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(54) SYSTEM AND METHOD FOR CONVERTERLESS OPERATION OF MOTOR-DRIVEN PUMPS

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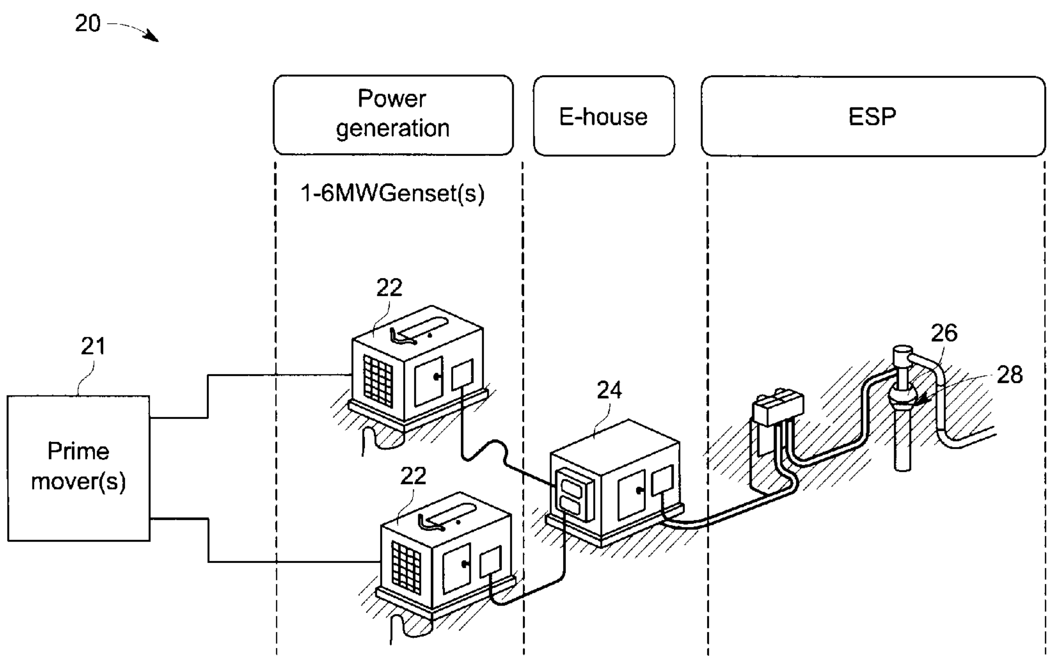
(57) ABSTRACT

A converterless motor-driven pump system includes an off-grid prime mover. The off-grid prime mover has a rotational driveshaft and operates in response to a throttle control command to control a rotation speed of the rotational driveshaft. An electric power generator is driven by the off-grid prime mover to generate AC power. A variable speed induction motor is directly powered by the electric power generator. A pump that may be submersible is driven by the at least one variable speed induction motor. A system controller that may be local or remote is programmed to generate the throttle control command in response to one or more pump operating characteristics such that the off-grid prime mover, the electric power generator, and the variable speed induction motor together operate to regulate a pressure at the inlet of the electric pump.



