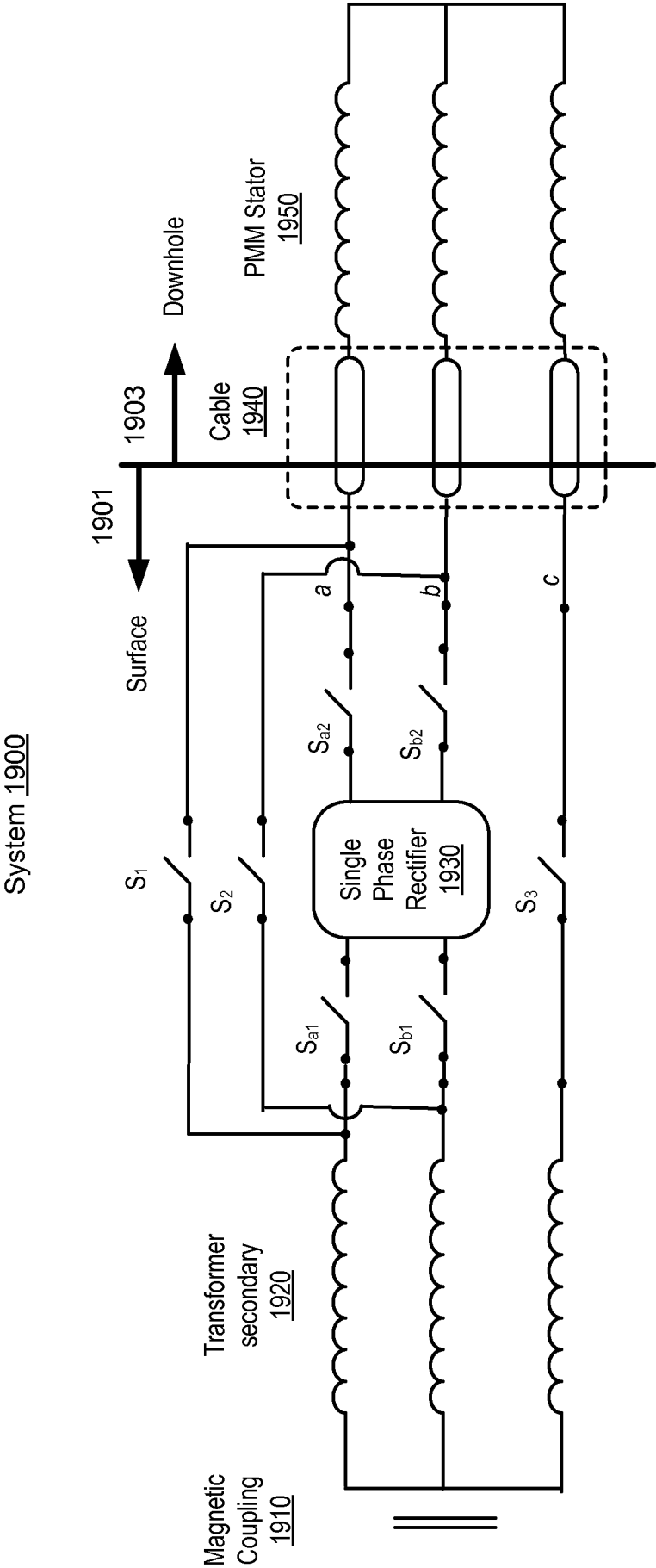


Fig. 19

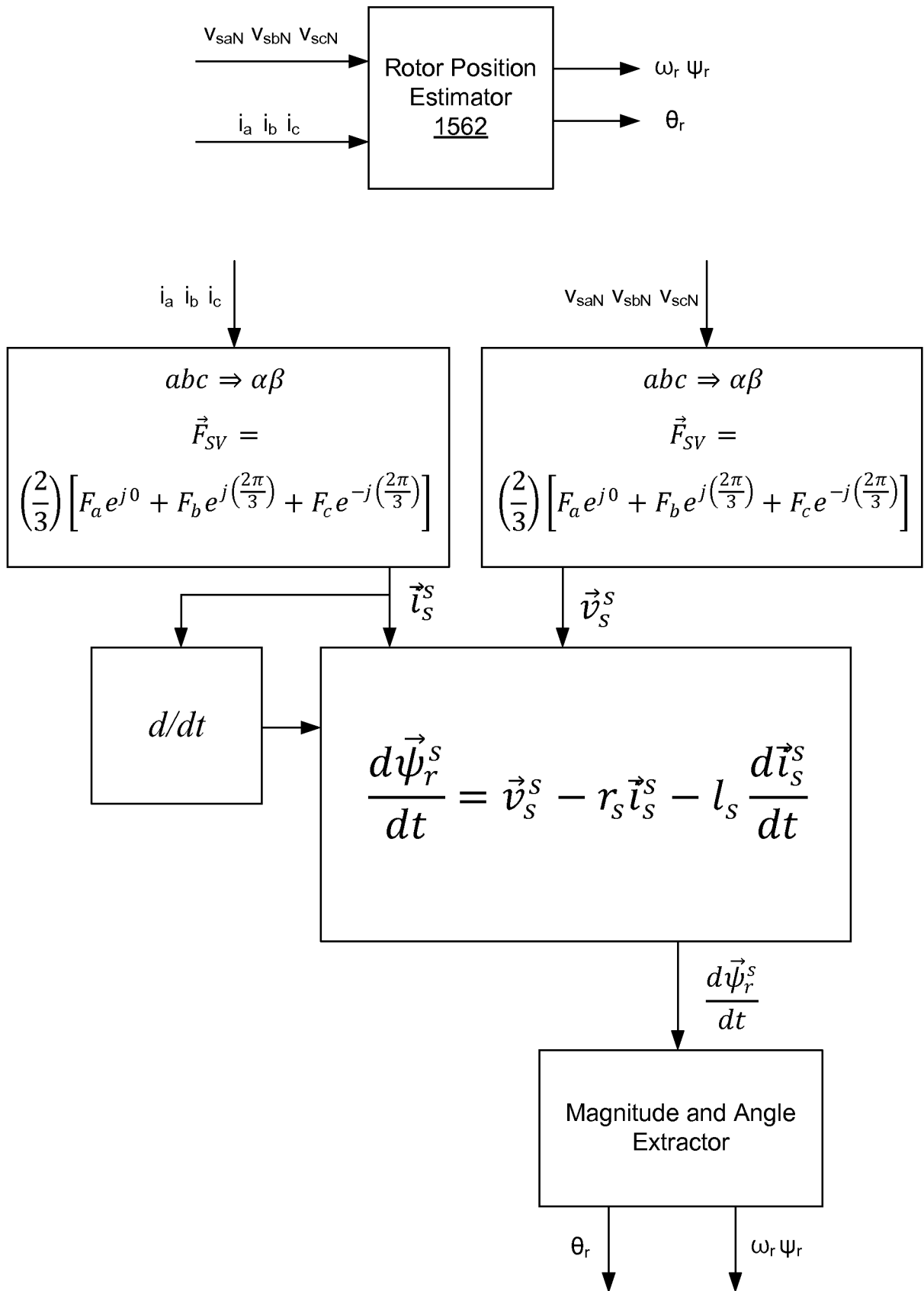


