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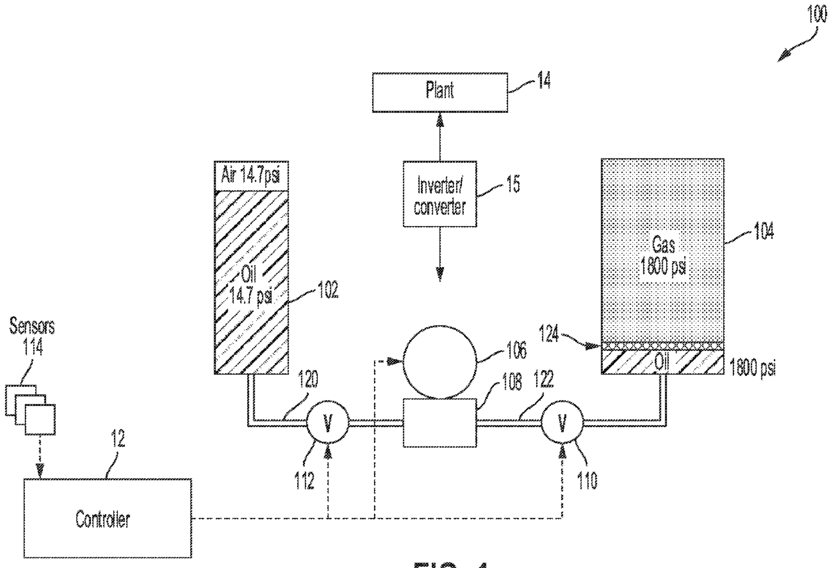

FIG. 1

(57) **Abstract:** Methods and systems are provided for improving storage of electrical power. A closed compressed gas storage system uses excess electrical power to drive a motor/generator which transfers hydraulic fluid via a hydraulic pump from a low-pressure tank to a high-pressure tank, further compressing a preloaded pressurized gas in the high-pressure tank via the fluid transfer and pressurization, and storing the electrical power in the form of compressed gas. When electrical power is demanded, decompression of the compressed gas is used to return hydraulic fluid to the low-pressure tank, while using the fluid transfer to drive a hydraulic pump that drives a motor/generator which generates electrical power.

[Continued on next page]

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METHOD AND SYSTEM FOR ELECTRICAL ENERGY STORAGE

FIELD

[0001] The present description relates generally to methods and systems for electrical energy storage.

BACKGROUND

[0002] Electrical energy has, and continues to be, a mainstay for meeting various residential and industrial power demands. Various forms of electrical energy generation have been developed, such as generation through coal, hydroelectric sources, nuclear sources, wind turbines, and solar arrays. As electrical energy generation has increased, power usage has also increased, rising to consume any advances in power generation. It is estimated that global electrical power usage is currently in the order of 23,000 terawatts per hour, more than double the 10,000 terawatts per hour consumed in 1990 (Global Energy Statistical Yearbook, 2018, Enerdata).

[0003] Outside of power generation, one of the largest issues associated with electrical energy usage is matching power usage with power supply availability. Certain technologies such as coal, nuclear, or geothermal cannot easily change generation production in order to meet changing conditions and thus can only provide baseload power. Solar and wind are too intermittent to rely on to meet differences in power usage and supply.

[0004] Various technologies have been developed for on demand power and/or power storage. Each technology has its own issues and limitations. Pumped water is limited by a lack of physical locations that can accommodate the necessary facilities. Natural gas and oil are limited by infrastructure availabilities. Batteries have a far less useful life than other technologies. Further, many of these technologies have environmental issues; batteries are chemical based, difficult to recycle and use precious metals only available from conflict zones; natural gas and oil usage releases carbon dioxide (CO_2) which drives climate change; and pumped water can cause ecological damage. There is therefore an unmet need for systems and methods for storing power and/or responding to fluctuations in energy demand.

SUMMARY

[0005] Disclosed herein is a method and system for electrical energy storage that relies on entrapped gas under preloaded high pressure for energy storage. One example embodiment of the system comprises an electrical power storage system including a first tank storing an incompressible hydraulic fluid and a compressible gas preloaded to a first pressure setting at or near atmospheric pressure; a second tank storing the incompressible hydraulic fluid and the compressible gas preloaded to a second pressure setting, higher than the first pressure setting; a reversible hydraulic fluid pump fluidically coupled to each of the first and second tank via corresponding connecting pipes; and a reversible motor/generator mechanically coupled to the fluid pump and electrically coupled to an electrical power source. In an alternate embodiment, the system may utilize a ground level reservoir, such as a pond or other body of water, to store the incompressible hydraulic fluid at a first, atmospheric pressure and a subterranean reservoir, such as an oil well or coal mine, to store the incompressible hydraulic fluid and the compressible gas at a second, higher pressure. The subterranean reservoir may be preloaded to the second pressure and similarly fluidically coupled to the ground level reservoir via the fluid pump. The system may be adjusted to a charged state by the fluid pump and may generate electrical power during a discharging operation. In another example, the second pressure setting may be a setting where the compressible gas is compressed into a liquid. Alternatively, the compressed gas may remain in the gaseous form at the second pressure setting. By cycling hydraulic fluid between the tanks in a power storage system sealed from the atmosphere, electrical power may be stored in the form of gas compressed to a higher pressure, and optionally liquefied at the higher pressure setting. The compressed or liquefied gas can, at a later time, be decompressed to a lower pressure to drive hydraulic fluid flow in a reverse direction between the tanks while generating electrical power on demand. The claimed approach provides various advantages. For example, the approach is not limited to a defined physical location, and does not necessitate expensive infrastructure such as pipelines or ship/truck distribution. Further, the proposed system has a relatively long service life, and reduced impact on the environment as compared to other known approaches since it does not rely on the use of precious metals. By selecting the compressed gas and the higher pressure setting so that the gas may be liquefied at higher pressures, a larger amount of energy may be stored at a given pressure and a given tank size. By relying on new workable technology, at a low cost, various existing issues in storing energy for future use are addressed, allowing for an improved balance of power usage with power supply.

[0006] It should be understood that the summary above is provided to introduce in simplified form a selection of concepts that are further described in the detailed description. It is not meant to identify key or essential features of the claimed subject matter, the scope of which is defined uniquely by the claims that follow the detailed description. Furthermore, the claimed subject matter is not limited to implementations that solve any disadvantages noted above or in any part of this disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 shows an example embodiment of a compressed gas based electrical energy storage system when discharged.

[0008] FIG. 2 shows an example embodiment of the electrical energy storage system of FIG. 1 when charged.

[0009] FIG. 3 shows another example embodiment of a compressed air based electrical energy storage system including a gas/fluid separator with a membrane.

[0010] FIG. 4 shows another example embodiment of a compressed air based electrical energy storage system, including a heating/cooling source, when discharged.

[0011] FIG. 5 shows an example embodiment of the electrical energy storage system of FIG. 4 when charged.

[0012] FIG. 6 shows an example method for operating a compressed gas based electrical energy storage system, according to the present disclosure.

[0013] FIG. 7 shows an example method for adjusting one or more parameters of a compressed gas based electrical energy storage system, according to the present disclosure.

[0014] FIG. 8 shows another example embodiment of a compressed gas based electrical energy storage system when discharged.

[0015] FIG. 9 shows an example embodiment of the electrical energy storage system of FIG. 8 when charged by liquefying the compressed gas at higher pressures.

[0016] FIG. 10 shows an example method for operating the compressed gas based electrical energy storage system of FIGS. 8-9, according to the present disclosure.

[0017] FIG. 11 shows an alternate embodiment of an electrical energy storage system when charged.

[0018] FIG. 12 shows the alternate embodiment of the electrical energy storage system of FIG. 11 when discharged.

DETAILED DESCRIPTION

[0019] The systems of FIGS. 1-12 describe example embodiments of an electrical energy storage system that use cycling of an incompressible hydraulic fluid between tanks or other reservoirs thereby further compressing a gas from a mid-range pressure to a maximum pressure to store electrical power. In particular, the system stores electrical power using gas compression. In some embodiments, such as those shown in FIGS. 1-5, the gas is compressed from a lower pressure setting to a higher pressure setting, but not liquefied. In other embodiments, such as those shown in FIGS. 8-9, the pressure level is such that the compressed gas changes state to a liquid. In either case, at a later time, the gas (or liquefied gas) can be decompressed responsive to a power demand, and the change in energy state harnessed for power generation. An additional alternate embodiment of the electrical energy storage system is shown in FIGS. 11 and 12 where the incompressible hydraulic fluid is cycled between a first side, at ground level and atmospheric pressure, and a second side, which may be subterranean and preloaded to a higher pressure. Examples of methods for operating the embodiments of the electrical energy system are shown in FIGS. 6, 7, and 10. The systems of FIGS. 1-12 provide various advantageous performance characteristics including various benefits over existing electrical power storage systems.

[0020] For example, due to the system being a closed system, energy can be stored using high pressure. The amount of energy created via the flow of fluid that is used to compress gas to a specified pressure may be determined based on equation (1):

$$\text{Energy} = (\text{pressure x flow}) \text{ x constant} \qquad (1)$$

Thus, horsepower generated may be determined as: (psi x gpm) x 1714. Horsepower can be converted into electrical energy such as kilowatts.

[0021] Since this invention stores energy between the approximate mid-range and the maximum pressure of the compressed gas in the closed system, the energy stored and released is always working on the high end of the pressure. By only working above the mid-range pressures, the system is far more efficient than if the full range of possible pressures were used (such as a range from a minimum pressure to a maximum pressure of the compressed gas in the closed system).

[0022] In comparison, open compressed air energy storage systems that use compressed air by working from ambient pressures to high pressures are far less efficient since they have to work at both the higher and lower ends. In those systems, ambient air is drawn in and then compressed. In the described invention of the present disclosure, a more efficient approach is provided since it only works on the higher end of pressures and energy is not used inefficiently for compressing a gas from ambient pressure conditions.

[0023] As another example, pumping fluids is more efficient than pumping gases. Thus, by pumping an incompressible hydraulic fluid (e.g., hydraulic oil) through a hydraulic pump, instead of pumping a gas, a more efficient system is created. Gases can be compressed to store energy, while fluids cannot be compressed. However, pumping fluids is more efficient than pumping air. This invention leverages the efficient pumping of fluids which indirectly compresses the gases, such as by compressing the gases to a higher pressure, or by compressing the gases to induce a phase change into a liquid phase, rather than directly pumping/compressing gases inefficiently.

[0024] As another example, the system described herein does not generate heat, reducing heat related issues and losses common to other energy storage systems. In conventional compressed gas systems, gases may be compressed into a fixed size tank (constant cubic area) which creates a considerable amount of heat. In contrast, in the current invention, no heat is created because the cubic area decreases while the corresponding pressure increases when the fluid volume increases. This can be demonstrated with classic ideal gas law as shown at equation (2):

$$PV = nRT \qquad (2)$$

wherein P = pressure, V = Volume, n = mols, R = ideal gas law constant, T = temperature.
Because this energy system does not create or lose any heat from gas compression or decompression, energy can be efficiently stored for days, months, or even years.

[0025] As yet another example, the described approach uses low cost equipment to pump. The capital cost of fluid pumps is less than the cost of gas compressors. Gas compressors are complicated machinery and must be designed to eliminate heat along the way because they may become too hot for the materials that they are constructed from. Loss of heat may be a significant factor. To arrive at high pressures, prior art systems may need to compress gasses in multiple stages, adding to the complexity of the equipment. In comparison, the current invention provides a simple and cost-effective approach.

[0026] As a further example, the current approach results in little to no penalty for deep drawdowns. This is unlike batteries that can have a significant reduction in expected life due to successive drawdowns on energy. Since battery chemistries can degrade with deep drawdown, batteries may not be cycled between 100% charged and 100% discharged states, causing a drop-in performance on each cycle. In the current invention, there is no degradation associated with deep drawdowns, and performance is maintained even after multiple cycles between 100% charged and 100% discharged states.

[0027] Furthermore, the components of the current invention degrade at a significantly slower pace than prior art approaches, such as relative to chemicals in batteries. This provides the current system with a long life, and requires infrequent replacement of components.

[0028] FIGS. 1-5, 8-9, and 11-12 show example configurations with relative positioning of the various components. If shown directly contacting each other, or directly coupled, then such elements may be referred to as directly contacting or directly coupled, respectively, at least in one example. Similarly, elements shown contiguous or adjacent to one another may be contiguous or adjacent to each other, respectively, at least in one example. As an example, components laying in face-sharing contact with each other may be referred to as in face-sharing contact. As another example, elements positioned apart from each other with only a space there-between and no other components may be referred to as such, in at least one example. As yet another example, elements shown above/below one another, at opposite sides to one another, or to the left/right of one another may be referred to as such, relative to one another. Further, as shown in the figures, a topmost element or point of element may be referred to as a "top" of the component and a bottommost element or point of the element may be referred to as a "bottom" of the component, in at least one example. As used herein, top/bottom, upper/lower, above/below, may be relative to a vertical axis of the figures and used to describe positioning of elements of the figures relative to one another. As such, elements shown above other elements are positioned vertically above the other elements, in one example. As yet another example, shapes of the elements depicted within the figures may be referred to as having those shapes (e.g., such as being circular, straight, planar, curved, rounded, chamfered, angled, or the like). Further, elements shown intersecting one another may be referred to as intersecting elements or intersecting one another, in at least one example. Further still, an element shown within another element or shown outside of another element may be referred as such, in one example.

[0029] FIG. 1 shows a first example embodiment 100 of a compressed gas based electric energy storage system. The system includes a first low-pressure fluid/gas tank 102 coupled to a second-high-pressure fluid/gas tank 104. In one example, the low-pressure fluid/gas tank is at atmospheric pressure.

[0030] The system is a closed storage system in that none of the tanks are coupled to the atmosphere. Rather, the contents of each tank are sealed from the atmosphere and are only fluidically coupled to each other when a hydraulic pump is operated, as elaborated below. Thus, even when the low-pressure tank is at atmospheric pressure, it is due to the compressed gas in the tank being at atmospheric pressure, and not due to the low-pressure tank being in fluidic communication with atmospheric air (as is the case in open systems). By operating as a closed system, various performance and efficiency advantages are achieved, as discussed earlier.

[0031] Each of the high pressure and low-pressure fluid/gas tanks may be configured as cylinders or cylindrical tanks although spheres could also be used. The tanks may be made of any suitable material that is able to contain fluids therein at pressure, such as metal, steel, plastic, and the like. The cylindrical shape of the tanks may be of a standard design. In some embodiments, the outer surface of the cylindrical tanks may be further reinforced with fiber glass, carbon fiber, and/or high strength alloy wire. As such, the tanks may be made of any number of different materials and may be manufactured via any number of manufacturing processes. Further, the tanks may be designed to hold a number of different pressure settings. As such, any suitable combination of material, manufacture, and pressure setting may be used as long as it is able to maintain a design pressure.