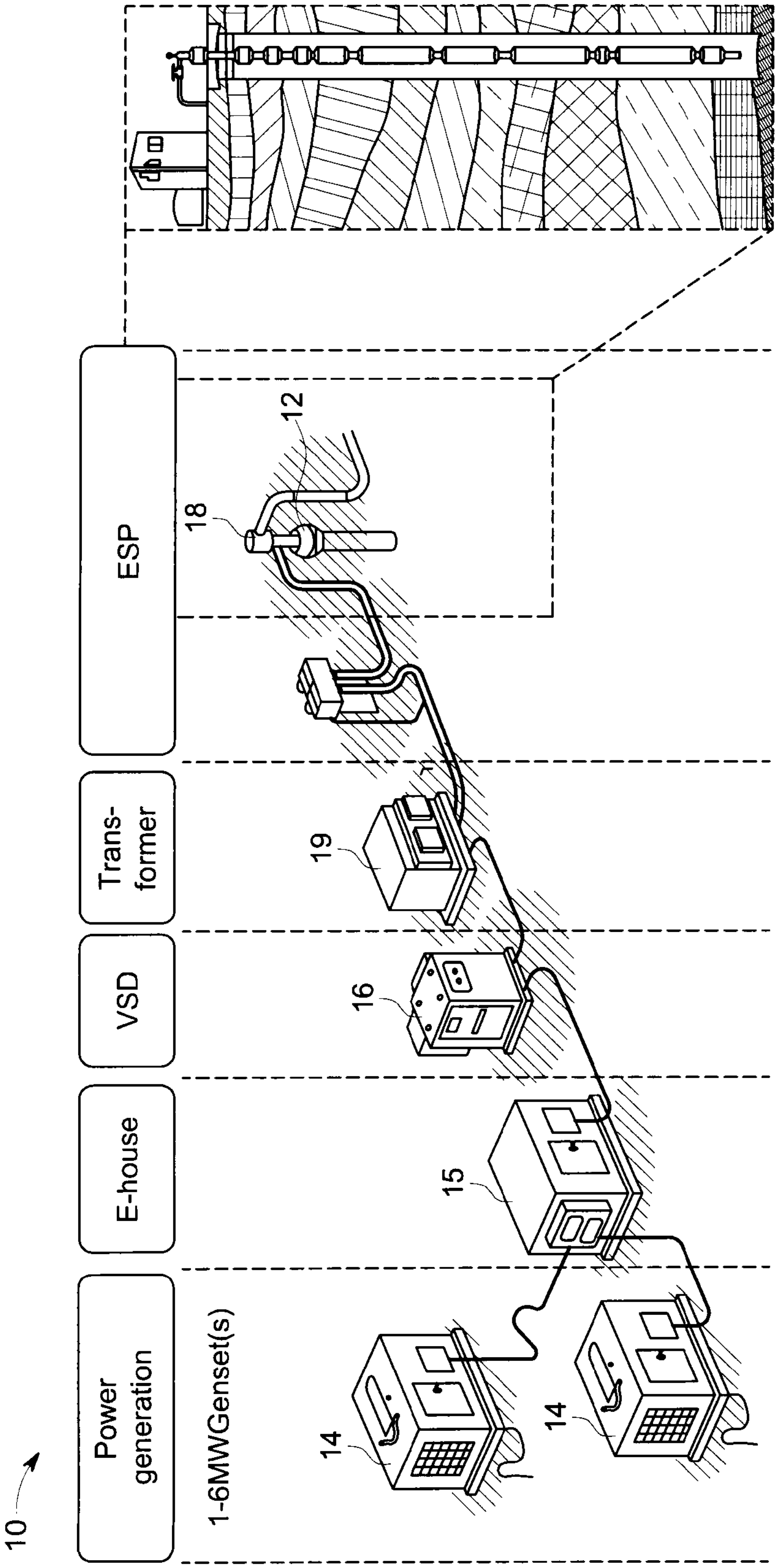


FIG. 1
PRIOR ART

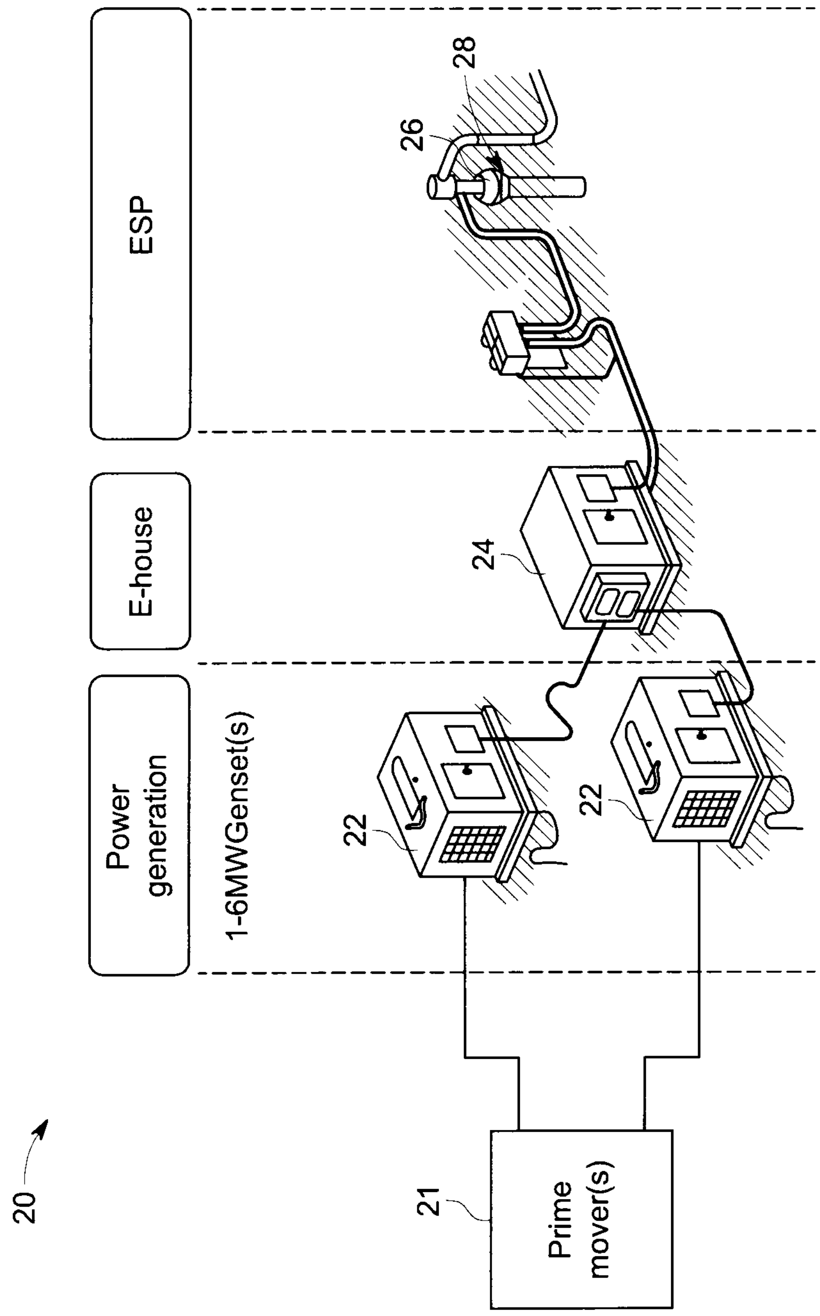

ESP
E-house
Power generation
1-6MWGenset(s)
Prime mover(s)
20
21
22
22
24
26
28

FIG. 2

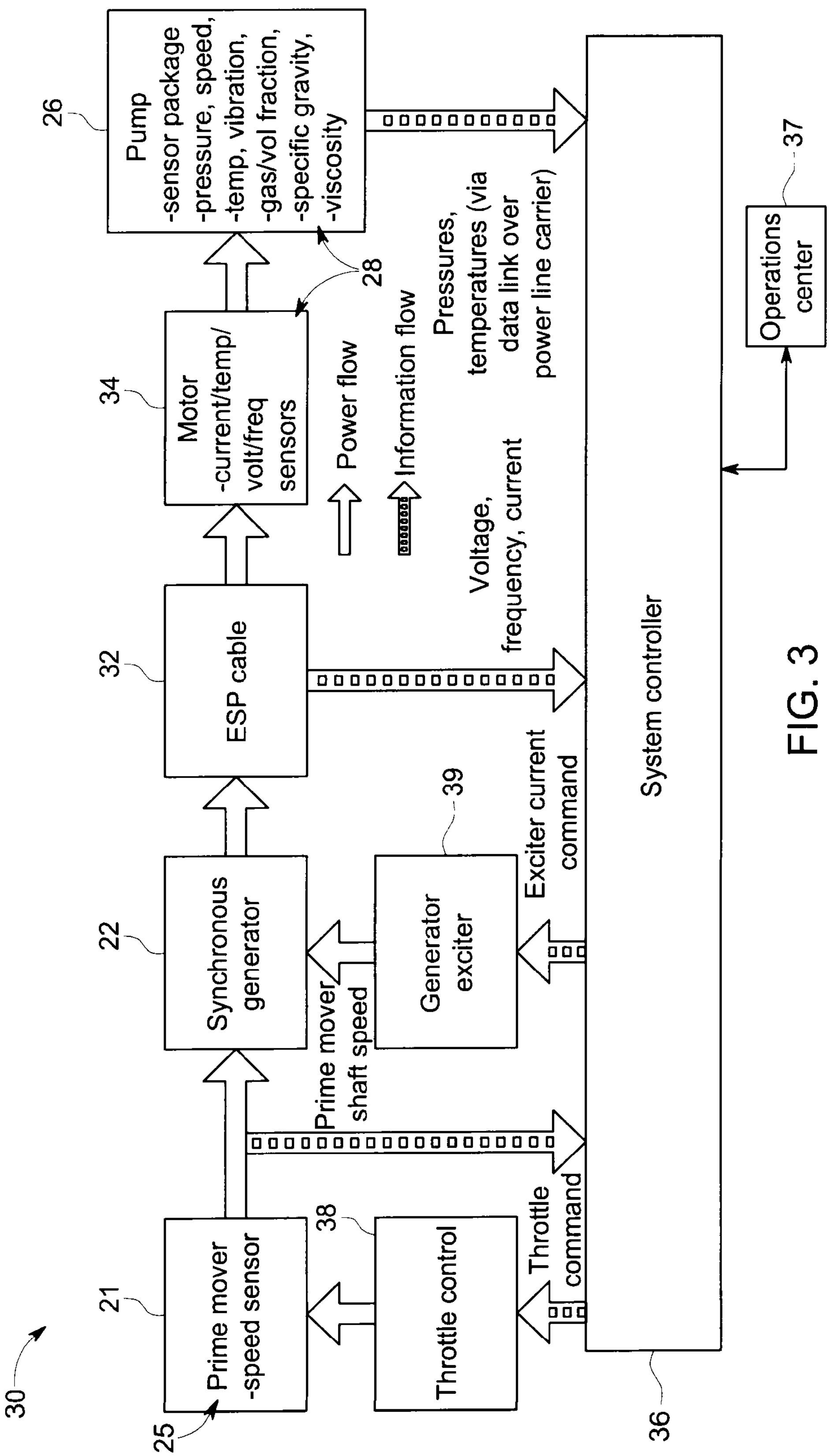

30
25
21
Prime mover
-speed sensor
38
Throttle control
Throttle
command
Prime mover
shaft speed
22
Synchronous
generator
39
Generator
exciter
Exciter current
command
32
ESP cable
Voltage,
frequency, current
34
Motor
-current/temp/
volt/freq
sensors
Power flow
Information flow
28
26
Pump
-sensor package
-pressure, speed,
-temp, vibration,
-gas/vol fraction,
-specific gravity,
-viscosity
Pressures,
temperatures (via
data link over
power line carrier)
System controller
36
37
Operations
center