Fig. 20

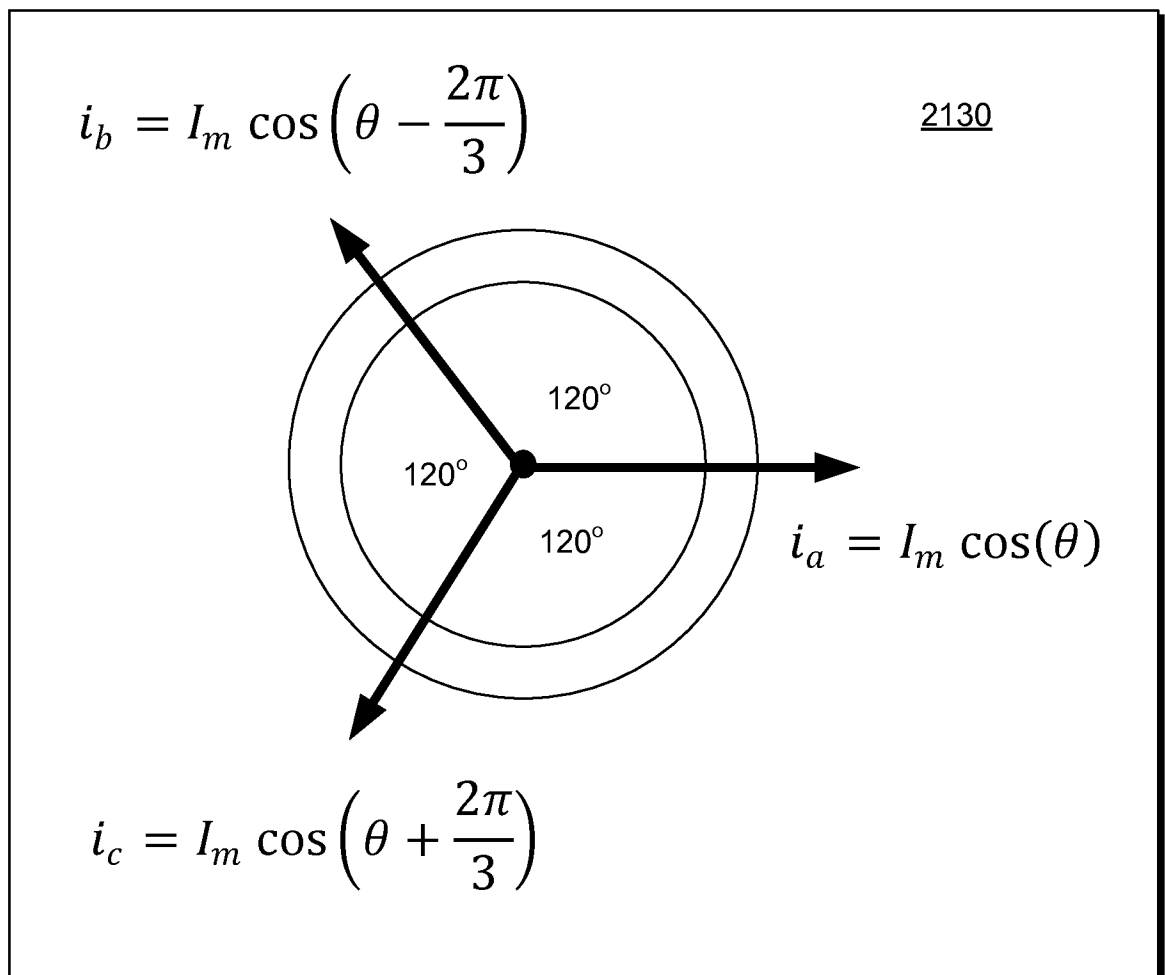