[0032] Example compositions for tanks 102, 104 include steel, a combination of steel and glass fiber, a combination of aluminum and carbon fiber, a combination of plastic and carbon fiber, and an all composite tank. Some of the manufacturing methods that may be used for the metal portion of the tanks includes steel plate (deep drawing), seamless tubes (hot spinning), and steel billet (piercing and drawing) based approaches.

[0033] In another embodiment, one or more of tanks 102, 104 may include a steel shell wrapped with high strength cables buried in concrete. In this configuration, the inner steel shell carries only a portion of the strength and pressure, and the rest is carried by high strength cables spread out over the whole surface with the concrete. It will be appreciated that high-pressure tanks for this invention are not limited to the above examples. Any tank made with any type of material capable of holding high pressures may qualify.

[0034] The service life of the tanks may be extended by a variety of methods. For example, the maximum acceptable pressure of a tank may be downgraded to a lower value after reaching its service life, allowing the tank to be continued to be used for an extended period of time. Composite exteriors may protect tanks from weather. Further, an inner surface of the tanks may be coated or treated to reduce reaction of the tank metal or other material with the gas and fluid stored inside the tank. In still further examples, the gas and fluid used inside the tank may be of an inert nature to reduce oxidative reactions with the tank's inner surface. Likewise, the exterior surface of the tanks may be treated or coated to protect the tank from oxidative reactions and corrosion.

[0035] Each of the tanks 102, 104 are preloaded with an incompressible hydraulic fluid and a compressible gas to a defined pressure setting. In particular, an incompressible hydraulic fluid, depicted in the present example as hydraulic oil, is stored in the low-pressure tank 102 at a lower pressure than the pressure setting of the high-pressure tank. For example, the fluid in the low-pressure tank may be stored at atmospheric pressure or 14.7psi, as in the depicted example. A grade and viscosity of the incompressible fluid may be selected based on pressure and temperature considerations. For example, hydraulic oil may be used. Water may be used as the incompressible fluid as long as operating conditions do not include below freezing temperatures. The low-pressure tank also stores a compressible gas, depicted in the present example as air or any other gas, at the lower pressure (such as at atmospheric pressure or 14.7psi, as depicted). It will be appreciated that an alternate compressible fluid may be used without departing from the scope of the invention as long as the fluid meets the operating conditions. As such, both the compressible gas and the incompressible fluid are stored in the low-pressure tank 102 at a common low pressure setting. The compressible gas may include any type of gas that does not turn into liquid at the design pressures. That is, the gas does not turn into liquid when compressed to the maximum achievable pressure setting of the high-pressure tank 104. When in a discharged state, a majority of the volume of the low-pressure tank is occupied by the incompressible fluid while a remaining volume is occupied by the compressible low or near atmospheric pressure gas. In one example, when the system 100 is fully discharged, a ratio of oil to gas in the low-pressure tank 102 is about 98%:2%.

[0036] The high-pressure fluid tank 104 may also store the same incompressible fluid (e.g., oil). When fully discharged the volume of oil is about 2% of high-pressure fluid tank 104 and the compressible gas occupies about the other 98% of tank volume. However, the compressible gas is preloaded in the high-pressure tank 104 and set to approximate 50% of the maximum achievable pressure of the high- pressure tank. Thus, due to the hydraulic fluid transfer from the low-pressure tank to the high-pressure tank, the compressed gas is pressurized to change from occupying ~98% of the tank volume to occupying ~50% of the tank volume. In the example shown in FIG. 1, the fluids are at 1800psi, indicating that the maximum achievable pressure in the high-pressure tank is 3600psi. However, this is not meant to be limiting. Rather, as detailed herein, the pressure setting of the gas in the high-pressure tank 104 may be varied, and the setting selected based on a desired function and configuration of the energy storage system Both the compressible gas and the incompressible fluid are stored in the high-pressure tank 104 at a common high pressure. When the energy system is fully charged the volume of fluid remaining in the low-pressure tank is about 2% and the high-pressure tank fluid is about 50% with the remaining 50% highly compressed gas.

[0037] As such, the incompressible fluid may have a higher density than the compressible gas, such that in both the high-pressure and the low-pressure tanks, the compressible gas (e.g. gas) rises towards a top end of the cylinder, while the incompressible fluid (e.g., oil) remains at a bottom end of the cylinder. As a result, the only fluid that travels through connecting pipes (e.g., a first, low-pressure line and a second, high-pressure line) 120, 122 is the oil.

[0038] Other example incompressible fluids that may be used in low- and high-pressure tanks 102, 104 include but are not limited to oil, synthetic oil, and water. In one example, the compressible gas may be air or an inert gas such as nitrogen or argon or any other noble gas. Use of an inert compressible gas can extend the life of the tanks by precluding occurrence of oxidation reactions between the metal of the tank and the compressible gas. Other examples of compressible gases that may be used in low and high-pressure tanks 102, 104 include helium and hydrogen.

[0039] Preloading the low-pressure and high-pressure tanks may include loading the incompressible fluid (e.g. oil) into the tanks first. The low-pressure tank may be preloaded first followed by the high-pressure tank. The oil may be loaded into the tanks by pumping the fluid into the tank via a fill/vent tube coupled to a valve located on a top of tank. A pressure relief valve may also be coupled to the top of at least the high-pressure tank, the pressure relief valve set to a maximum pressure setting for safety purposes. A motor/generator which is connected to a hydraulic pump of the system (see below) may be briefly turned on so as to load fluid into the connecting pipes, hydraulic pump, as well into the high-pressure tank. When loaded the low-pressure tank will be about 98% full of fluid, the connecting pipes and hydraulic pump 100% full of the fluid, and the high-pressure tank about 2% full of the hydraulic fluid. The low-pressure tank is then vented to the atmosphere to equilibrate it to atmospheric pressure before it is resealed by closing the valve at the top surface. After the low-pressure tank is preloaded, the high-pressure tank is preloaded with the gas (e.g., nitrogen, argon, air) compressed to a target high pressure. The compressed gas is loaded through the fill/vent tube via a valve coupled to the top surface of the high-pressure tank, the compressed gas loaded into the high-pressure tank to the design pressure of the high-pressure tank, which is typically the mid-point of the maximum pressure setting of the high-pressure tank.

[0040] In embodiments where air is used as the compressed gas, a conventional air compressor may be used to achieve the target pressures for preloading. Once fully loaded to the target design pressures, the fill/vent valve of the corresponding tanks are closed. In embodiments where air is not used as the compressed gas, a vacuum pump may be attached to the fill/vent tube via the open valve to remove any air from the high-pressure tank. Subsequently, the selected gas is loaded into the tank. A gas compressor may be used to transfer the selected gas to be loaded into the high-pressure tank. When fully loaded to design pressure in the high-pressure tank, the fill/vent valve will be closed.

[0041] It will be appreciated that while the examples depicted herein describe preloading the high-pressure tank to the midpoint pressure setting (that is, the midpoint of the maximum pressure setting of the high-pressure tank), in alternate embodiments, the high-pressure tank may be preloaded to a higher pressure setting than the midpoint pressure setting.

[0042] In further examples, the preloading may be varied as a function of seasonal temperatures. For example, the midpoint gas pressure that would be preloaded into the high-pressure tank may be optimized for the average temperature for the year for a particular location. As an example, when temperatures are colder than the average, more fluid may be pumped in to achieve the high-pressure tank’s maximum pressure, thereby effectively storing more power. In comparison, when the average temperature is warmer, less fluid may be pumped in effectively storing less power. The increases and decreases may cancel each other over the year to the optimized average.

[0043] In the winter seasons there may be more stored power which at the lowest point (coldest day) will be approximately 10% below the average. However over the winter season it will average out at about 5% below the average for the year. The summer is the reverse. Alternatively, the energy storage system could be enclosed in an insulated building or container wherein the temperature could be kept constant all year with no significant fluctuation in energy storage during that year.

[0044] In the depicted example, the compressible gas and the incompressible fluid are in fluidic contact at an interface in each of the tanks 102, 104. Thus, the fluids may be selected to ensure that they are not miscible. In alternate examples, to reduce issues associated with miscibility and the ingress of the gas into the fluid at the interface, the gas and the fluids may be separated from each other by an intermediate device 124. The intermediate device may be a piston, bladder, membrane, or any other device that ensures separation of the fluids. In some examples, the gas may separate out from the fluid upon discharge of fluid from the high-pressure tank to the low pressure tank, thereby slowly reducing a maximum reachable pressure in the high-pressure tank. This results in a drop in storage capacity of the electrical energy storage system.

[0045] The first tank 102 is coupled to the second tank 104 via a hydraulic reversible fluid pump 108. Mechanical operation of the hydraulic pump in a first direction during a charging operation (as described below) creates a vacuum at the pump inlet at the side of the low-pressure tank 102, forcing oil from low-pressure tank into the first low pressure line 120 and onward through the pump 108. In addition, the mechanical action delivers this oil to a pump outlet and forces it into the second high-pressure line 122 and thereon into the high-pressure tank 104. It will be appreciated that the pump 108 produces liquid movement or flow between the tanks and through pressure lines 120, 122 with pressure. It produces the flow necessary for the development of pressure in the second tank, as discussed below. The hydraulic reversible fluid pump 108 may be configured to enable fluid movement in either direction through the pump. In one example, the fluid pump may be a standard off the shelf hydraulic pump, thereby reducing the cost of the energy storage system.

[0046] The mechanical operation of the hydraulic pump in the first direction is driven by motor/generator 106 acting in a motoring mode. Motor/generator 106 may be configured as a DC brushless motor, providing the advantages of the ability to operate at various speeds thereby being able to charge and discharge with a considerable range of operation. First low-pressure line 120, configured as a low-pressure connecting pipe with a valve 112, couples the low-pressure tank 102 to the DC motor/generator 106. Valve 112 may be a simple on/off valve wherein when in the on position, the motor/generator is fluidically connected to the oil in the low-pressure tank. Alternatively, valve 112 may be a variable position valve such that a flow rate of oil through the valve 112 can be varied by varying a degree of opening of the valve. In some embodiments, valve 112 may be a solenoid valve. By varying the rate of oil flow through the valve, a rate of charging or discharging of the high-pressure tank can be varied. Second high-pressure line 122, configured as a high pressure connecting pipe with a valve 110, couples the high-pressure tank 104 to the DC motor/generator 106. Valve 110 may also be a simple on/off valve wherein when in the on position, the motor/generator is fluidically connected to the oil in the high-pressure tank. Alternatively, valve 110 may be a variable position valve such that a flow rate of oil through the valve 110 can be varied by varying a degree of opening of the valve. In some embodiments, valve 110 may be a solenoid valve. By varying the rate of oil flow through the valve, a rate of charging or discharging of the high-pressure tank can be varied. In one example, the connecting pipes and valves may be standard off the shelf high-pressure pipes and valves, thereby reducing the cost of the energy storage system.

[0047] Additional electrical components, such as inverters and converters 15 may be coupled to the system, such as between motor/generator 106 and an electrical source (or power plant) 14. When included, the inverters and converters 15 may be configured to convert AC power to DC power, or vice versa. For example, during a charging operation, AC electrical power received from source 14 is converted to DC power at the converter, and then the DC power is used to operate the motor/generator 106. During a discharging operation, DC electrical power generated by the motor/generator 106 is converted to AC power at the inverter, and then the AC power is transmitted to source 14 or used to meet an electrical power demand.

[0048] In the fully discharged state, as shown at FIG. 1, the low-pressure tank 102 is almost fully filled with the hydraulic oil. Also, the DC motor/generator 106 is at rest. The high-pressure tank 104 is filled with gas at a pressure that approximates 50% of the maximum achievable pressure of the high-pressure tank. Both valves 110, 112 in the corresponding connecting pipes are held closed.

[0049] The electrical energy storage system 100 may be controlled at least partially by a control system including controller 12. Controller 12 may receive various signals from sensors 114 coupled to electrical energy storage system 100, and send control signals to the various actuators listed above. The various sensors may include, for example, various temperature and pressure sensors coupled to the high and low-pressure tanks. The various actuators may include, for example, valves 110, 112, and motor/generator 106. Controller 12 may include a microcomputer, including a microprocessor unit, input/output ports, and an electronic storage medium for executable programs and calibration values. The control methods and routines disclosed herein may be stored as executable instructions in non-transitory memory and may be carried out by the control system including the controller in combination with the various sensors, actuators, and other electrical energy storage system components. The specific routines described herein may represent one or more of any number of processing strategies such as event-driven, interrupt-driven, multi-tasking, multi-threading, and the like. As such, various actions, operations, and/or functions illustrated may be performed in the sequence illustrated, in parallel, or in some cases omitted. Likewise, the order of processing is not necessarily required to achieve the features and advantages of the example embodiments described herein, but is provided for ease of illustration and description. One or more of the illustrated actions, operations and/or functions may be repeatedly performed depending on the particular strategy being used. Further, the described actions, operations and/or functions may graphically represent code to be programmed into non-transitory memory of the computer readable storage medium in the engine control system, where the described actions are carried out by executing the instructions in a system including the various engine hardware components in combination with the electronic controller.

[0050] A charging operation can be performed via controller 12 while the system 100 is in the fully discharged state. As elaborated at FIG. 7, during the charging operation, electrical power is applied to the DC motor 106 which operates in the motoring mode and drives the hydraulic fluid pump 108. Electrical power used to operate the DC motor/generator can be drawn from a power source 14. The power source may be a small power plant, a solar farm, wind turbine farm, a geothermal plant, etc. Alternatively, the power may be drawn from a large power plant via a transmission line. Both valves 110, 112 of the connecting lines are held open during the charging operation. As a result of the operation, the incompressible hydraulic fluid (e.g., the hydraulic oil of FIGS. 1-5) is pumped under pressure from the low-pressure fluid tank into the high-pressure fluid tank, causing compression of the compressible gas (e.g., the gas of FIGS. 1-5) in the high-pressure tank. As more oil is pumped under pressure from the low-pressure tank into the high-pressure tank, the gas in the high-pressure tank is compressed to a higher pressure. Once substantially all of the oil has been transferred under pressure from the low-pressure tank to the high-pressure tank, and the gas in the high-pressure tank has been compressed to the maximum achievable pressure setting (e.g., 3600 psi in the depicted example), the energy storage system 100 is determined to be fully charged (See FIG 3). At this time, once fully charged, the electrical power that was drawn from the power source and used to power the motor/generator is stored in the form of compressed gas in the high-pressure tank. As such, it will be appreciated that the degree of charging of the energy storage system may be varied by varying a duration of operation and speed of the DC motor/generator 106. Thus, when the system is less than fully charged, a portion of the oil may remain in the low-pressure tank and the pressure of compressed air in the high-pressure tank may be less than the maximum achievable value.