FIG. 3

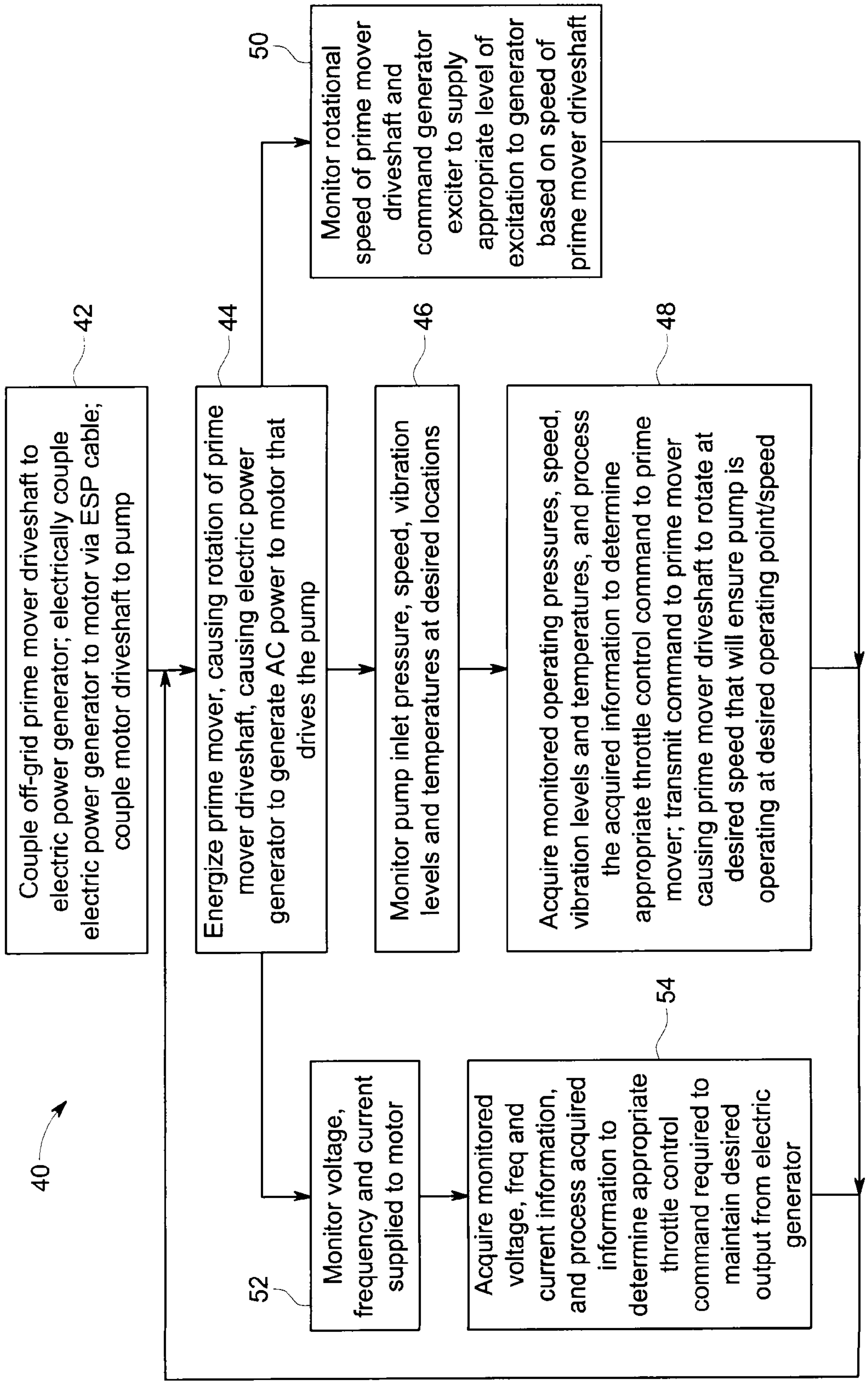

40
42
Couple off-grid prime mover driveshaft to electric power generator; electrically couple electric power generator to motor via ESP cable; couple motor driveshaft to pump
44
Energize prime mover, causing rotation of prime mover driveshaft, causing electric power generator to generate AC power to motor that drives the pump
46
Monitor pump inlet pressure, speed, vibration levels and temperatures at desired locations
48
Acquire monitored operating pressures, speed, vibration levels and temperatures, and process the acquired information to determine appropriate throttle control command to prime mover; transmit command to prime mover causing prime mover driveshaft to rotate at desired speed that will ensure pump is operating at desired operating point/speed
50
Monitor rotational speed of prime mover driveshaft and command generator exciter to supply appropriate level of excitation to generator based on speed of prime mover driveshaft
52
Monitor voltage, frequency and current supplied to motor
54
Acquire monitored voltage, freq and current information, and process acquired information to determine appropriate throttle control command required to maintain desired output from electric generator

FIG. 4

SYSTEM AND METHOD FOR CONVERTERLESS OPERATION OF MOTOR-DRIVEN PUMPS

BACKGROUND

[0001] The subject matter of this disclosure relates generally to motor-driven pumps, and more particularly, to a system and method for converterless operation of motor-driven pumps.