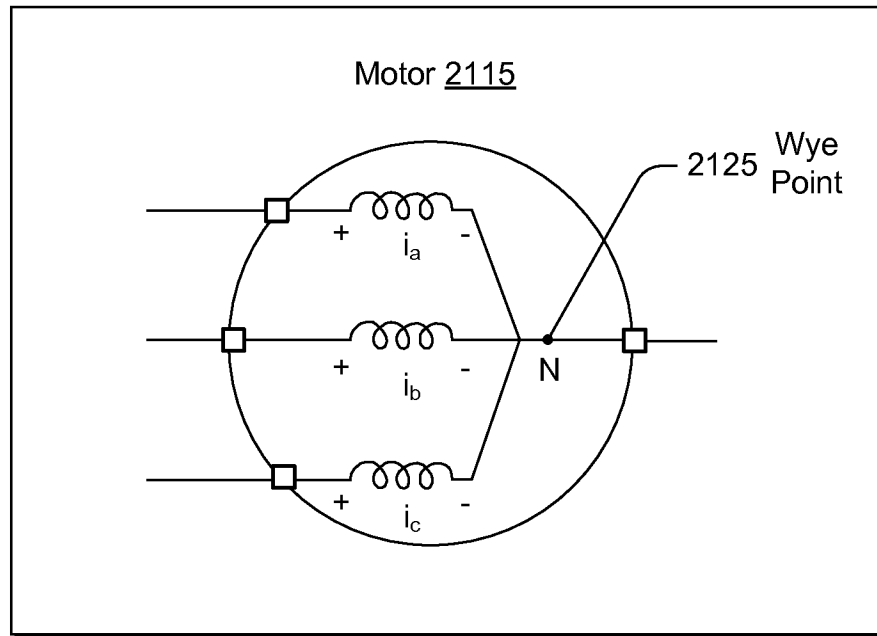
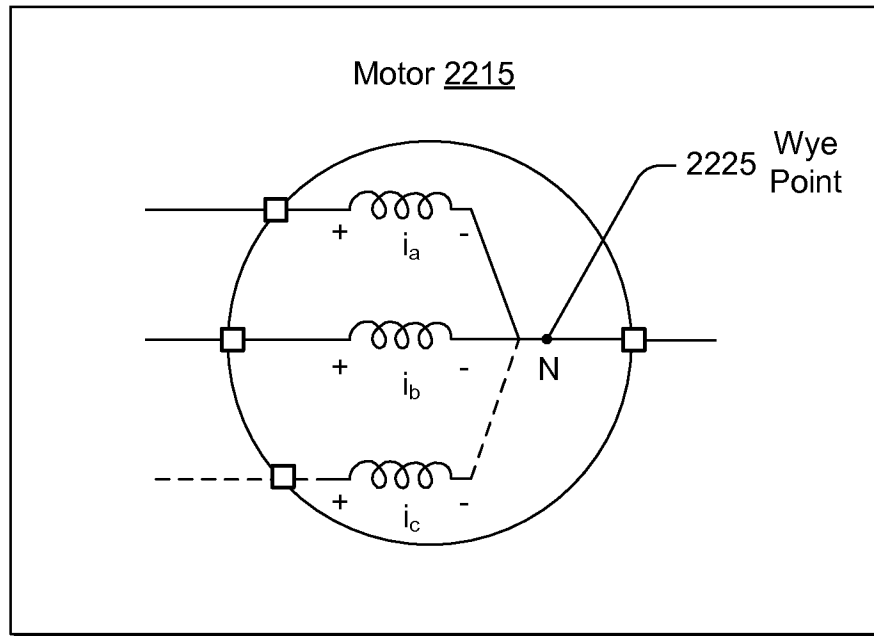