[0051] Once the system has been fully charged, valves 110, 112 are closed to maintain the pressure in the tanks in isolation. The electrical power to the DC motor is also turned off. At this time, the low-pressure tank is empty and the high-pressure tank is approximately 50% full of the incompressible fluid and 50% full of the compressible gas that has been compressed to a pressure of about 2 times prior to charging. FIG. 3 shows an example embodiment of the electrical energy storage system of FIG. 1 in a fully charged state. All components previously introduced in FIG. 1 are numbered the same.

[0052] A discharging operation can be performed via controller 12 while the system 100 is in the fully (or partially) charged state. As elaborated at FIGS. 6-7, during the discharging operation, both valves 110, 112 are opened to fluidically connect the tanks 102, 104 to the motor/generator 106. In one example, both valves 110, 112 are fully opened. In another example, a degree of opening of valves 110, 112 may be varied to control the flow rate of the oil between the tanks. Upon opening the valves, the pressure difference between the high-pressure fluid in the high-pressure tank and the low-pressure fluid in the low-pressure tank drives fluid transfer between the tanks. In particular, the high pressure of the compressed gas in the high-pressure tank 104 drives the oil from the high-pressure tank though second connecting line 122 into the hydraulic pump operating in reverse 108, and then on through the first connecting line 120 into the low-pressure tank 102.

[0053] As elaborated at FIGS. 6-7, during the discharging operation, electrical power is generated at the DC motor 106 which operates in a generating mode. In particular, the flow of oil through the hydraulic reversible fluid pump 108 (due to the pressure difference between the tanks when the valves are opened) drives the pump, which in turn drives the motor/generator. Electrical power generated by the DC motor/generator can be used for meeting an electrical power demand, such as a surge in power demand. Alternatively, the electrical power can be transferred to a grid source coupled to the power source. As more oil is transferred from the high-pressure tank into the low-pressure tank, the pressure of the compressed gas in the high-pressure tank dissipates. Once substantially all of the oil has been transferred from the high-pressure tank to the low-pressure tank, and the pressure of the compressed gas in the high-pressure tank has dissipated to the default high-pressure value (e.g., the 50% value of the maximum achievable pressure setting, 1800 psi in the depicted example), the energy storage system 100 is determined to be fully discharged. At this time, once fully discharged, the electrical power that was stored in the form of compressed gas in the high-pressure tank has been converted back into electrical power that can be used for meeting an electrical power demand. As such, it will be appreciated that the degree of discharging of the energy storage system may be varied by varying a flow rate of the oil through the valves and the hydraulic pump, and the output of the DC motor/generator 106. Thus, when the system is less than fully discharged, a portion of the oil may remain in the high-pressure tank and the pressure of compressed gas in the high-pressure tank may be less than the maximum achievable value and higher than the lower default value. FIG. 1 shows an example embodiment of an electrical energy storage system in the fully discharged state.

[0054] In this way, the incompressible fluid in the high-pressure tank acts as a piston to compress the compressible gas in the high-pressure tank, thereby storing energy in the form of compressed gas. It will be appreciated that in alternate embodiments, one or more intermediate fluids and/or devices may be included in the high-pressure tank to improve the efficiency of fluid compression. For example, a mechanical piston may be provided in the tank such that transfer of pressurized oil from the low-pressure tank to the high-pressure tank drives a shaft of the piston, pushing the piston head towards a top end of the cylinder, and compressing the gas.

[0055] In some scenarios, during compression and decompression cycles of the compressible gas, there may be ingress of the gas into the fluid (e.g. oil). In particular, some of the compressed gas may infuse itself into the fluid (hydraulic oil) in the high-pressure tank. This may occur even though the pressure of the gas is the same as the pressure of the fluid. In addition, a portion of the gas in the high-pressure tank may be unintentionally ingested in the low-pressure tank. Any transfer of compressed gas out of the high-pressure tank would result in a drop in the efficiency of the system as it results in a drop in the maximum achievable pressure setting of the compressed gas. In particular, when the fluid (hydraulic oil) containing some compressed gas is expanded over to the low-pressure tank during a discharging operation, the gas is released due to the pressure difference between the gas in the fluid and the pressure in the low-pressure tank. This causes the gas pressure in the high-pressure tank to decline over time.

[0056] One or more approaches may be used to address this issue. As a first example approach, no immediate action may be taken. In this first approach, the fact that the amount of gas (e.g., nitrogen gas) being removed is significantly small (e.g., smaller than a threshold amount), means that the power loss associated with the gas ingress may be smaller than the power cost of addressing the gas removal (such as via the use of a gas compressor or through the active recharging of the high-pressure tank with additional compressed air). Alternatively, the nitrogen gas captured in the low-pressure tank may be compressed by a gas compressor and used to recharge the high-pressure tank on an occasional basis. The occasional recharging may reduce the costs of addressing the gas ingress. It may also be assumed in this approach that any of the amount of nitrogen gas is so small that it does not cause any cavitation of the impeller blades of the hydraulic pump. Even if it did, a hydraulic pump made of stainless steel or other quality materials may be used to stop the cavitation.

[0057] In the above approach, the gas would be allowed to ingress into the fluid and upon discharge the gas would escape into the low-pressure tank. If the escaping gas was air, the fill/vent tube and associated valve would remain open in the low-pressure tank. When the high-pressure tank has lost a set amount of air pressure, a standard air compressor would be operated to bring the high-pressure tank back to its optimized pressure through the opened fill/vent tube valve. When fully loaded to design pressure the fill/vent valve would be closed. If the escaping gas was not air but some other gas, the fill/vent valve would be closed in the low-pressure tank. When the low-pressure tank reached a set pressure, a gas compressor with both tanks fill/vent valves open would transfer the gas back under high pressure from the low-pressure tank to the high-pressure tank. When fully loaded to design pressure both fill/vent valves will be closed. It will be appreciated that for both the above scenarios, the operations would be performed when the energy system was fully discharged.

[0058] As another approach, the ingress may be reduced via the use of a bladder that separates the gas from the oil in the high-pressure tank. As yet another approach, a piston may be used in the high-pressure tank to separate the gas and the fluid to prevent ingress. As still another approach, a diaphragm may be used in the high-pressure tank to separate the gas and the fluid to prevent ingress. By including a piston, bladder, or diaphragm inserted in the tank that separates the gas from the fluid, ingress of gas into the fluid is prevented, and no pressure adjustments are required to be made to the system.

[0059] As yet another approach, a fluid that prevents ingress of the gas into the fluid in the high-pressure tank may be used as the incompressible fluid. As still another approach, a gas may be chosen that prevents the ingress of the gas into the fluid in the high-pressure gas/fluid tank.

[0060] As a further approach, a gas/fluid separator may be placed between the high-pressure tank and the high pressure hydraulic pump. This approach is shown in the example embodiment 300 of FIG. 3 which includes gas/fluid separator 304. Therein, a membrane may be included inside the gas/fluid separator 304 that allows gasses but does not allow fluid to pass through. The pressure of the gasses inside gas/fluid separator 304 is set a little lower than the midpoint pressure of the high-pressure tank. On discharge, the gas is captured at a relatively high pressure before it goes through the high pressure hydraulic pump without causing cavitation. This results from the gas capture being based on the difference between the pressures of the fluid and the gas at the interface of the membrane. After a threshold amount of gas has been captured, at least some of the gas captured in the gas/fluid separator 304 may be returned back into the high-pressure tank. This may be done by using a gas compressor 302 to transfer the gas back to high-pressure tank 104. The pressure differences may be small enough such that the cost of operating the gas compressor 302 may be small. Another approach may include letting the high pressure hydraulic pump 108 push oil into the gas portion of the separator 304 and generate enough pressure difference to transfer the gas.

[0061] In still a further embodiment, as depicted at FIGS. 4-5, a heat exchanger 402 may be coupled to the high-pressure tank 104, specifically to the upper part 404 of the tank where only gas is placed, such that the heat exchanger is only coupled to the gas and not to the hydraulic oil. FIG. 4 shows such an embodiment fully charged while FIG. 5 shows such an embodiment fully discharged. During a discharging operation, the heat exchanger 402 may be operated such that heat can be added to the gas, thereby increasing the pressure of the gas in the high-pressure tank.

This results in more energy being delivered through the hydraulic pump 106 and on into the motor/generator 108. The heat source in the heat exchanger may be any low cost heat source including, such as but not limited to, waste heat, solar energy, biomass, natural gas, etc. After fully discharging compressed gas from the high-pressure tank, a cold source, including but not limited to cold water, cool air, coolant, refrigerant, etc., that is cool (e.g., lower than a threshold temperature) can be run through the heat exchanger to cool the air and lower the pressure back to close to optimum pressure. For example, the cold source may be delivered to the heat exchanger 402 through an inlet 406 and circulated out of the heat exchanger 402 through an outlet 408.

[0062] In some examples, the heat exchanger 402 may also be used to adjust the pressure of the compressed air in the high-pressure tank 104 following changes in pressure due to temperature variations, such as due to seasonal operation of the energy storage system. As an example, during discharging operations occurring while ambient temperatures are low (such as in winter climates or cold operating regions), there may be a slight drop in the pressure of the compressed gas in the high-pressure tank (as per Charles' and Boyles' gas laws which correlate temperature and pressure of a gas). As discussed earlier, the drop in pressure may affect the power storage efficiency of the high-pressure tank. Thus, to return the compressed gas to the target high pressure (e.g., 3600 psi), the controller may transiently operate the heat exchanger 402 to raise the temperature and pressure of the compressed gas.

[0063] It will be appreciated that while the systems of FIGS. 1-5 show a single low-pressure tank coupled to a single high-pressure tank, this is not meant to be limiting. In further embodiments, the first cylinder coupled to the second cylinder may be considered a single unit of the energy storage system, and multiple such units may be coupled in series or in parallel based on the power storage requirements. For example, multiple low pressure cylinders may be coupled to each other in series, and similarly multiple high pressure cylinders may be coupled to each other in series, and the low pressure series may be coupled to the high pressure series via a common motor/generator and hydraulic pump. Furthermore, there can be multiple groupings of a single group of low-pressure and high-pressure tanks coupled with a single motor/generator and hydraulic pump. In addition, since the high-pressure tank is about twice the size in volume as the low-pressure tank, a low-pressure tank twice as big can be coupled to one high-pressure tank.

[0064] The preload pressures may also be optimized to provide a target pressure difference and a corresponding rate of pressure drop and energy transfer (and rate of electrical power generation). Example preload pressures optimized for different functions are shown at Table 1A and 1B. It will be appreciated that while the preload pressures when the storage system is fully discharged typically approximates the midpoint of the maximum pressure setting of the high-pressure tank, this may not always be the case. For example, when preload pressure is increased the volume of fluid decreases and vice versa, that is, when preload pressure is decreased the volume of fluid increases. Pressure and volume of fluid is offsetting as to the amount of power that can be stored and released but can be optimized. Depending on the cost of the various components and the interaction of pressure and fluid flows, the preload pressures may be varied to optimize the system. The optimum preload pressure for any function or configuration may be set to be in the vicinity of but not necessarily right at the midpoint of the maximum pressure setting of the high pressure gas/fluid tank.

Table 1A

Example pressure settings and associated parameters for example configurations of the energy storage system of FIGS. 1-5

	Unit of Measure	Amount	Amount	Amount	Amount	Amount	Amount	Amount
Givens								
Size of Air Tank	ft3	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Base Pressure of Tank	psi	2,500	2,400	2,300	2,200	2,100	2,000	1,900
Base Free Air	ft3	170,068	163,265	156,463	149,660	142,857	136,054	129,252
Target Pressure of Tank	psi	3,571	3,582	3,594	3,607	3,621	3,636	3,585
Size of Oil Gear Pump	in2/rpm	0.343	0.377	0.411	0.445	0.480	0.514	0.537
Revolutions/Minute	rpm	3,600	3,600	3,600	3,600	3,600	3,600	3,600
Kilowatts Charged/Cycle								
Size of Tank Charged								
For Oil	ft3	300.0	330.0	360.0	390.0	420.0	450.0	470.0
For Air	ft3	700.0	670.0	640.0	610.0	580.0	550.0	530.0
Total	ft3	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0
		0.71	0.79	0.86	0.93	1.00	1.07	1.12
Cubic Feet/Minute of Oil Charging	ft3/min	0.71	0.79	0.86	0.93	1.00	1.07	1.12
Gallons/Minute of Oil Charging	gal/min	5.36	5.89	6.42	6.95	7.50	8.03	8.39
Minutes to Charge	min/chg.	419.8	420.2	420.4	420.7	420.0	420.2	420.1
Hours to Charge	hrs./chg.	7.00	7.00	7.01	7.01	7.00	7.00	7.00
Midpoint PSI	psi	2,941	2,857	2,840	2,716	2,658	2,564	2,468
Horsepower	hp	9.2	9.8	10.6	11.0	11.6	12.0	12.1
Kilowatts/Hour	kW/hr.	6.9	7.4	8.0	8.3	8.7	9.0	9.1
Kilowatts Charged/Cycle	kw/cycle	**48**	**52**	**56**	**58**	**61**	**63**	**63**
Kilowatts/Hour	kW/hr	6.9	7.4	8.0	8.3	8.7	9.0	9.1
Percent of 1,600 Preload		**71%**	**76%**	**82%**	**85%**	**90%**	**93%**	**93%**

Note: Used 81% efficiency in computing horsepower and kilowatts.

Table 1B

Example pressure settings and associated parameters for example configurations of the energy storage system of FIGS. 1-5.