[0002] The conventional approach to controlling the speed of motor-driven pumps is through the use of a variable speed drive (VSD) that is fed by a fixed frequency AC supply. The VSD synthesizes voltages and currents of such frequency as is necessary to operate the pump in the desired manner. In the oil and gas industry, the voltage output by the VSD is usually stepped up to a medium voltage using a transformer because high voltage motors are deployed in wells to reduce the size of the power cable needed to supply the motor.

[0003] FIG. **1** illustrates a conventional system **10** that is known in the oil and gas industry for operating electric submersible pumps (ESPs) **12** in an off-grid application. One or more prime movers that are directly coupled to generators **14** produce an AC voltage having a fixed frequency and amplitude to supply electrical loads **15**. The prime movers may comprise, for example, a reciprocating engine that is fueled by either natural gas or diesel fuel, or a turbine. The generated AC power is fed to a VSD **16** that is responsible for regulating the operation of the ESPs **12** subsequent to stepping up the AC voltage to a medium voltage level that is supplied to ESP motor(s) **18** via a suitable transformer **19**.

[0004] There is a need in the oil and gas industry to provide a system for operating ESPs that is less complex, less costly, and that has a smaller footprint. A system that reduces the capital expense, weight and footprint size will advantageously reduce the time it takes to put a well into production using power generated on-site when compared with the time it takes to put a well into production using utility power because of the delays associated with getting the utility to install necessary power lines.

[0005] It is possible to use the natural gas produced by the well to support operation of the generator, thereby reducing the operating expense of the system. Depending on the selection of the generator and the prime mover, it may be necessary to couple the generator and the prime mover through a gearbox. It is generally possible to select a gearbox with a fixed ratio, thereby avoiding the need for changing gear ratios during system operation.

BRIEF DESCRIPTION

[0006] According to one embodiment, a converterless motor-driven pump system comprises:

[0007] at least one off-grid prime mover comprising a rotational driveshaft and operating in response to a throttle control command to control a rotation speed of the rotational driveshaft;

[0008] at least one electric power generator driven by the at least one off-grid prime mover to generate AC power;

[0009] at least one variable speed motor directly powered by the at least one electric power generator;

[0010] at least one electric submersible pump driven by the at least one variable speed motor, wherein one or more operating characteristics associated with the at least one electric submersible pump are monitored by one or more corresponding sensors;

[0011] a system controller programmed to generate the throttle control command in response to the one or more pump operating characteristics such that the at least one off-grid prime mover, the at least one electric power generator, and the at least one variable speed motor together operate to regulate a pressure at the inlet of the at least one electric submersible pump; and

[0012] monitoring and protection equipment comprising circuit breakers to ensure safety to personnel around the system, and to provide protection to the prime mover, generator, and variable speed motor during system starting, or in response to equipment failure or in response to occurrence of one or more unforeseen events.

[0013] According to another embodiment, a method of operating an electric submersible pump comprises:

[0014] controlling a driveshaft speed of an off-grid prime mover in response to a throttle control command;

[0015] controlling an AC power output of an electric power generator in response to the driveshaft speed of the off-grid prime mover;

[0016] controlling a speed of a variable speed motor directly in response to the AC power output of the electric power generator; and

[0017] monitoring operating characteristics of the electric submersible pump and generating the throttle control command in response thereto such that together the off-grid prime mover, the electric power generator, and the variable speed motor operate to regulate a pressure at an inlet to the electric submersible pump.

DRAWINGS

[0018] These and other features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings, wherein:

[0019] FIG. **1** illustrates a conventional electrical submersible pump (ESP) system that is known in the art;

[0020] FIG. **2** illustrates a converterless ESP system according to one embodiment;

[0021] FIG. **3** is a block diagram illustrating a system controller interfacing with and controlling a converterless ESP system according to one embodiment; and

[0022] FIG. **4** is a block diagram illustrating a method of providing off-grid power to a motor-driven submersible well pump according to one embodiment.

[0023] While the above-identified drawing figures set forth particular embodiments, other embodiments of the present invention are also contemplated, as noted in the discussion. In all cases, this disclosure presents illustrated embodiments of the present invention by way of representation and not limitation. Numerous other modifications and embodiments can be devised by those skilled in the art which fall within the scope and spirit of the principles of this invention.

DETAILED DESCRIPTION

[0024] The embodiments described herein are directed to control of motor-driven pumps in applications that are operating independently of a utility power grid, and combine the control of a prime mover and an AC generator to provide substantially similar functionality as a variable speed drive

(VSD) to reduce system complexity, cost and footprint size. Such embodiments are particularly useful in the oil and gas industry where the usual control objective is to regulate the pressure at the inlet of the motor driven submersible pump, although other control objectives, including without limitation, temperature, speed, or vibration can be applied in like fashion.