Fig. 21



$$i_b = \sqrt{3}I_m \sin(\theta)$$

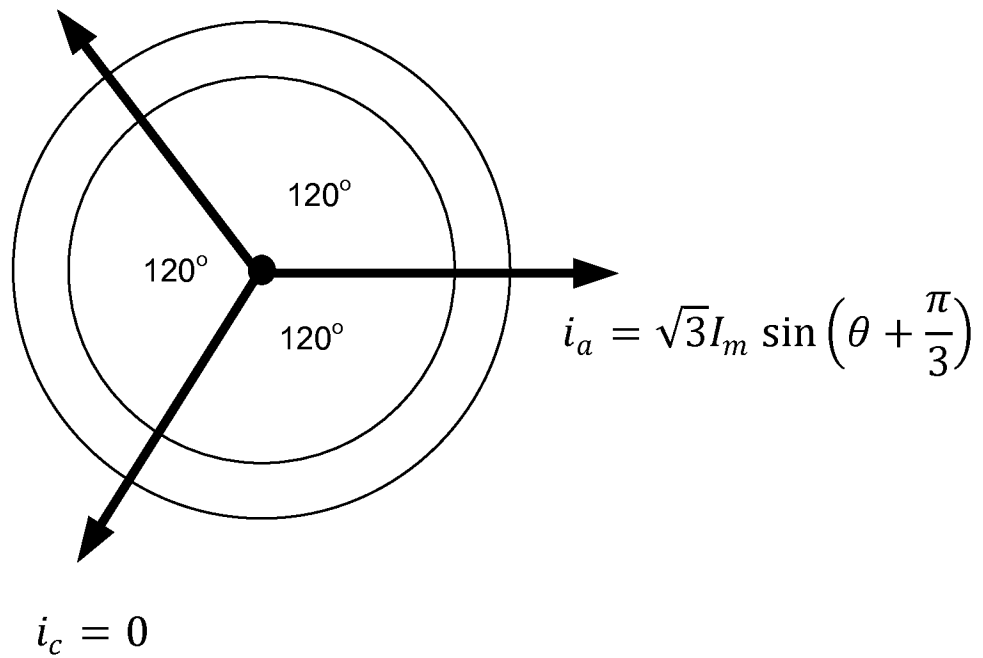
2230

Fig. 22

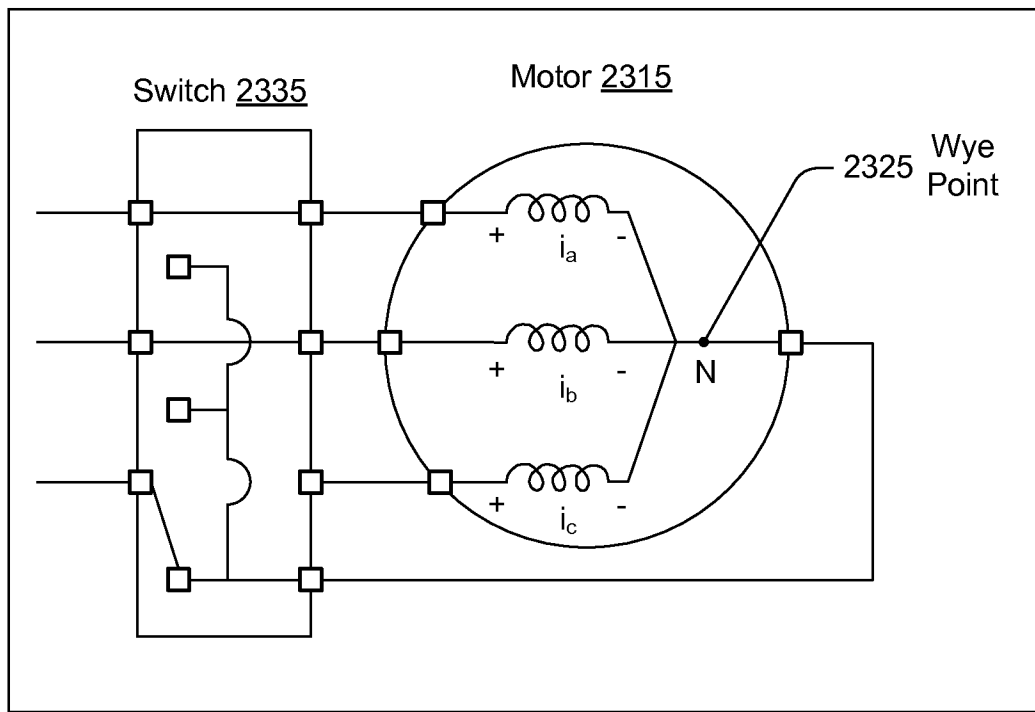
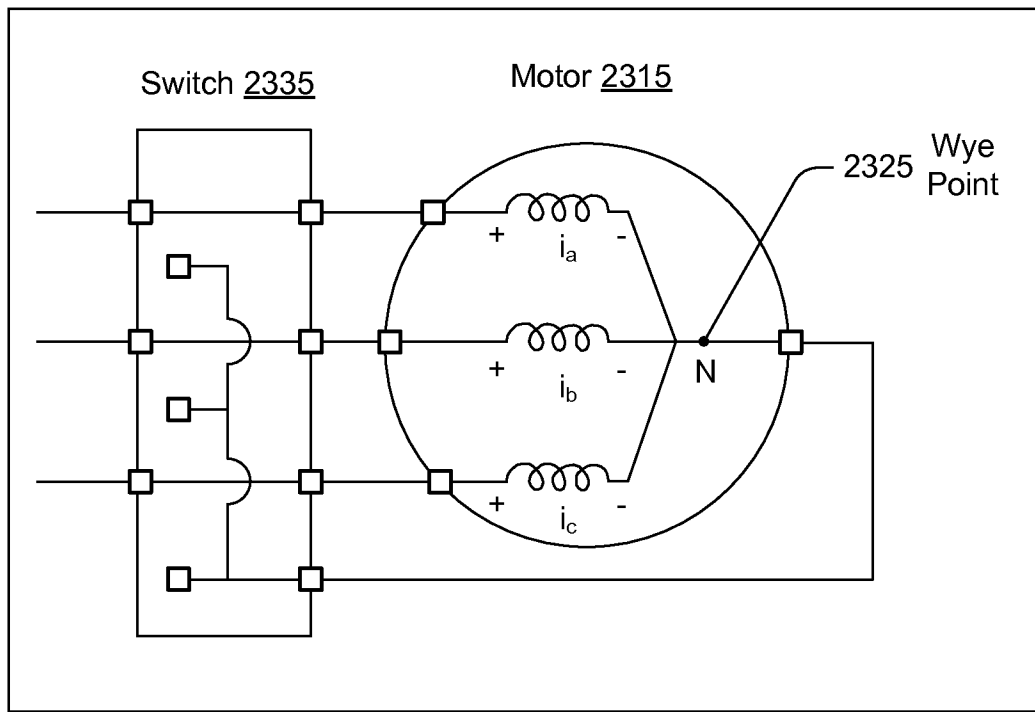
System 2300