It will be appreciated that Table 1B is a continuation of Table 1A

Amount Use	Amount	Amount	Amount	Amount	Amount	Amount	Amount	Amount	Amount	Amount
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
1,800	1,700	1,600	1,500	1,400	1,300	1,200	1,100	1,000	900.0	800.0
122,449	115,646	108,844	102,041	95,238	88,435	81,633	74,830	68,027	61,224	54,422
3,600	3,617	3,636	3,571	3,590	3,611	3,636	3,667	3,571	3,600	3,636
0.571	0.606	0.640	0.663	0.697	0.731	0.766	0.799	0.823	0.857	0.891
3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600
500.0	530.0	560.0	580.0	610.0	640.0	670.0	700.0	720.0	750.0	780.0
500.0	470.0	440.0	420.0	390.0	360.0	330.0	300.0	280.0	250.0	220.0
1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0
1.19	1.26	1.33	1.38	1.45	1.52	1.60	1.67	1.71	1.79	1.86
1.19	1.26	1.33	1.38	1.45	1.52	1.60	1.66	1.71	1.79	1.86
8.92	9.47	10.00	10.36	10.89	11.42	11.97	12.48	12.86	13.39	13.92
420.3	419.8	420.0	419.9	420.1	420.2	419.8	420.5	419.9	420.1	420.2
7.01	7.00	7.00	7.00	7.00	7.00	7.00	7.01	7.00	7.00	7.00
2,400	2,297	2,222	2,113	2,000	1,912	1,791	1,692	1,563	1,429	1,311
12.5	12.7	13.0	12.8	12.7	12.7	12.5	12.3	11.7	11.2	10.7
9.4	9.5	9.7	9.6	9.5	9.6	9.4	9.2	8.8	8.4	8.0
66	**67**	**68**	**67**	**67**	**67**	**66**	**65**	**62**	**59**	**56**
9.4	9.5	9.7	9.6	9.5	9.6	9.4	9.2	8.8	8.4	8.0
96%	**98%**	**100%**	**98%**	**98%**	**98%**	**96%**	**95%**	**90%**	**86%**	**82%**

[0065] Another advantage of the disclosed system is that ambient temperature variations may only slightly affect the stored energy capacity of the system. The Ideal Gas Law says that as temperature changes, the pressure of the gas will also change. Therefore, as ambient temperatures fluctuate, so will the pressure in the high-pressure tank. Preloaded gas pressures in the high-pressure tank can be set for location (e.g., based on ambient temperature as well as altitude) and by season to optimize the energy storage of the system. For example, if the energy system preload pressure had been set when the average temperature had been set for 70 degrees Fahrenheit and now it is winter and the average temperature is 30 degrees, then the pressure of the gas must be increased as the temperature change causes a pressure drop in the high-pressure tank. Conversely if the example above is reversed, some gas may be released to accommodate an increase in pressure due to temperature increase.

[0066] In some embodiments, temperature differences may be modeled to determine the effect on the energy storage performance. Generally, if optimized by location and by season, there may be no more than a 3 to 4% loss from the optimum preload pressures. If no adjustment was made for seasonal temperature differences there may only be a loss of about 10%. As such, these may not be significant losses. In other words, the invention has an insignificant change in performance as compared to batteries which may be significantly limited in their ability to hold charge during cold weather, as well as having a reduced cycle life during hot conditions.

[0067] The materials used in the described system also render the storage system environmentally non-hazardous. In particular, the materials used may be non-flammable and easy to recycle. This may be significantly different from batteries which in some cases are flammable and in almost all cases are difficult to recycle due to the materials used to produce the chemistries required. Furthermore, no precious metals are used in the development of the described system. Many battery systems incorporate precious metals that can only be found in sometimes hostile and/or unstable countries. An availability of the precious metals may be hindering when large amounts of electrical energy are demanded. The systems described herein are not subject to such issues since they use common and easily obtainable materials.

[0068] Turning now to FIGS. 6-7, an example method for operating the system of FIGS. 1-5 is described at FIG. 6 and continued at FIG. 7. Instructions for carrying out methods 600 and 700 and the rest of the methods included herein may be executed by a controller based on instructions stored on a memory of the controller and in conjunction with signals received from sensors of the energy storage system, such as the sensors described above with reference to FIG. 1. The controller may employ actuators of the system to adjust system operation, according to the methods described below.

[0069] At 602 of FIG. 6, the method includes preloading a first, low-pressure tank and a second, high-pressure tank of an energy storage system to pressure settings selected based on various considerations of the energy storage system. The pressure settings may be selected or predetermined based on a function of the system (e.g., based on whether the system is to be primarily used for grid balancing, for short term power storage and delivery, for long term power storage and delivery), size of the system (e.g., size or capacity of the tanks, the pressure settings for a large tank being higher than the pressure settings for a smaller tank), nature of gas and hydraulic fluid used in the tanks (e.g., based on what gas is selected as the compressible gas and what oil is selected as the incompressible fluid), ambient conditions and seasonal considerations (e.g., based on whether the storage system will be housed in an indoor or outdoor location, whether the storage system will be operated in summer or winter seasons, etc.). In one example, the pressure settings may be selected to provide a pressure difference across the tanks that accounts for the above-described considerations. For example, the pressure setting may be adjusted during winter seasons as compared to summer seasons. A storage system service technician may refer to a look-up table stored in a memory of the system controller to determine the pressure settings. Then, based on the settings, the technician may preload the tanks. Preloading the tanks includes filling the corresponding tanks (which may be configured as cylinders) with a defined amount of hydraulic fluid (e.g., oil) and then coupling a gas compressor to the tanks to add compressed gas to the defined pressure setting.

[0070] At 604, it is determined if charging conditions are present. Charging conditions may be confirmed if the storage system is already 100% discharged, and if electrical power is available for operating a hydraulic fluid pump via a motor/generator. The storage system is deemed to be 100% discharged when the low-pressure tank is substantially filled with hydraulic fluid at the defined low pressure setting and the high-pressure tank is substantially filled with compressed gas at the defined high pressure setting. In one example, the low pressure setting is atmospheric pressure and the high pressure setting is 50% of a maximum achievable pressure of the compressed gas in the high-pressure tank. Electrical power may be available from a power source for operating the hydraulic fluid pump. As an example, where the electrical energy storage system is coupled to a solar power source, electrical power may be available during peak solar loading hours of a given region (such as between 9am and 4pm). As another example, where the electrical energy storage system is coupled to a wind turbine, electrical power may be available during windy conditions. As yet another example, electrical power may be available from a grid during “sleeping hours” when power demand is low, allowing for grid balancing to be performed. Therein, the storage system is charged while the power demand is low, and power is retrieved from the storage system when the power demand surges, allowing the power plant to produce power at a constant rate all through the day. If charging conditions are not met, then the method moves to 606 to maintain the status of the cylinders of the high and low-pressure tanks. This includes leaving the cylinders as is. The method optionally further moves to adjusting various cylinder parameters to maintain the pressure status of the cylinders, as elaborated below at FIG. 7. This includes performing one or more actions to address any changes in tank pressure from a target pressure for one or more of the low pressure and high-pressure tanks.

[0071] If charging conditions are confirmed, then at 608, the method includes drawing electrical power from the power source to operate the motor/generator coupling the first low pressure tank to the second high pressure tank via the hydraulic pump. In particular, the motor/generator may be operated with an output (e.g., output speed) that is based on the excess power available at the power source, or the maximum speed of the hydraulic pump and motor/generator until maximum gas pressure is obtained in the high-pressure tank. In one example, the motor/generator is operated in the motoring mode at the highest speed setting.

[0072] At 610, the method includes opening valves in the connecting pipes coupling the low pressure and high pressure tanks to the hydraulic pump, and operating the hydraulic pump via the motor/generator. As a result of pump operation, pressurized hydraulic fluid is transferred from the first, low pressure tank to the second, high pressure tank. As more hydraulic fluid is transferred into the second tank, the volume of gas existing in the second tank is compressed to a higher pressure setting. In one example, when all of the fluid has been transferred from the first tank to the second tank, the compressed gas in the second tank may reach the maximum achievable pressure setting in the fully charged state, the maximum pressure setting being about twice the original high pressure setting at the fully discharged state.

[0073] In one example, the controller may fully open a first valve coupled in a first connecting pipe between the first tank and the hydraulic pump and fully open a second valve coupled in a second connecting pipe between the second tank and the hydraulic pump. By fully opening both valves, and operating the motor/generator at the highest speed setting, fluid transfer can be enabled in the least amount of time, allowing for a quick charging of the energy storage system. In other examples, one or both of the valves may be set to a less than 100% degree of opening to control the flow rate of fluid, thereby varying the rate of charge transfer. Another way is to restrict the power to the motor generator so as to lower the speed of charge. In one example, a slower rate of charge transfer may be desired when there is a low amount of power available to store. By transferring the hydraulic fluid from the low-pressure tank to the high-pressure tank, and pressurizing the gas in the high-pressure tank via electric actuation of the motor/generator, the electrical power drawn from the energy source is stored in the form of compressed gas in the high-pressure tank of the energy storage system.

[0074] After the charge transfer is completed, at 612, the method includes fully closing the valves. The controller may then update the controller's memory with an amount of power stored in the high pressure tank. The estimation may be based on a duration of motor operation and a final pressure setting of the gas compressed in the high pressure tank. For example, if the final pressure setting is the maximum achievable pressure setting of the high pressure tank, the tank may be determined to be 100% charged and a corresponding energy amount (e.g., in terms of kilowatts of energy) may be learned and stored in the memory of the controller.

[0075] At 614, it is determined if discharging conditions are present. Discharging conditions may be confirmed if the storage system is already 100% charged, and if electrical power is required to be drawn into the power plant, such as for grid balancing (or for operating a device electrically coupled to the storage system). The storage system is deemed to be 100% charged when the high-pressure tank is approximately 50% filled with hydraulic fluid at the maximum achievable pressure setting and the low-pressure tank is substantially filled with gas at the defined low pressure setting. Electrical power may be required at the power source for grid balancing, or to meet a peak or other transient power demand. As an example, where the electrical energy storage system is coupled to a solar power source, electrical power may be demanded during off-peak solar loading hours of a given region (such as between 9pm and 4am). As another example, electrical power may be required at the power source during "waking hours" when power demand is high, allowing for power source balancing to be performed. If discharging conditions are not met, then the method moves to 616 to maintain the status of the cylinders of the high and low-pressure tanks. This includes leaving the tanks as is. The method optionally further moves to adjusting various cylinder parameters to maintain the pressure status of the tanks, as elaborated below at FIG. 7. This includes performing one or more actions to address any changes in tank pressure from a target pressure for one or more of the low pressure and high-pressure tanks.

[0076] If discharging conditions are confirmed, then at 618, the method includes opening valves in the connecting pipes coupling the first and second cylinders to each other via a hydraulic pump, and driving the hydraulic pump via the ensuing hydraulic flow. As a result of valve opening, and due to the pressure difference across the tanks, the compressed gas in the second tank forces the hydraulic fluid to flow from the second tank towards the lower pressure first tank. This flow continues until the tanks have equilibrated. As hydraulic fluid flows from the second tank to the first tank through the reversible pump, the motor generator is driven, producing power which is delivered to the power source. In one example, hydraulic fluid flow continues until substantially all the hydraulic fluid has been transferred from the second tank into the first tank. When all of the fluid has been transferred, the compressed gas in the second tank may reach the default pressure setting of the fully discharged state, which may be half the maximum pressure setting at the fully charged state.

[0077] In one example, the controller may fully open the first valve coupled in the first connecting pipe between the first tank and the hydraulic pump and fully open the second valve coupled in the second connecting pipe between the second tank and the hydraulic pump. By fully opening both valves, fluid transfer can be enabled in the smallest amount of time, allowing for a quick discharging of the energy storage system. In other examples, one or both of the valves may be set to a less than 100% degree of opening to control the flow rate of fluid, thereby varying the rate of charge transfer. In one example, a slower rate of charge transfer may be desired when the demand for power to the power source is low.

[0078] At 620, the method includes operating the motor/generator in a generating mode via the hydraulic pump to generate electrical power during hydraulic fluid transfer. The generated electrical power is then transferred to the power source. In particular, the hydraulic pump that is driven by the hydraulic fluid flow may in turn drive the motor/generator which operates in a generating mode to generate electrical power. The motor/generator may be operated with an output (e.g., output speed) between the demand for power and the maximum speed of the reversible hydraulic pump and motor/generator until design transfer of fluid has been achieved. In one example, the motor/generator is operated in the generating mode at the highest speed setting. By transferring the hydraulic fluid from the high-pressure tank to the low-pressure tank and depressurizing the gas in the high-pressure tank while harnessing the depressurization power in the form of electrical energy at the motor/generator, the compressed gas in the high-pressure tank of the energy storage system is converted back into electrical power that is returned to the power source for use.

[0079] Turning now to FIG. 7, a method 700 is shown for adjusting various parameters of the cylinders so as to maintain pressure settings and reduce charge loss due to pressure loss. At 702, the method includes determining if there is an indication of gas ingress into hydraulic fluid in the second, high pressure cylinder. In one example, where a pressure sensor is coupled to the high pressure tank, gas ingress may be identified responsive to a drop in pressure reading from the pressure setting read when the high pressure tank was 100% charged. In another example, gas ingress may be determined by build-up of gas pressure in the low-pressure tank. Herein, the pressure setting of the high-pressure tank may be continuously monitored.

[0080] If gas ingress is indicated, then at 704, the method includes temporarily operating a gas compressor to remove gas from the low-pressure tank and transfer it back into the high-pressure tank. The gas compressor may be operated for a duration until the pressure setting is returned to the pressure settings for either the low-pressure tank and/or the high-pressure tank when the energy system was fully discharged. Another approach is to use a gas compressor as shown in the embodiment of FIG. 3 which may be used to address the gas ingress. Other approaches for addressing gas ingress may be used, such as membranes, bladders, and pistons, as discussed earlier.

[0081] At 706, it may be determined if the pressure of the compressed gas in the second cylinder is outside the target setting. This may include where the pressure setting is higher or lower than the target setting. Pressure variations may occur due to temperature fluctuations in the cylinder's environment, such as during summer versus winter seasons, or based on whether the cylinder is housed in an outdoor or indoor location. One method is to use a gas compressor when pressure needs to be raised and a pressure relief valve to remove excess pressure.

[0082] If there is a pressure change due to a temperature fluctuation, then at 708, another method includes operating a heat exchanger, or other heating/cooling system, to continuously heat/cool the compressed gas to the target temperature and pressure. For example, if the pressure has dropped below the target, as inferred based on input from a pressure sensor coupled to the second cylinder, then the heat exchanger may be operated to heat the compressed air and raise the pressure. In one example, the heat exchanger of the embodiment of FIGS. 4-5 may be used to address the pressure fluctuation.

[0083] In still further examples, continuous heating/cooling of the high-pressure tank may be used to improve the power storage efficiency of the system. For example, after charging the high-pressure tank, heating of the high-pressure tank may be used to further increase the pressure of the compressed gas, thereby increasing the power stored therein. As another example, after discharging the high-pressure tank, cooling of the high-pressure tank may be used to further decrease the pressure of the compressed gas, thereby increasing the power receiving ability of the given volume of compressed gas in the high-pressure tank.