[0025] FIG. **2** illustrates a converterless ESP system **20** according to one embodiment. In this embodiment, the prime mover(s) **21** is/are directly controlled to regulate the pump inlet pressure. More specifically, the ESP system **20** comprises one or more prime movers **21** that are coupled to one or more generators **22**, means **24** for electrically connecting the output of the generator(s) **22**, and a motor-driven pump **26**. The prime mover **21** is typically a reciprocating engine that is fueled by either natural gas or diesel fuel, but is not so limited, as other types of prime movers such as, without limitation, turbines may also be employed as the prime mover **21**. Depending on the selection of the prime mover **21** and the generator **22**, it may be desirable to use a gearbox to match the shaft speeds of the prime mover **21** and generator **22**. It is preferable to use a fixed ratio gearbox to keep the system **20** as simple as possible. The motor-driven pump **26** is typically located within a well for purposes of artificially lifting a fluid from the well. The fluid could be, without limitation, water, gas or oil in a well, or a combination thereof. It is likely some amount of solids, such as sand or proppant, will be entrained with the fluid.

[0026] A sensor package **28** is attached to the motor-driven pump **26** that may comprise, for example, one or more temperature sensors and one or more pressure sensors to provide an indication of various pump operating temperatures and pressures. An important pressure is the inlet pressure to the pump **26**, since this pressure provides a direct indication of whether the well is being operated at the proper loading for maximizing well production. The sensor package **28** may further comprise one or more vibration sensors configured to monitor various pump vibration characteristics and to provide an indication whether a predetermined vibration level is exceeded. At least one speed sensor may be included in the sensor package **28** in order to accurately monitor the rotational speed of the pump. Other types of sensors may be included in the sensor package **28** depending on the particular application requirements.

[0027] The converterless ESP system **20** advantageously i) eliminates the need for a variable speed drive and transformer, simplifying the system, resulting in improved system reliability, ii) can use pumped gas via the pump **26** itself as the fuel to run the prime mover **22**, resulting in very low fuel costs, and iii) operates independently of a utility power grid.

[0028] It can be appreciated that there may be reasons to retain a transformer between the generator **22** and the motor driven pump **26**. Such reasons may include, without limitation, minimizing system cost and/or maximizing operational flexibility. According to one aspect, the decision to retain or remove the transformer from the system **20** may be made on the basis of system optimization rather than conceptual operation of the system **20**.

[0029] FIG. **3** is a block diagram illustrating the flow of power and information for a converterless ESP system **30** according to one embodiment. The power flows from the prime mover **21** through the generator **22** and cable **32** to the motor **34** and subsequently the pump **26**. The power between the prime mover **21** and the generator **22** is mechanical driveshaft power, as is the power between the induction motor **34** and the pump **26**. A gearbox between the prime mover **21** and the generator **22** may advantageously be employed for purposes of system optimization, as stated herein.

[0030] The programmable system controller **36** is responsible for monitoring the pump operating conditions, including without limitation input and output pressures, pump temperature(s), pump vibration levels, and pump rotational speed, and commanding the throttle position control **38** of the prime mover **21** that will drive the pump **26** output to the desired pump operating point in response to one or more of the monitored operating conditions. According to one aspect, the system controller **36** also monitors the shaft speed of the prime mover **21** and commands the generator exciter **39** of the synchronous generator **22** accordingly.

[0031] The programmable system controller **36** may comprise, without limitation, one or more computers and/or data processors/devices and associated display devices. The data processors/devices may comprise one or more CPUs, DSPs and associated data storage devices, data acquisition devices and corresponding handshaking devices that may be integrated with the system controller **36** and/or distributed throughout the converterless ESP system **30**. The system controller **36** may communicate with a remote operations center **37** that is able to monitor system operation and modify system operating objectives without requiring action of a local operator.

[0032] According to another aspect, the system controller **36** monitors the voltage, frequency and current being supplied to the motor **34**, and generates the prime mover throttle control command in response to the monitored information to modify control of the prime mover **21**. The rate of change in prime mover driveshaft speed, for example, might be controlled to maintain the generator current below a specified value by limiting the current being supplied by the generator **22**. Such operation can help reduce stress on the system, thereby making the converterless ESP system **30** more reliable.

[0033] According to another aspect, the generator **22** may be a permanent magnet generator that does not require excitation. It can be appreciated that use of a permanent magnet generator would further simplify the converterless ESP system **30** without sacrificing performance.

[0034] It can be appreciated that the pump motor **34** may be any electric motor that can be line started, including not only induction motors, but also a special class of permanent magnet motors known as line-start permanent magnet motors.

[0035] In summary explanation, a converterless ESP system eliminates the variable speed drive and, potentially, its associated transformer from a motor driven submersible pump system, resulting in a simpler system that reduces capital expense, weight and system footprint. The use of power generated on-site advantageously reduces the time it takes to put a well into production resulting from delays in getting the utility to install requisite power lines. Further, the use of natural gas produced by the well itself advantageously reduces the operating expense.

[0036] Since the output of the generator **22** is substantially sinusoidal when compared with the output of a variable speed drive, a filter is not required between the generator **22** and the motor **34**. The output of a variable VSD, for example, contains significant high frequency content, the result of chopping up DC voltage/current to produce AC voltage/current. This chopping action disadvantageously creates high frequency components called harmonics that are detrimental to the motor driving the pump. A filter is usually installed between the VSD and the motor; however, anecdotal data suggest that even such a filter may not always adequately filter out the harmonics, leading to accelerated aging of the insulation systems in the transformer **19**, cable **32**, and motor **34**. This disadvantageously reduces the life of the ESP system

[0037] A VSD also draws nonsinusoidal currents from its supply, unless an active front end is applied to the VSD. These resulting harmonics are detrimental to the generator supplying the VSD. Many system designs oversize the generator so that it can better tolerate the harmonic currents drawn by the VSD. Other system designs will use an active power filter to source the harmonic currents drawn by the VSD, thereby alleviating the generator from having to supply them. Either of such approaches adds to the cost and complexity of the system.