Fig. 23

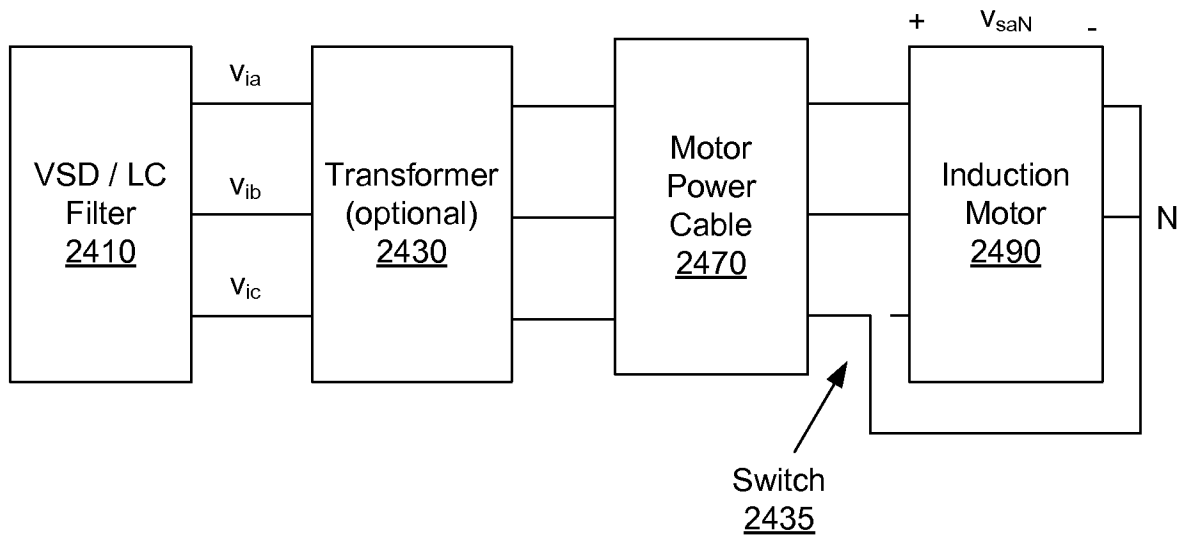
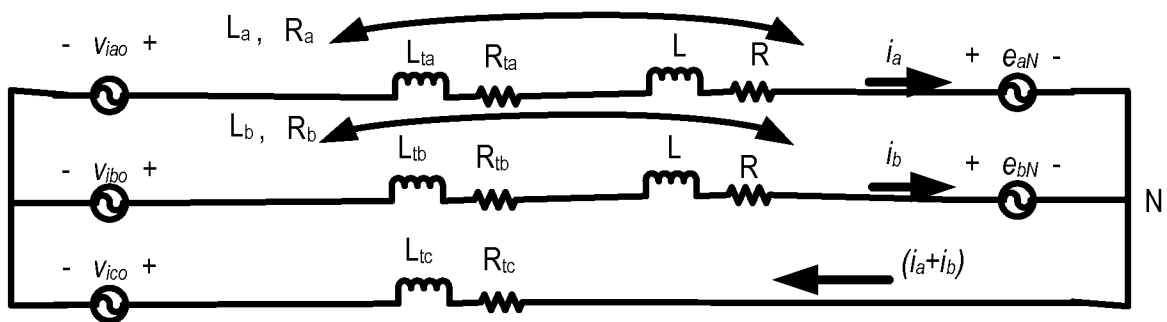
System 2400Schematic 2405