[0084] An alternate embodiment of a compressed gas based energy storage system 1100 is illustrated in FIGS. 11-12. The energy storage system 1100 includes a first, low pressure side 1102 (e.g., atmospheric pressure) and a second, high pressure side 1104. Instead of tanks, the first and second sides 1102, 1104 may include a ground level fluid reservoir, such as a pond or other body of water, at the first side 1102 and a subterranean reservoir, such as an oil well or coal mine, at the second side 1104. In this way, the energy storage system 1100 may leverage a presence of already existing, large-scale reservoirs capable of high pressure storage. For example, an oil well used in fracking may have a volume of 467,000 ft^3, thus able to store large quantities of air and water. The first side 1102 of the energy storage system 1100 may be open to the atmosphere, e.g., an open system, and store an incompressible hydraulic fluid such as water. The second side 1104 may be a sealed or closed system and store both a compressible gas, such as air, and water at high pressure. In one example, the air may be preloaded to between 2,500 to 15,000 psi. In another example, the air may be preloaded to between 2,500 to 7,500 psi. In one example, the preloaded air pressure may be 2,500 psi. In other examples, the compressible gas may be another type of gas, as described above, such as nitrogen.

[0085] FIG. 11 shows the energy storage system 1100 in a charged state. In the charged state, the first side 1102 is mostly filled with air at atmospheric pressure with a small volume of water. The second side 1104 is air compressed to, for example, 2,500 psi, and a large volume of water. For example, the second side 1104 may be 50% compressed air and 50% water. The first side 1102 and the second side 1104 may be fluidically coupled by a hydraulic reversible pump 1108 (similar to the pump 108 of FIGS. 1-5), with a first, low-pressure line 1110 extending between the first side 1102 and the pump 1108 and a second, high-pressure line 1112 extending between the second side 1104 and the pump 1108. The first line 1110 includes a first valve 1114 controlling flow through the first line 1110 and the second line 1112 includes a second valve 1116 controlling flow through the second line 1112, the first valve 1114 and the second valve 1116 similar to the valves 112, 110, respectively, of FIGS. 1-5.

[0086] During charging of the energy storage system 1100, mechanical operation of the pump 1108 in a first direction may force water from the first side 1102, through the first line 1110 with the first valve 1114 in an open position, through the second line 1112 with the second valve 1116 in an open position, and into the second side 1104. Pressure at the second side 1104 rises as water is pumped in. The mechanical operation of the pump 1108 in the first direction is driven by motor/generator 1118, similar to motor/generator 106 of FIGS. 1-5. The first and second valves 1114, 1116 may be closed once the energy storage system reaches a fully charged state. During discharging of the energy storage system 1100, the high pressure at the second side 1104 drives flow of water from the second side 1104 to the first side 1102, when the first and second valves 1114, 1116 are open, generating electrical power at the motor/generator 1118 which may be stored as described above.

[0087] The energy storage system 1100 is shown in a discharged state in FIG. 12. In the discharged state, the first side 1102 is filled with water at atmospheric pressure. A volume of water in the second side 1104 is decreased. For example, the volume of the second side 1104 may be 90% air and 10% water. The increase in air volume relative to the charged state reduces the air pressure from 5,000 psi to 2,500 psi. As described above, the charging and discharging of the energy storage system 1100 may be performed via a controller, such as the controller 12 shown in FIG. 1.

[0088] Utilization of abandoned oil wells and coal mines as high-pressure reservoirs for compressed gas based energy storage systems may yield large quantities of stored energy for high energy-consuming applications. For example, in the U.S., approximately 2.11 trillion ft^3 may be attributed to coal mines and 1.3 trillion ft^3 to oil wells.

[0089] Another example embodiment of a compressed gas based energy storage system is shown with reference to FIGS. 8-9. In the embodiment of FIGS. 8-9, the compressed gas is liquefied at higher pressure settings. Components previously introduced in earlier embodiments are numbered similarly and not described again for reasons of brevity.

[0090] FIGS. 8-9 show an example embodiment 800 of a compressed gas based electric energy storage system including a first low-pressure fluid/gas tank 102 coupled to a second-high-pressure fluid/gas tank 104. FIG. 8 shows a discharged setting, while FIG. 9 shows a charged setting. In one example, the low-pressure fluid/gas tank is at atmospheric pressure.

[0091] The system is a closed storage system in that none of the tanks are coupled to the atmosphere. Rather, the contents of each tank are sealed from the atmosphere and are only fluidically coupled to each other when hydraulic pump 108 is operated.

[0092] Each of the tanks 102, 104 is preloaded with an incompressible hydraulic fluid and a compressible gas to a defined pressure setting. In particular, an incompressible hydraulic fluid, depicted in the present example as hydraulic oil, is stored in the low-pressure tank 102 at a lower pressure than the pressure setting of the high-pressure tank 104. For example, the fluid in the low-pressure tank 102 may be stored at atmospheric pressure or 14.7 psi, as in the depicted example. The low-pressure tank also stores a compressible gas at the lower pressure setting. In the depicted example, the compressible gas is a gas that turns into liquid when compressed to a higher pressure setting. Therefore, the maximum achievable pressure setting of the high-pressure tank 104 is selected to be at or higher than the pressure setting at which the compressible gas turns into liquid. As an example, if the phase change from gas to liquid occurs at 3400 psi, the high-pressure tank 104 may be preloaded to 3600 psi.

[0093] The material of the high pressure tank 104 may any of the materials described above with reference to FIGS. 1-5 if a chemically compatible type of gas is used. In some examples, the high pressure tank 104 may be formed of materials providing increased chemical resistance to non-inert gases. For example, the high pressure tank 104 may also be formed from the materials described above and combined with a metal-free inner liner such as a polytetrafluoroethylene liner.

[0094] In some examples, the compressible gas and the incompressible fluid of FIGS. 8-9 may cycled between a first, ground-level side at atmospheric pressure and a second, subterranean, high pressure side, similar to the energy storage system 1100 depicted in FIGS. 11 and 12. As such, the compressible gas may be compressed to a liquid at the second side, when the compressible gas is not air but a gas with a suitable phase change pressure within a pressure range of the second side, provided the second side is at a suitable temperature. Although the first side is an open system and open to the atmosphere, loss of the compressible gas is precluded due to the second side remaining a closed system and cycling of the compressible gas between high and moderate pressure.

[0095] The compressible gas selected for compression in the example embodiment 800 shown in FIGS. 8-9 may be of a type with a critical temperature at least above room temperature to preclude energy costly methods of maintaining the high pressure tank 104 at below room temperature. A pressure at which the gas condenses to a liquid may be lower than a maximum pressure tolerance of the high pressure tank 104. Examples of gases which may be compressed into a liquid in the example embodiment 800 includes nitrous oxide, ethane, carbon dioxide, ammonia, and propane, amongst others.

[0096] When in a discharged state, a majority of the volume of the low-pressure tank 102 is occupied by the incompressible fluid while a remaining volume is occupied by the compressible/liquefiable low or near atmospheric pressure gas. In one example, when the system 100 is fully discharged, a ratio of oil to gas in the low-pressure tank 102 is about 98%:2%. In the embodiment of FIGS. 1-2, the compressible gas is preloaded in the high-pressure tank 104 and set to approximate 50% of the maximum achievable pressure of the high-pressure tank. Then, due to the hydraulic fluid transfer from the low-pressure tank to the high-pressure tank, the compressed gas is pressurized to change from occupying ~98% of the tank volume to occupying ~50% of the tank volume. However, in the embodiment of FIGS. 8-9, upon compression, the compressible gas is turned to liquid, changing its density and allowing it to occupy a smaller volume. As a result of the change in density, more space is created for transferring and storing the hydraulic fluid, allowing more of the hydraulic fluid to be stored. In the embodiment of FIGS. 1-2, only 50% of additional fluid transfer could occur from the low-pressure tank 102 to the high-pressure tank 104 since the compressed gas occupied the remaining volume. In the embodiment of FIGS. 8-9, since the gas is compressed and liquefied by the pressure caused by the hydraulic fluid transfer, at the maximum achievable pressure in the high-pressure tank, the liquefied gas may then occupy a smaller volume than 50%, allowing for more hydraulic fluid to be transferred. As an example, as shown in FIGS. 8-9, 90% of the hydraulic fluid can be transferred from the low-pressure tank to the high-pressure tank. Thus, when the energy system is fully charged, as shown in FIG. 9, the volume of fluid remaining in the low-pressure tank is about 2% and the high-pressure tank fluid is about 90% with the remaining 10% as liquefied gas. In this way, the change in density of the compressible gas upon liquefaction is taken advantage of. Due to the large change in densities, more space is created, allowing for transfer of more hydraulic fluid. As an example, carbon dioxide gas is 9 times denser following a phase change at or above 918 psi.

[0097] Compare, for example, the midpoint pressure of the high-pressure tank and the volume of the high-pressure tank that is filled with fluid for a base case, as described with reference to the embodiment of FIGS. 1-2, with the phase change case described with reference to the embodiments of FIGS. 8-9. In the base case, the midpoint pressure may be 2700 psi and the fluid volume in the tank may be 50%. In the phase change case, the midpoint pressure may be 3500 psi and the fluid volume in the tank may be 90%.

[0098] The midpoint pressure is higher and the volume of fluid is greater for the phase change scenario. Since energy stored is computed by computing volume of fluid times pressure times a constant, in the example case, there is a 230% increase in energy stored. Since the tank cost is the same, the overall leveled cost of energy stored is dropped from 3.9 cents to 1.7 cents per kWh stored, providing an almost 60% savings. It may be possible to further optimize the system and get the total cost to under 3 cents/kWh, which would render this solution comparable to pumped water storage solutions.

[0099] Turning now to FIG. 10, an example method for operating the system of FIGS. 8-9 is described. Instructions for carrying out method 1000 may be executed by a controller based on instructions stored on a memory of the controller and in conjunction with signals received from sensors of the energy storage system, such as the sensors described above with reference to FIGS. 1-5, and 8-9. The controller may employ actuators of the system to adjust system operation, according to the methods described below.

[00100] At 1002, the method includes preloading a first, low-pressure tank and a second, high-pressure tank of an energy storage system to pressure settings selected based on various considerations of the energy storage system. The pressure settings may be selected or predetermined based on a function of the system (e.g., based on whether the system is to be primarily used for grid balancing, for short term power storage and delivery, for long term power storage and delivery), size of the system (e.g., size or capacity of the tanks, the pressure settings for a large tank being higher than the pressure settings for a smaller tank), nature of gas and hydraulic fluid used in the tanks (e.g., based on what gas is selected as the compressible gas and what oil is selected as the incompressible fluid), ambient conditions and seasonal considerations (e.g., based on whether the storage system will be housed in an indoor or outdoor location, whether the storage system will be operated in summer or winter seasons, etc.). Preloading the tanks includes filling the corresponding tanks (which may be configured as cylinders) with a defined amount of hydraulic fluid (e.g., oil) and then coupling a gas compressor to the tanks to add compressed gas to the defined pressure setting.

[00101] In other examples, the hydraulic fluid may be flowed between a ground-level reservoir at atmospheric, such as a pond, and a subterranean reservoir at higher pressure, such as an oil well or coal line, as described above with reference to FIGS. 11 and 12. In such instances, the system may be operated similarly, with the nature of the gas and hydraulic fluid, ambient conditions, seasonal considerations, etc. taken into account. The subterranean reservoir may be preloaded to a specific pressure according to a predetermined pressure tolerance of the reservoir to compress the gas to a desired level.

[00102] At 1004, it is determined if charging conditions are present. Charging conditions may be confirmed if the storage system is already 100% discharged, and if electrical power is available for operating a hydraulic fluid pump via a motor/generator. The storage system is deemed to be 100% discharged when the low-pressure tank is substantially filled with hydraulic fluid at the defined low pressure setting and the high-pressure tank is substantially filled with compressed gas at the defined high pressure setting. If charging conditions are not met, then the method moves to 1006 to maintain the status of the cylinders of the high and low-pressure tanks. This includes leaving the cylinders as is.

[00103] If charging conditions are confirmed, then at 1008, the method includes drawing electrical power from the power source to operate the motor/generator coupling the first low pressure tank to the second high-pressure tank. In particular, the motor/generator may be operated with an output (e.g., output speed) that is based on the excess power available at the power source, or the maximum speed of the hydraulic pump and motor/generator until maximum gas pressure is obtained in the high-pressure tank. In one example, the motor/generator is operated in the motoring mode at the highest speed setting.

[00104] At 1010, the method includes opening valves in the connecting pipes coupling the low pressure and high pressure tanks to a hydraulic pump, and operating the hydraulic pump via the motor/generator. As a result of pump operation, pressurized hydraulic fluid is transferred from the first, low pressure tank to the second, high pressure tank. As more hydraulic fluid is transferred into the second tank, the volume of gas existing in the second tank is compressed to a higher pressure setting. In one example, when all of the fluid has been and transferred from the first tank to the second tank, the compressed gas in the second tank may reach the maximum achievable pressure setting in the fully charged state, causing the compressed gas to liquefy. The resulting increase in density allows the now liquefied gas to occupy a smaller volume, and also enables additional hydraulic fluid to be the transferred from the low-pressure tank to the high-pressure tank. In one example, the high pressure compression of the gas to a liquid allows hydraulic fluid transfer so that upon completion of charging, the hydraulic fluid occupies 90% of the volume of the high-pressure tank. As a result, the average maximum pressure setting in the high-pressure tank is significantly higher than the original high pressure setting at the fully discharged state.

[00105] In one example, the controller may fully open a first valve coupled in a first connecting pipe between the first tank and the hydraulic pump and fully open a second valve coupled in a second connecting pipe between the second tank the hydraulic pump. By fully opening both valves, and operating the motor/generator at the highest speed setting, fluid transfer can be enabled in the least amount of time, allowing for a quick charging of the energy storage system. In other examples, one or both of the valves may be set to a less than 100% degree of opening to control the flow rate of fluid, thereby varying the rate of charge transfer. By transferring the hydraulic fluid from the low-pressure tank to the high-pressure tank, and pressurizing the gas in the high-pressure tank via electric actuation of the motor/generator, the electrical power drawn from the energy source is stored in the form of liquefied gas in the high-pressure tank of the energy storage system.

[00106] After the charge transfer is completed, at 1012, the method includes fully closing the valves. The controller may then update the controller's memory with an amount of power stored in the high pressure tank. The estimation may be based on a duration of motor operation and a final pressure setting of the gas compressed in the high pressure tank. For example, if the final pressure setting is the maximum achievable pressure setting of the high pressure tank, the tank may be determined to be 100% charged and a corresponding energy amount (e.g., in terms of kilowatts of energy) may be learned and stored in the memory of the controller.