[0038] The principles described herein with reference to the various embodiments include reduced capital expense and more timely well production. The off-grid converterless system embodiments advantageously allow putting a well into production sooner since there is frequently a substantial waiting period for the utility to install supply lines to the well site, as stated herein. At such time as utility power is available, the well operator can remove the prime mover and generator, replacing them with a variable speed drive and transformers if desired.

[0039] FIG. **4** is a block diagram illustrating a method **40** of providing off-grid power to a motor-driven submersible well pump **26** according to one embodiment. A prime mover **21** driveshaft is coupled directly or indirectly to a generator **22**; while the generator **22** is electrically coupled to a motor that may be a line start motor such as an induction motor or permanent magnet motor **34** via a power cable **32** that may be, for example, without limitation, an electrical submersible pump cable; and the motor driveshaft is directly coupled to the submersible well pump **26**, as represented in block **42**. The prime mover **21** is turned-on to rotate its driveshaft, causing the generator **22** to produce AC power sufficient to power the motor **34**, that subsequently drives the submersible well pump **26**, as represented in block **44**. A sensor package **28** that may comprise, without limitation, various pressure sensors, temperature sensors, vibration sensors, and speed sensors associated with the submersible well pump **26** function to monitor operating conditions including without limitation, pump inlet pressure, pump vibration levels, pump rotational speed, and temperatures at desired points associated with the submersible well pump **26**, as represented in block **46**. The monitored operating data is acquired by a system controller **36** that determines whether the prime mover driveshaft should be rotating at a different speed. The system controller **36** then transmits an appropriate throttle control command **38** to the prime mover **21**, causing the prime mover driveshaft to rotate faster or slower as necessary to ensure the submersible well pump **26** is operating at the desired operating point, as represented in block **48**. According to one embodiment, the system controller **36** also monitors the rotational speed of the prime mover driveshaft via one or more speed sensors **25** associated with the driveshaft of the prime mover **21**, and commands the exciter **39** of a generator **22** to supply an appropriate level of excitation to the generator **22** when the generator **22** is a synchronous generator, as represented in block **50**.

[0040] For reasons of safety and system protection, system elements may be included that are responsible for monitoring the operation of the system equipment, with means to instruct the controller **36** to shut down the system **30** if a failure or external event causes an exception to intended operation. Exemplary system elements may include, without limitation, one or more pump pressure sensors, pump speed sensors, pump temperature sensors, pump vibration sensors, pump viscosity sensors, pump gas volume fraction sensors, specific gravity sensors, motor current sensors, motor temperature sensors, motor voltage sensors, and motor frequency sensors. A pump gas volume fraction sensor, for example, may be employed to determine a volumetric ratio of liquid versus gas that is flowing through the pump(s). External events causing a system shutdown may include, for example, i) a volume fraction that gets too large, i.e., too much gas for pump to handle, ii) a motor temperature that gets too high, or iii) a clogged pump, causing pump pressure to get too high. Monitored sensor signals are transmitted to the system controller **36** that ensures that the motor **34** and pump **26** are operating within prescribed design, safety, specification and/or threshold limits

[0041] Another embodiment includes monitoring the voltage, frequency, temperature and current being supplied to the motor **34** via the generator **22**, and acquiring the monitored information, as represented in block **52**. The acquired motor supply voltage, frequency, temperature and current information is used by the system controller **36** to determine whether the prime mover driveshaft should rotate at a different speed. If a different prime mover driveshaft speed is required, the system controller **36** transmits an appropriate throttle command **38** to the prime mover **21**, causing a change in the running speed of the prime mover **21**, as represented in block **54**. This embodiment can be employed in applications where it might be of interest to, for example, limit the current being supplied by the generator **22**; so the rate of change in prime mover speed could be controlled to keep the generator current less than a specified value.

[0042] Since some applications may employ a permanent magnet generator that does not require excitation, it can be appreciated that a generator exciter will not be required in such applications. The use of a permanent magnet generator further simplifies the converterless ESP system **30** without sacrificing performance, as stated herein.

[0043] Although particular embodiments have been described herein with application to electric submersible pumps, the principles described herein can just as easily be applied to other applications including without limitation, geothermal applications. In such applications, gas turbines or reciprocating engines can be employed to rotate the generator.

[0044] The principles described herein can be applied to a motor generator set feeding a plurality of ESPs (i.e., when an existing oil field is to be expanded to include, for example, 50% more wells, wherein the wells are in close proximity to each other). The controller **36** in this application is further programmed according to one embodiment to provide for load balancing among the ESP motors, thereby reducing unwanted losses.

[0045] The controller **36** may further be configured with synchronization logic and programmed according to yet another embodiment to generate a control signal that activates an auxiliary/spare generator to provide a parallel operation capability.