Fig. 24

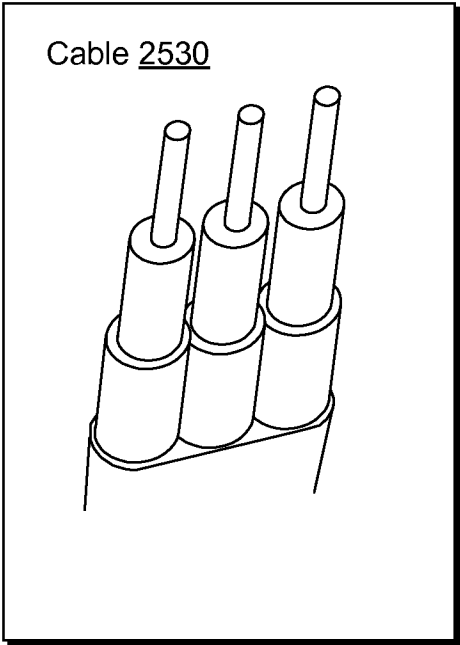
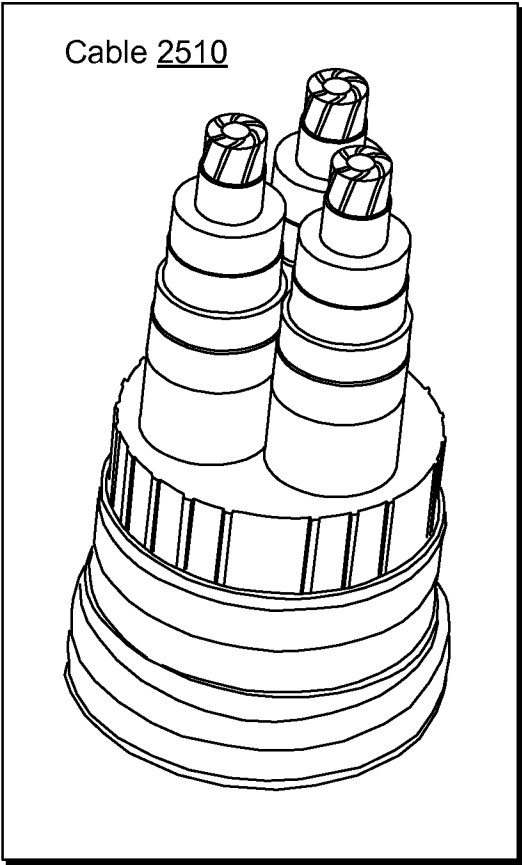