[00107] At 1014, it is determined if discharging conditions are present. Discharging conditions may be confirmed if the storage system is already 100% charged, and if electrical power is required to be drawn into the power plant, such as for grid balancing (or for operating a device electrically coupled to the storage system). The storage system is deemed to be 100% charged when the high-pressure tank is approximately 90% filled with hydraulic fluid at the maximum achievable pressure setting and the low-pressure tank is substantially filled with gas at the defined low pressure setting. Electrical power may be required at the power source for grid balancing, or to meet a peak or other transient power demand. If discharging conditions are not met, then the method moves to 1016 to maintain the status of the cylinders of the high and low-pressure tanks. This includes leaving the tanks as is.

[00108] If discharging conditions are confirmed, then at 1018, the method includes opening valves in the connecting pipes coupling the first and second cylinders to each other via a hydraulic pump, and driving the hydraulic pump via the ensuing hydraulic flow. As a result of valve opening, and due to the pressure difference across the tanks, the high pressure liquefied gas in the second tank decompresses to compressed gas, and forces the hydraulic fluid to flow from the second tank towards the first tank at the lower pressure. This flow continues until the tanks have equilibrated. As hydraulic fluid flows from the second tank to the first tank through the reversible pump, the motor generator is driven producing power delivered to the power source. In one example, hydraulic fluid flow continues until substantially all the hydraulic fluid has been transferred from the second tank into the first tank. When all of the fluid has been transferred, the compressed gas in the second tank may reach the default pressure setting of the fully discharged state.

[00109] In one example, the controller may fully open the first valve coupled in the first connecting pipe between the first tank and the hydraulic pump and fully open the second valve coupled in the second connecting pipe between the second tank and the hydraulic pump. By fully opening both valves, fluid transfer can be enabled in the smallest amount of time, allowing for a quick discharging of the energy storage system. In other examples, one or both of the valves may be set to a less than 100% degree of opening to control the flow rate of fluid, thereby varying the rate of charge transfer. In one example, a slower rate of charge transfer may be desired when the demand for power to the power source is low.

[00110] At 1020, the method includes operating the motor/generator in a generating mode via the hydraulic pump to generate electrical power during hydraulic fluid transfer. The generated electrical power is then transferred to the power source. In particular, the hydraulic pump that is driven by the hydraulic fluid flow may in turn drive the motor/generator which operates in a generating mode to generate electrical power. The motor/generator may be operated with an output (e.g., output speed) between the demand for power and the maximum speed of the reversible hydraulic pump and motor/generator until design transfer of fluid has been achieved. In one example, the motor/generator is operated in the generating mode at the highest speed setting. By transferring the hydraulic fluid from the high-pressure tank to the low-pressure tank and depressurizing the liquefied gas in the high-pressure tank while harnessing the depressurization power in the form of electrical energy at the motor/generator, the compressed gas in the high-pressure tank of the energy storage system is converted back into electrical power that is returned to the power source for use. Note that the example control and estimation routines included herein can be used with various system configurations. The control methods and routines disclosed herein may be stored as executable instructions in non-transitory memory and may be carried out by the control system including the controller in combination with the various sensors, actuators, and other hardware. The specific routines described herein may represent one or more of any number of processing strategies such as event-driven, interrupt-driven, multi-tasking, multi-threading, and the like. As such, various actions, operations, and/or functions illustrated may be performed in the sequence illustrated, in parallel, or in some cases omitted. Likewise, the order of processing is not necessarily required to achieve the features and advantages of the example embodiments described herein, but is provided for ease of illustration and description. One or more of the illustrated actions, operations and/or functions may be repeatedly performed depending on the particular strategy being used. Further, the described actions, operations and/or functions may graphically represent code to be programmed into non-transitory memory of the computer readable storage medium in the engine control system, where the described actions are carried out by executing the instructions in a system including the various engine hardware components in combination with the electronic controller.

[00111] It will be appreciated that the configurations and routines disclosed herein are exemplary in nature, and that these specific embodiments are not to be considered in a limiting sense, because numerous variations are possible. The subject matter of the present disclosure includes all novel and non-obvious combinations and sub-combinations of the various systems and configurations, and other features, functions, and/or properties disclosed herein.

[00112] In one embodiment a system includes a first tank storing an incompressible hydraulic fluid and a compressible gas preloaded to a first pressure setting, a second tank storing the incompressible hydraulic fluid and the compressible gas preloaded to a second pressure setting, higher than the first pressure setting, a reversible hydraulic fluid pump fluidically coupled to each of the first and second tank via corresponding connecting pipes, and a DC motor/generator mechanically coupled to the fluid pump and electrically coupled to an electrical power source. In a first example of the system, the system is sealed from atmosphere. A second example of the system optionally includes the first example, and further includes one or more valves coupled to the connecting pipes, wherein flow of hydraulic fluid through the pipes is varied via a position of the valves. A third example of the system optionally includes one or more of the first and second examples, and further includes a controller with executable instructions for drawing electrical power from the power source to actuate the motor/generator, driving the fluid pump via the motor/generator with the one or more valves open to transfer hydraulic fluid from the first tank into the second tank, and pressurize the compressible gas in the second tank via the hydraulic fluid transfer, the hydraulic fluid and compressible gas pressurized to a third pressure setting, higher than the second pressure setting. A fourth example of the system optionally includes one or more of the first through third examples, and further includes, wherein pressuring the compressible gas results in a phase change of the gas to liquid form. A fifth example of the system optionally includes one or more of the first through fourth examples, and further includes a controller with executable instructions for transferring the hydraulic fluid with the one or more valves open from the second tank to the first tank via depressurizing of the pressurized compressible gas from the third pressure setting to the second pressure setting, generating electrical power by driving the motor/generator via the transferring of the fluid, and transmitting the generated electrical power to a grid or power source. A sixth example of the system optionally includes one or more of the first through fifth examples, and further includes a heat exchanger coupled to a top region of the second tank, and wherein the controller includes instructions for flowing a heated/cooling fluid through the heat exchanger and transferring heat from the heated/cooling fluid to the compressed gas in the second tank, the flowing responsive to an output of a pressure sensor coupled to the second tank. A seventh example of the system optionally includes one or more of the first through sixth examples, and further includes a gas-fluid separator coupled at an interface of the gas and the fluid in the second tank, the separator including one of a membrane, a bladder, and a piston. An eighth example of the system optionally includes one or more of the first through seventh examples, and further includes, wherein the hydraulic fluid has a higher density than the compressible gas and wherein in each of the first and second tank, the compressible gas is layered on top of the hydraulic fluid. A ninth example of the system optionally includes one or more of the first through eighth examples, and further includes a gas compressor coupled between the first and second tank wherein the controller includes instructions for operating the compressor to lower pressure in the first tank and raise the pressure of the compressed gas in the second tank responsive to an indication of gas ingress into the fluid at the second tank, the indication based on an output of a pressure sensor coupled to and/or the first or second tank. A tenth example of the system optionally includes one or more of the first through ninth examples, and further includes a gas-fluid separator coupled between the hydraulic pump and the second tank, the separator including one of a membrane and a gas compressor between the gas-fluid separator and the second tank. An eleventh example of the system optionally includes one or more of the first through tenth examples, and further includes a controller, wherein the controller includes executable instructions for operating the compressor to increase pressure in the gas-fluid separator and raise the pressure of the compressed gas in the second tank, wherein the compressor executes instructions to increase pressure responsive to an indication of gas ingress into the fluid at the second tank, the indication based on an output of a pressure sensor coupled to the gas-fluid separator or second tank.

[00113] In another embodiment, a system includes a first tank storing an incompressible hydraulic fluid and a compressible gas preloaded to a first pressure setting, a second tank storing the incompressible hydraulic fluid and the compressible gas preloaded to a second pressure setting, higher than the first pressure setting, a reversible hydraulic fluid pump fluidically coupled to each of the first and second tank via corresponding connecting pipes, a DC motor/generator mechanically coupled to the fluid pump and electrically coupled to an electrical power source, and a controller with executable instructions stored on non-transitory memory that when executed cause the controller to transfer, via operation of the pump and the DC motor, the hydraulic fluid from the first tank to the second tank while pressurizing the compressible gas into a liquid form. In a first example of the system, the controller has further instructions that cause the controller to transfer, via operation of the pump and the DC generator, the hydraulic fluid from the second tank to the first tank while depressurizing the compressible gas from the liquid form to gaseous form.

[00114] In yet another embodiment, a method includes, responsive to confirmation of charging conditions, activating a motor/generator as a motor to operate a fluid pump in a first direction to deliver an incompressible fluid from a first tank to a second tank, the second tank at a higher pressure than the first tank and fluidically coupled to the first tank by the fluid pump, and, responsive to confirmation of discharging conditions, opening valves positioned between the first tank and the second tank to flow the first fluid from the second tank to the first tank, wherein the flow of the incompressible fluid drives operation of the fluid pump in a second direction, opposite of the first direction to operate the motor/generator as a generator. In a first example of the method, delivering the incompressible fluid from the first tank to the second tank includes increasing a pressure in the second tank to pressurize a compressible gas in the second tank and wherein delivering the incompressible fluid from the second tank to the first tank includes decreasing the pressure in the second tank. A second example of the method optionally includes the first example, and further includes, wherein pressurizing the compressible gas in the second tank includes liquefying the compressible gas. A third example of the method optionally includes one or more of the first and second examples, and further includes, wherein decreasing the pressure in the second tank includes decompressing the liquefied compressible gas to a compressed gas. A fourth example of the method optionally includes one or more of the first through third examples, and further includes, wherein operating the motor/generator as a motor includes drawing electrical energy from a power source coupled to the motor/generator to power the motor/generator. A fifth example of the method optionally includes one or more of the first through fourth examples, and further includes, wherein operating the motor/generator as a generator includes generating electrical power when the motor/generator is operated in the second direction and delivering the electrical power to the power source.

[00115] A used herein, the term “approximately” is construed to mean plus or minus five percent of the range unless otherwise specified.

[00116] The following claims particularly point out certain combinations and sub-combinations regarded as novel and non-obvious. These claims may refer to “an” element or “a first” element or the equivalent thereof. Such claims should be understood to include incorporation of one or more such elements, neither requiring nor excluding two or more such elements. Other combinations and sub-combinations of the disclosed features, functions, elements, and/or properties may be claimed through amendment of the present claims or through presentation of new claims in this or a related application. Such claims, whether broader, narrower, equal, or different in scope to the original claims, also are regarded as included within the subject matter of the present disclosure.

CLAIMS:

1. An electrical power storage system, comprising:

a first tank storing an incompressible hydraulic fluid and a compressible gas preloaded to a first pressure setting;

a second tank storing the incompressible hydraulic fluid and the compressible gas preloaded to a second pressure setting, higher than the first pressure setting;

a reversible hydraulic fluid pump fluidically coupled to each of the first and second tank via corresponding connecting pipes; and

a DC motor/generator mechanically coupled to the fluid pump and electrically coupled to an electrical power source.

2. The system of claim 1, wherein the system is sealed from atmosphere.

3. The system of claim 1, further comprising one or more valves coupled to the connecting pipes, wherein flow of hydraulic fluid through the pipes is varied via a position of the valves.

4. The system of claim 3, further comprising a controller with executable instructions for:

drawing electrical power from the power source to actuate the motor/generator;

driving the fluid pump via the motor/generator with the one or more valves open to transfer hydraulic fluid from the first tank into the second tank; and

pressurize the compressible gas in the second tank via the hydraulic fluid transfer, the hydraulic fluid and compressible gas pressurized to a third pressure setting, higher than the second pressure setting.

5. The system of claim 4, wherein pressuring the compressible gas results in a phase change of the gas to liquid form.

6. The system of claim 4, further comprising a controller with executable instructions for:

transferring the hydraulic fluid with the one or more valves open from the second tank to the first tank via depressurizing of the pressurized compressible gas from the third pressure setting to the second pressure setting;

generating electrical power by driving the motor/generator via the transferring of the fluid; and

transmitting the generated electrical power to a grid or power source.

7. The system of claim 6, further comprising a heat exchanger coupled to a top region of the second tank, and wherein the controller includes instructions for flowing a heated/cooling fluid through the heat exchanger and transferring heat from the heated/cooling fluid to the compressed gas in the second tank, the flowing responsive to an output of a pressure sensor coupled to the second tank.

8. The system of claim 6, further comprising a gas-fluid separator coupled at an interface of the gas and the fluid in the second tank, the separator including one of a membrane, a bladder, and a piston.

9. The system of claim 1, wherein the hydraulic fluid has a higher density than the compressible gas and wherein in each of the first and second tank, the compressible gas is layered on top of the hydraulic fluid.

10. The system of claim 1, further comprising a gas compressor coupled between the first and second tank wherein the controller includes instructions for operating the compressor to lower pressure in the first tank and raise the pressure of the compressed gas in the second tank responsive to an indication of gas ingress into the fluid at the second tank, the indication based on an output of a pressure sensor coupled to and/or the first or second tank.

11. The system of claim 1, further comprising a gas-fluid separator coupled between the hydraulic pump and the second tank, the separator including one of a membrane and a gas compressor between the gas-fluid separator and the second tank.

12. The system of claim 1, further comprising a controller, wherein the controller includes executable instructions for:

operating the compressor to increase pressure in the gas-fluid separator and raise the pressure of the compressed gas in the second tank, wherein the compressor executes instructions to increase pressure responsive to an indication of gas ingress into the fluid at the second tank, the indication based on an output of a pressure sensor coupled to the gas-fluid separator or second tank.

13. An electrical power storage system, comprising:

a first tank storing an incompressible hydraulic fluid and a compressible gas preloaded to a first pressure setting;

a second tank storing the incompressible hydraulic fluid and the compressible gas preloaded to a second pressure setting, higher than the first pressure setting;

a reversible hydraulic fluid pump fluidically coupled to each of the first and second tank via corresponding connecting pipes;

a DC motor/generator mechanically coupled to the fluid pump and electrically coupled to an electrical power source; and

a controller with executable instructions stored on non-transitory memory that when executed cause the controller to:

transfer, via operation of the pump and the DC motor, the hydraulic fluid from the first tank to the second tank while pressurizing the compressible gas into a liquid form.

14. The system of claim 13, wherein the controller has further instructions that cause the controller to:

transfer, via operation of the pump and the DC generator, the hydraulic fluid from the second tank to the first tank while depressurizing the compressible gas from the liquid form to gaseous form.

15. A method for operating an electrical power storage system, comprising:

responsive to confirmation of charging conditions;

activating a motor/generator as a motor to operate a fluid pump in a first direction to deliver an incompressible fluid from a first tank to a second tank, the second tank at a higher pressure than the first tank and fluidically coupled to the first tank by the fluid pump; and

responsive to confirmation of discharging conditions;

opening valves positioned between the first tank and the second tank to flow the first fluid from the second tank to the first tank, wherein the flow of the incompressible fluid drives operation of the fluid pump in a second direction, opposite of the first direction to operate the motor/generator as a generator.