[0046] While the invention has been described in terms of various specific embodiments, those skilled in the art will recognize that the invention can be practiced with modification within the spirit and scope of the claims.

1. A converterless motor-driven pump system comprising:

at least one off-grid prime mover comprising a rotational driveshaft and operating in response to a throttle control command to control a rotation speed of the rotational driveshaft;

at least one electric power generator driven directly or indirectly by the at least one off-grid prime mover to generate AC power;

at least one variable speed motor directly or indirectly powered by the at least one electric power generator;

at least one electric submersible pump driven by the at least one variable speed motor, wherein one or more operating characteristics associated with the at least one electric submersible pump are monitored by one or more corresponding sensors; and

a system controller programmed to generate the throttle control command in response to the one or more pump operating characteristics such that the at least one off-grid prime mover, the at least one electric power generator, and the at least one variable speed motor together operate to regulate a pressure at the inlet of the at least one electric submersible pump such that a desired operating point of the at least one electric submersible pump is maintained.

2. The converterless motor-driven pump system according to claim 1, wherein the system controller is integrated with the converterless motor-driven pump system.

3. The converterless motor-driven pump system according to claim 1, wherein the system controller communicates with an operation center remote from the converterless motor-driven pump system.

4. The converterless motor-driven pump system according to claim 1, wherein the prime mover comprises at least one of a reciprocating engine or a turbine.

5. The converterless motor-driven pump system according to claim 1, wherein the electric generator comprises at least one of a permanent magnet generator and a wound-field synchronous generator.

6. The converterless motor-driven pump system according to claim 5, further comprising a generator exciter configured to provide excitation to the wound-field synchronous generator.

7. The converterless motor-driven pump system according to claim 6, further comprising a speed sensor configured to monitor the rotation speed of the rotational driveshaft.

8. The converterless motor-driven pump system according to claim 7, wherein the system controller is further programmed to control the excitation of the generator exciter in response to the rotation speed of the rotational driveshaft.

9. The converterless motor-driven pump system according to claim 1, further comprising an electric submersible pump cable directly or indirectly linking the generated AC power to the variable speed motor.

10. The converterless motor-driven pump system according to claim 1, further comprising a pressure sensor configured to monitor the inlet pressure of the at least one electric submersible pump.

11. The converterless motor-driven pump system according to claim 1, further comprising a transformer between the at least one generator and the at least one electric submersible pump.

12. The converterless motor-driven pump system according to claim 1, wherein the system controller is further programmed to shut down the converterless motor-driven pump system in response to one or more variable speed motor sensor signals that exceed prescribed limits or one or more electric submersible pump signals that exceed prescribed limits.

13. A method of operating a converterless motor-driven pump system, the method comprising:

controlling an AC power output of an electric power generator in response to an off-grid prime mover driveshaft speed, wherein the driveshaft speed of the off-grid prime mover is controlled via a throttle control command;

controlling a speed of a variable speed motor directly in response to the AC power output of the electric power generator;

controlling an electric submersible pump (ESP) in response to the speed of the motor, and

monitoring operating characteristics of the ESP and generating the throttle control command in response thereto such that together the off-grid prime mover, the electric power generator, and the variable speed motor operate to regulate a pressure at an inlet to the ESP and further to maintain a desired operating point for the ESP.

14. The method of operating a converterless motor-driven pump system according to claim 13, wherein monitoring operating characteristics comprises monitoring operating characteristics via a localized controller.

15. The method of operating a converterless motor-driven pump system according to claim 13, wherein monitoring operating characteristics comprises monitoring operating characteristics via a remote control center.

16. The method of operating a converterless motor-driven pump system according to claim 13, wherein controlling a driveshaft speed of an off-grid prime mover comprises controlling a driveshaft speed of at least one of a reciprocating engine and a turbine engine.

17. The method of operating a converterless motor-driven pump system according to claim 13, wherein controlling an AC power output of an electric power generator comprises controlling an AC power output of at least one of a wound-field synchronous generator and a permanent magnet generator.

18. The method of operating a converterless motor-driven pump system according to claim 17, wherein controlling an AC power output of the wound-field synchronous generator comprises controlling an AC power output of a wound-field exciter.

19. The method of operating a converterless motor-driven pump system according to claim 18, further comprising controlling the AC power output of the wound-field exciter in response to the driveshaft speed of the off-grid prime mover.

20. The method of operating a converterless motor-driven pump system according to claim 17, further comprising controlling the AC power output of the permanent magnet generator in response to the driveshaft speed of the off-grid prime mover.

21. The method of operating a converterless motor-driven pump system according to claim 13, further comprising

directly or indirectly linking the generated AC power to the variable speed motor via an electrical submersible pump cable.

22. The method of operating a converterless motor-driven pump system according to claim **13**, further comprising linking the generated AC power to the variable speed motor via a transformer and an electrical submersible pump cable.

23. The method of operating a converterless motor-driven pump system according to claim **13**, wherein monitoring operating characteristics of the ESP comprises monitoring an inlet pressure to the ESP, and generating the throttle control command in response thereto such that a desired ESP operating point is maintained.

* * * * *