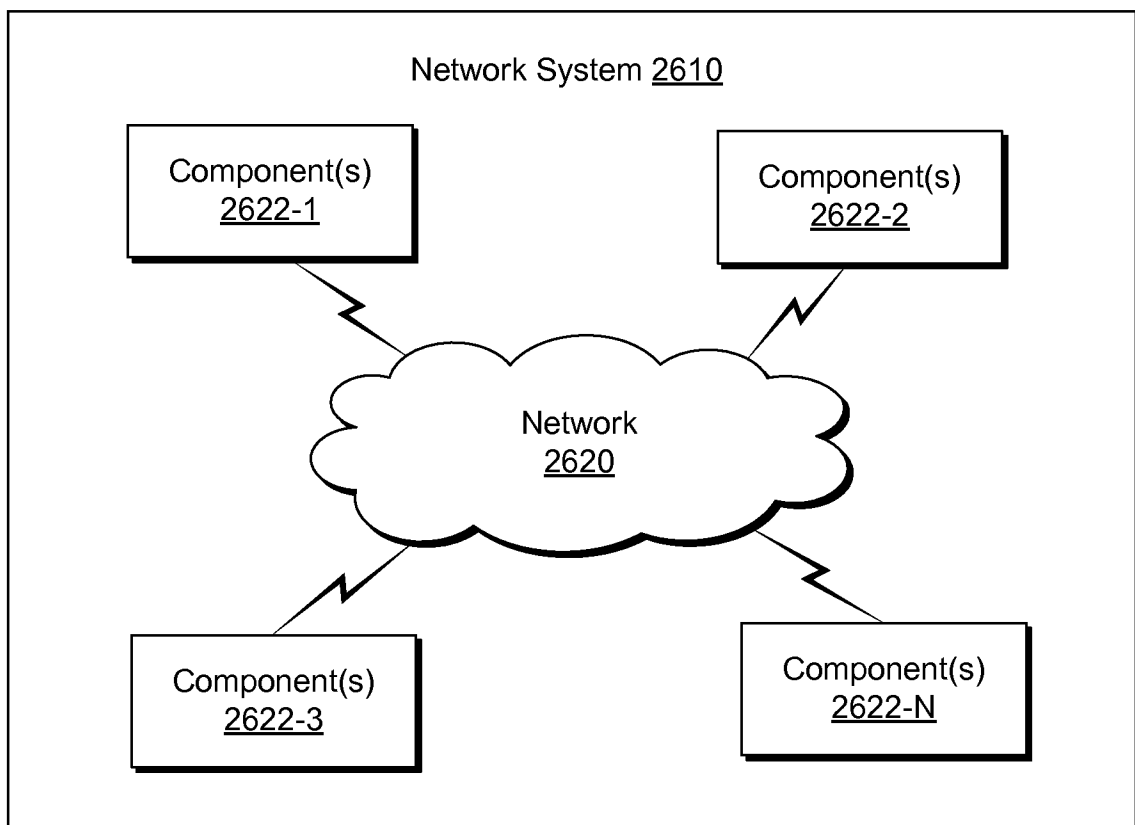
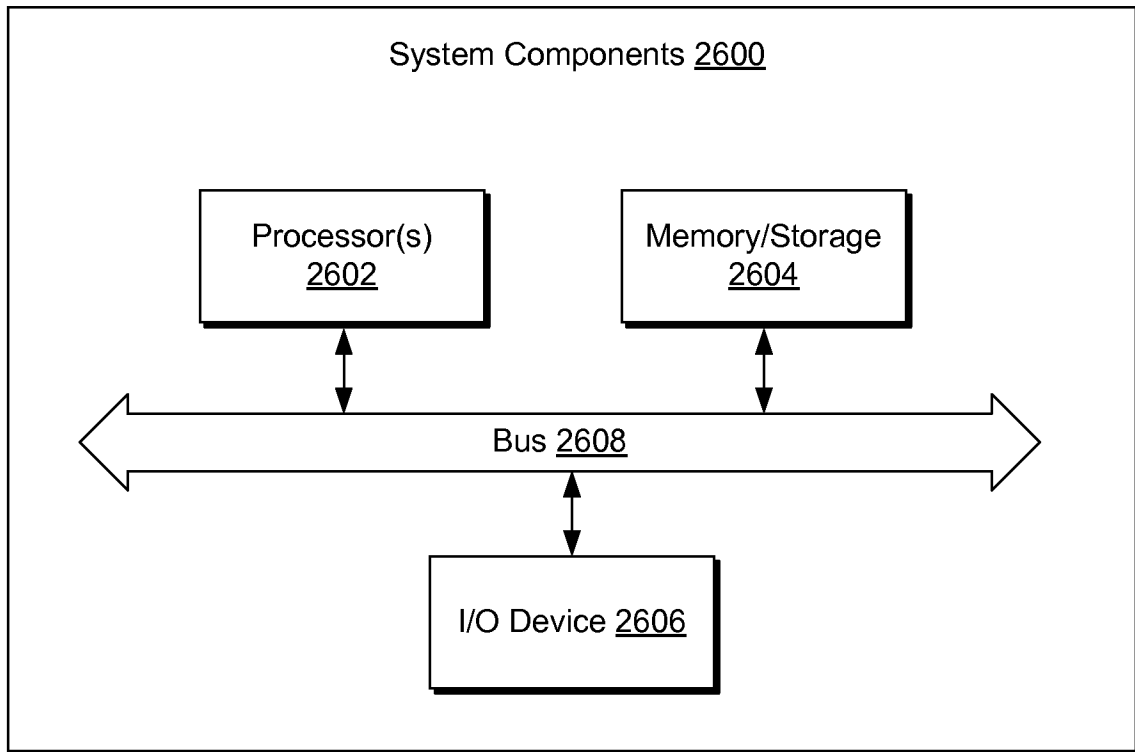