16. The method of claim 15, wherein delivering the incompressible fluid from the first tank to the second tank includes increasing a pressure in the second tank to pressurize a compressible gas in the second tank and wherein delivering the incompressible fluid from the second tank to the first tank includes decreasing the pressure in the second tank.

17. The method of claim 16, wherein pressurizing the compressible gas in the second tank includes liquefying the compressible gas.

18. The method of claim 17, wherein decreasing the pressure in the second tank includes decompressing the liquefied compressible gas to a compressed gas.

19. The method of claim 15, wherein operating the motor/generator as a motor includes drawing electrical energy from a power source coupled to the motor/generator to power the motor/generator.

20. The method of claim 19, wherein operating the motor/generator as a generator includes generating electrical power when the motor/generator is operated in the second direction and delivering the electrical power to the power source.

AMENDED CLAIMS
received by the International Bureau on 21 August 2020 (21.08.2020)

CLAIMS:

1. An electrical power storage system, comprising:

a first tank storing an incompressible hydraulic fluid and a compressible gas preloaded to a first pressure setting;

a second tank storing the incompressible hydraulic fluid and the compressible gas preloaded to a second pressure setting, higher than the first pressure setting;

a reversible hydraulic fluid pump fluidically coupled to each of the first and second tank via corresponding connecting pipes; and

a DC motor/generator mechanically coupled to the fluid pump and electrically coupled to an electrical power source;

one or more valves coupled to the connecting pipes, wherein flow of hydraulic fluid through the connecting pipes is varied via a position of the valves; and

a controller with executable instructions for:

drawing electrical power from the power source to actuate the motor/generator;

driving the fluid pump via the motor/generator with the one or more valves open to transfer hydraulic fluid from the first tank into the second tank; and

pressurizing the compressible gas in the second tank via the hydraulic fluid transfer, the hydraulic fluid and compressible gas pressurized to a third pressure setting, higher than the second pressure setting.

2. The system of claim 1, wherein the system is sealed from atmosphere.

3.

4.

5. The system of claim 1, wherein pressuring the compressible gas results in a phase change of the gas to liquid form.

6. The system of claim 1, further comprising a controller with executable instructions for:

transferring the hydraulic fluid with the one or more valves open from the second tank to the first tank via depressurizing of the pressurized compressible gas from the third pressure setting to the second pressure setting;

generating electrical power by driving the motor/generator via the transferring of the fluid; and

transmitting the generated electrical power to a grid or power source.

7. The system of claim 6, further comprising a heat exchanger coupled to a top region of the second tank, and wherein the controller includes instructions for flowing a heated/cooling fluid through the heat exchanger and transferring heat from the heated/cooling fluid to the pressurized compressible gas in the second tank, the flowing responsive to an output of a pressure sensor coupled to the second tank.

8. The system of claim 6, further comprising a gas-fluid separator coupled at an interface of the gas and the fluid in the second tank, the separator including one of a membrane, a bladder, and a piston.

9. The system of claim 1, wherein the hydraulic fluid has a higher density than the compressible gas and wherein in each of the first and second tank, the compressible gas is layered on top of the hydraulic fluid.

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21. An electrical power storage system, comprising:

a first, open air reservoir storing an incompressible hydraulic fluid at a first pressure setting;

a second reservoir storing the incompressible hydraulic fluid and a compressible gas preloaded to a second pressure setting higher than atmospheric pressure;

a reversible hydraulic fluid pump fluidically coupled to each of the first and second reservoirs via corresponding connecting pipes;

one or more valves coupled to the connecting pipes, the one or more valves configured to adjust flow of the incompressible hydraulic fluid through the connecting pipes;

a DC motor/generator mechanically coupled to the fluid pump and electrically coupled to an electrical power source; and

a controller with executable instructions for:

drawing electrical power from the power source to actuate the motor/generator;

driving the fluid pump via the motor/generator with the one or more valves open to transfer hydraulic fluid from the first reservoir into the second reservoir; and

pressurizing the compressible gas in the second reservoir via the hydraulic fluid transfer, the hydraulic fluid and compressible gas pressurized to a third pressure setting, higher than the first pressure setting.

22. The electrical power storage system of claim 21, wherein the first pressure setting is atmospheric pressure.

23. The electrical power storage system of claim 21, wherein the first reservoir is a ground level fluid reservoir.

24. The electrical power storage system of claim 21, wherein the second reservoir is a closed system sealed from atmosphere.

25. The electrical power storage system of claim 24, wherein the second reservoir is a subterranean reservoir.

26. The electrical power storage system of claim 25, wherein the subterranean reservoir is an oil well.

27. The electrical power storage system of claim 25, wherein the second reservoir is a coal mine.

28. The electrical power storage system of claim 21, wherein the controller includes further executable instructions for:

transferring the hydraulic fluid with the one or more valves open from the second reservoir to the first reservoir via depressurizing of the pressurized compressible gas from the third pressure setting to a fourth pressure setting, the fourth pressure setting higher than the first pressure setting;

generating electrical power by driving the motor/generator via the transferring of the fluid; and

transmitting the generated electrical power to a grid or power source.

29. The electrical power storage system of claim 28, wherein the fourth pressure setting is similar to the second pressure setting.

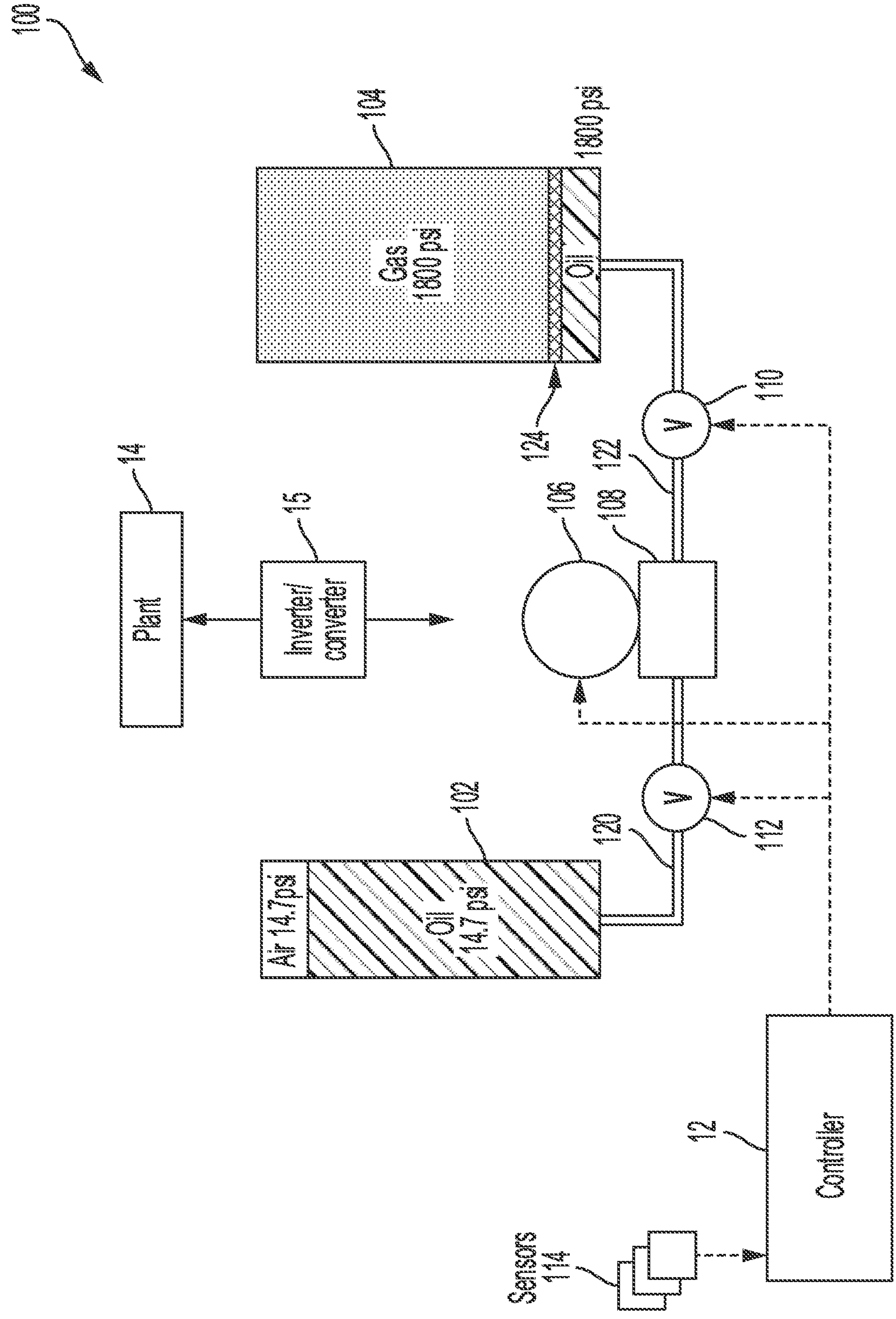
100
104
Gas
1800 psi
Oil
1800 psi
124
V
110
122
14
Plant
15
Inverter/
converter
106
108
102
Air 14.7psi
Oil
14.7 psi
120
V
112
12
Controller
Sensors
114

FIG. 1

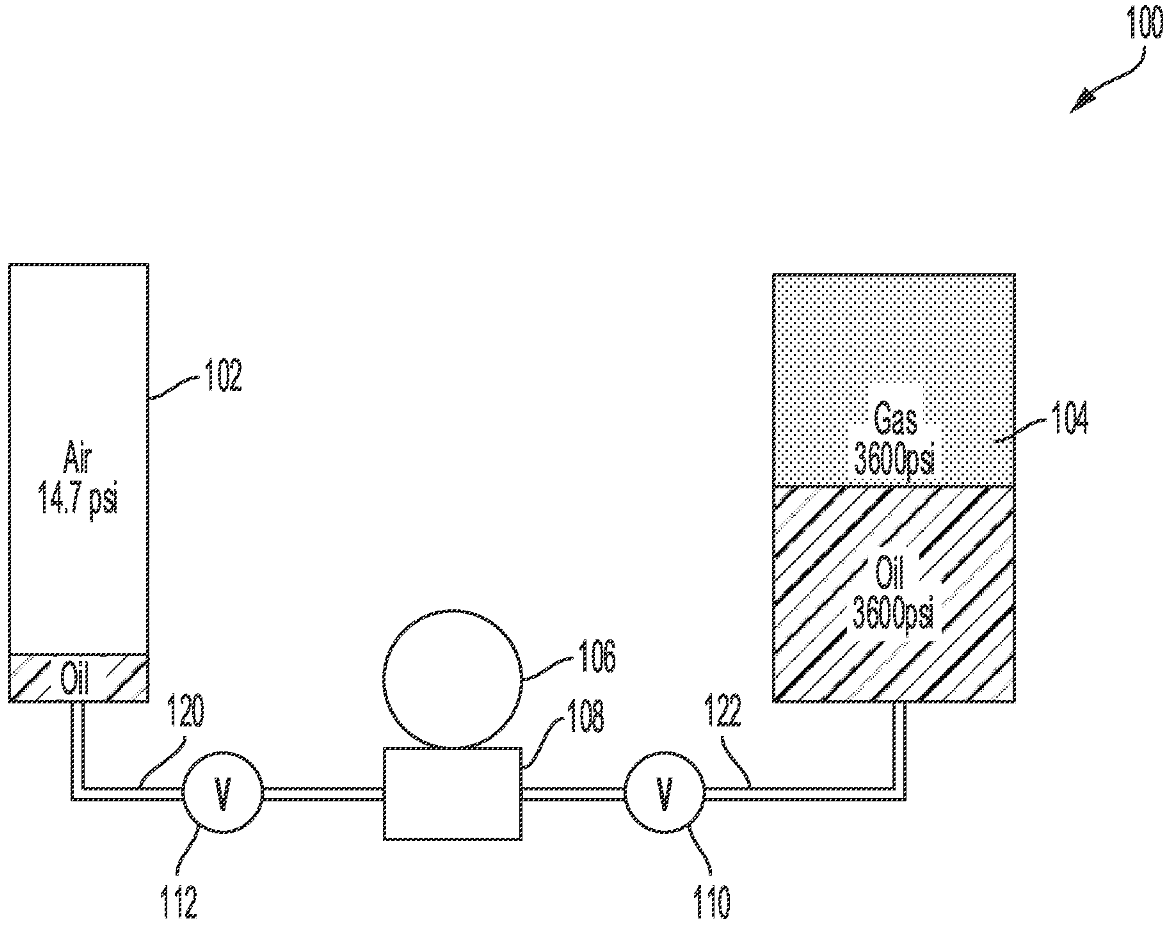
100
102
Air
14.7 psi
Oil
104
Gas
3600psi
Oil
3600psi
106
108
120
122
V
V
112
110