Table 2550

	Without Cable			With Flat Cable		
	Voltage Unbalance		Current Unbalance	Voltage Unbalance		Current Unbalance
	Surface	Motor		Surface	Motor	
Percent Unbalance	NA	0.07%	0.9%	0.1%	0.7%	3.6%

Fig. 25

**Fig. 26**

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/021390**A. CLASSIFICATION OF SUBJECT MATTER****F04D 13/10(2006.01)i, F04D 15/00(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 13/10; H02P 23/00; F04D 13/08; H02P 7/42; G05B 19/042; F04D 27/00; H02P 27/04; F04D 15/00; H02P 21/00

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, motor system, multiphase, current controller, state-space based control logic, and switch assembly

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3991354 A (ROSA et al.) 09 November 1976	20
A	See abstract, column 4, lines 8-25, claim 1, and figures 1-2.	1-19
A	WO 2014-063722 A1 (ABB AB) 01 May 2014	20
	See page 5, line 7 - page 7, line 14 and figures 1-2.	
A	US 2007-0262744 A1 (KAHLER et al.) 15 November 2007	1-19
	See paragraphs [0025]-[0039] and figures 1-3, 7.	
A	US 2009-0021207 A1 (KEZOBO et al.) 22 January 2009	1-19
	See paragraphs [0044]-[0058] and figures 1-2.	
A	WO 2014-120847 A1 (SCHLUMBERGER CANADA LIMITED) 07 August 2014	1-19
	See paragraphs [0074]-[0081] and figures 1-5.	



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

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

15 December 2015 (15.12.2015)

Date of mailing of the international search report

18 December 2015 (18.12.2015)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea

Facsimile No. +82-42-472-7140

Authorized officer

LEE, Dal Kyong

Telephone No. +82-42-481-8440



INTERNATIONAL SEARCH REPORTInternational application No.
PCT/US2015/021390**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Group I. Claims 1-19 directed to a system comprising a current controller.

Group II. Claim 20 directed to a system comprising a three phase motor and a switch assembly.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/021390

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 3991354 A	09/11/1976	None	
WO 2014-063722 A1	01/05/2014	CN 104813245 A EP 2909682 A1	29/07/2015 26/08/2015
US 2007-0262744 A1	15/11/2007	DE 102007021892 A1 US 7528562 B2	20/12/2007 05/05/2009
US 2009-0021207 A1	22/01/2009	CN 101401295 A CN 101401295 B EP 2009782 A1 EP 2009782 A4 JP 04772116 B2 KR 10-1040890 B1 KR 10-1139146 B1 KR 10-2008-0108121 A KR 10-2011-0036650 A US 7990093 B2 WO 2007-129359 A1	01/04/2009 17/07/2013 31/12/2008 14/11/2012 14/09/2011 16/06/2011 26/04/2012 11/12/2008 07/04/2011 02/08/2011 15/11/2007
WO 2014-120847 A1	07/08/2014	None	