FIG. 2

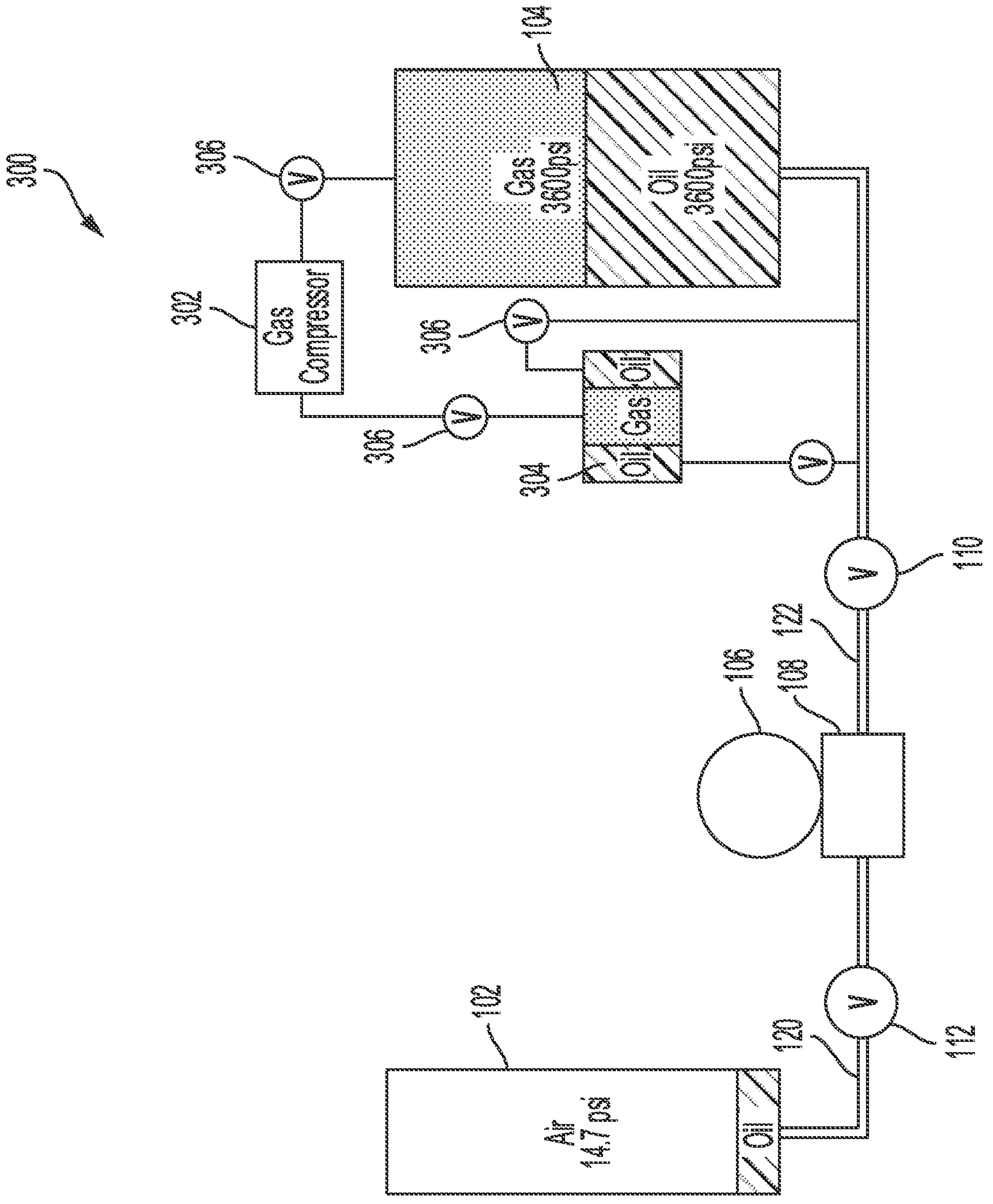
300
302
Gas Compressor
306
V
306
V
306
V
104
Gas 3600psi
Oil 3600psi
304
Oil
Gas
Oil
V
110
V
122
106
108
102
Air 14.7 psi
Oil
120
V
112

FIG. 3

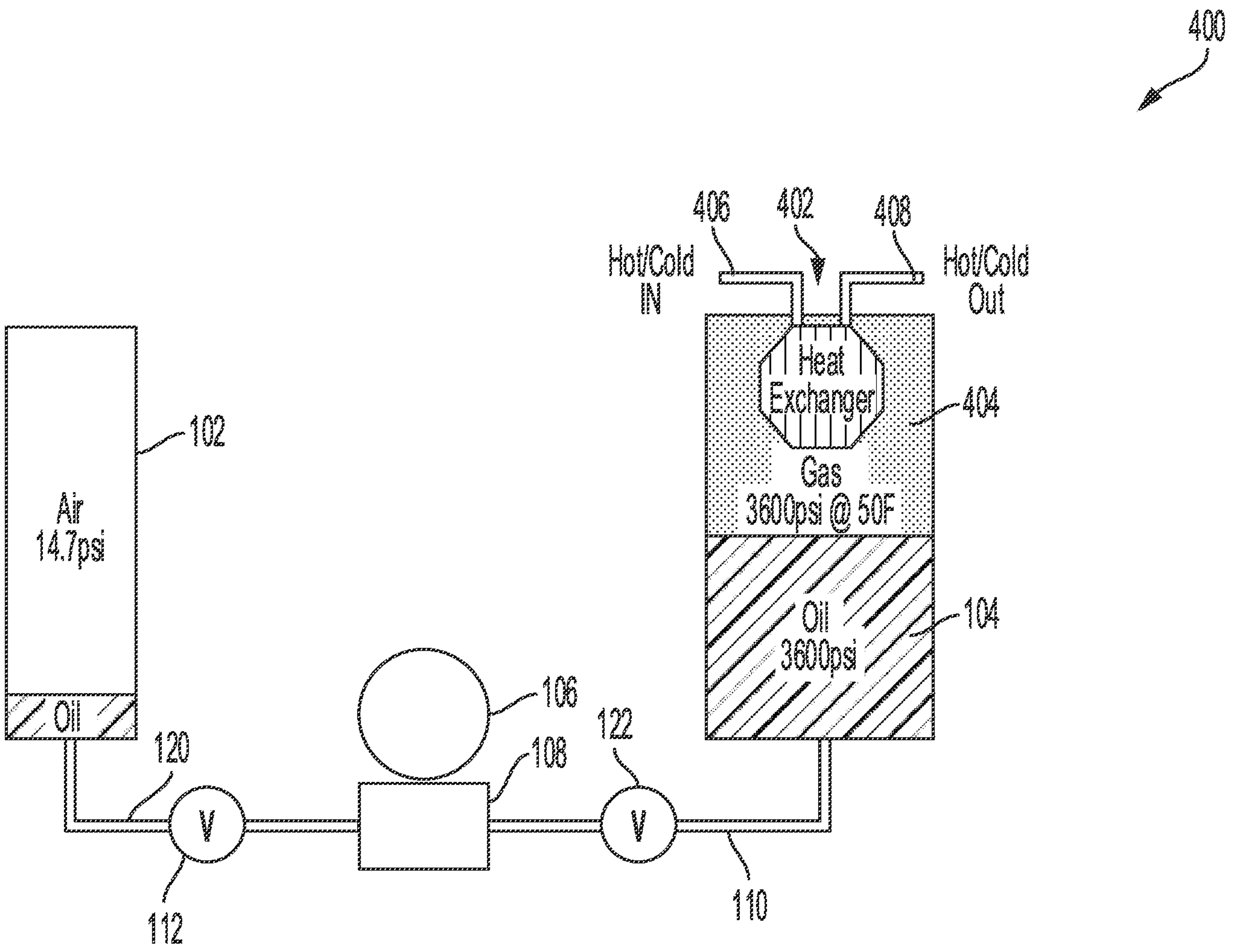
400
406
402
408
Hot/Cold
IN
Hot/Cold
Out
Heat
Exchanger
404
Gas
3600psi @ 50F
Oil
3600psi
104
102
Air
14.7psi
Oil
106
108
120
122
V
V
112
110

FIG. 4

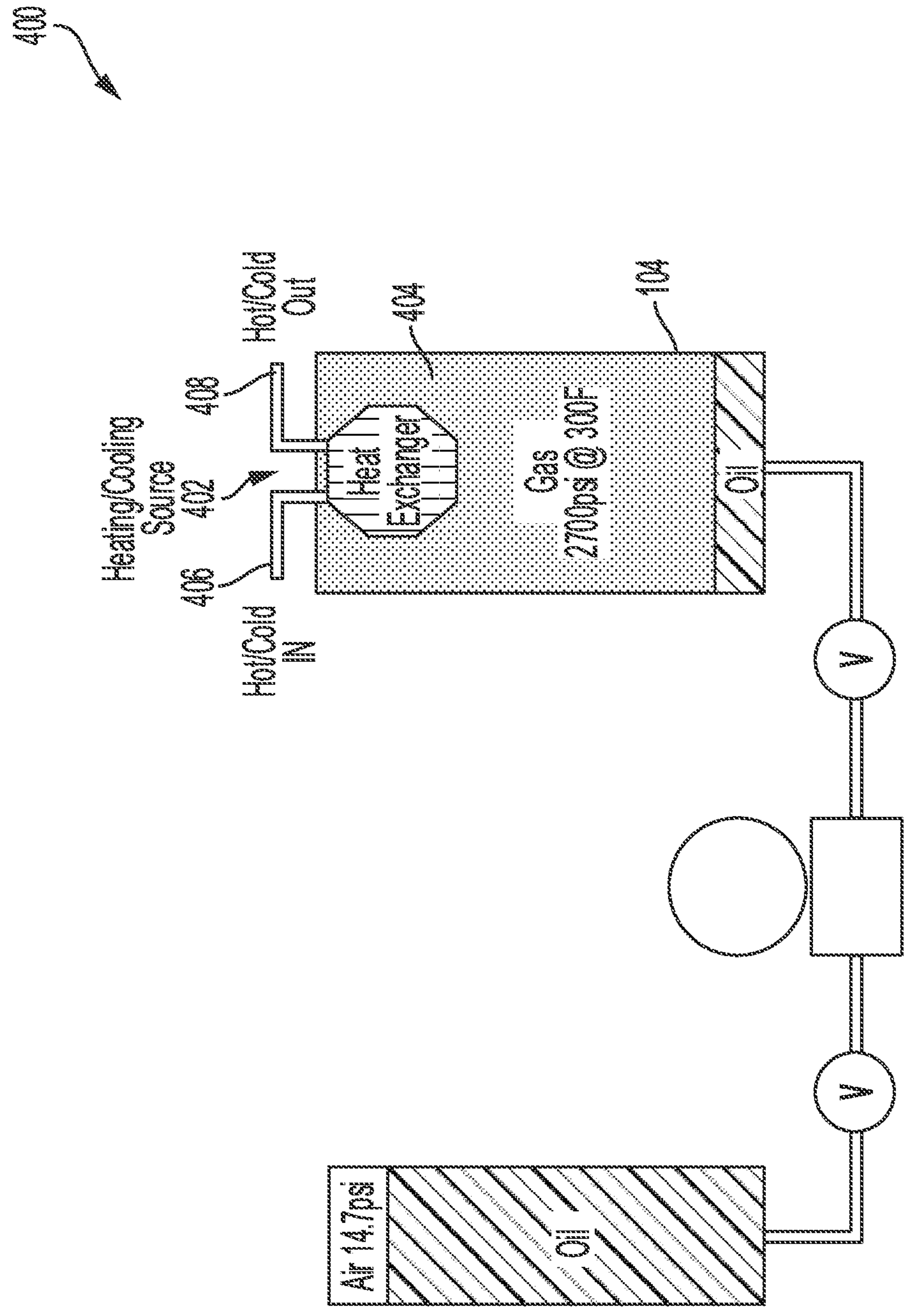
400
Hot/Cold Out
404
104
408
Heating/Cooling Source
402
406
Hot/Cold IN
Heat Exchanger
Gas
2700psi @ 300F
Oil
V
V
Air 14.7psi
Oil

FIG. 5

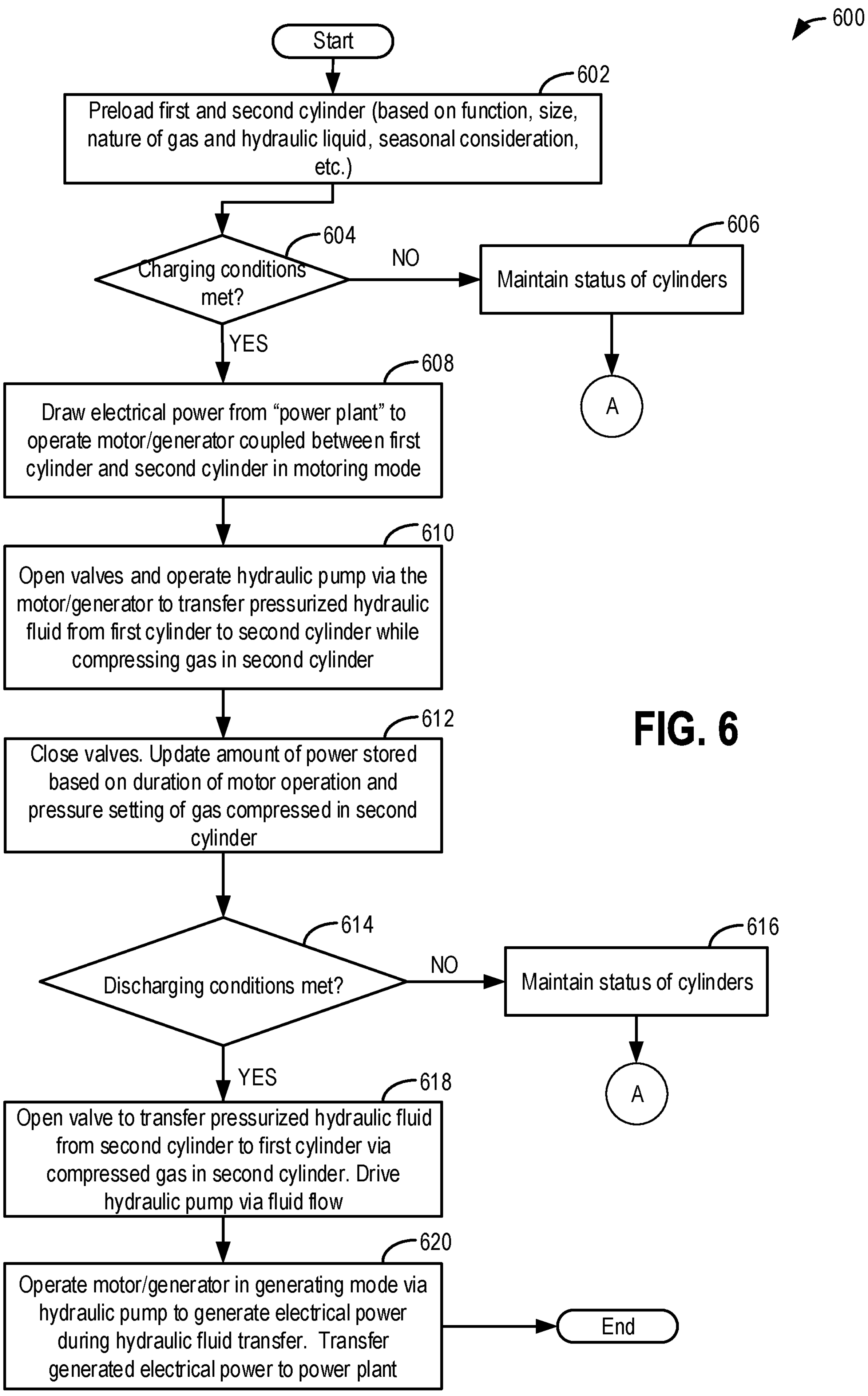
600
Start
602
Preload first and second cylinder (based on function, size, nature of gas and hydraulic liquid, seasonal consideration, etc.)
604
Charging conditions met?
NO
606
Maintain status of cylinders
A
YES
608
Draw electrical power from "power plant" to operate motor/generator coupled between first cylinder and second cylinder in motoring mode
610
Open valves and operate hydraulic pump via the motor/generator to transfer pressurized hydraulic fluid from first cylinder to second cylinder while compressing gas in second cylinder
612
Close valves. Update amount of power stored based on duration of motor operation and pressure setting of gas compressed in second cylinder
614
Discharging conditions met?
NO
616
Maintain status of cylinders
A
YES
618
Open valve to transfer pressurized hydraulic fluid from second cylinder to first cylinder via compressed gas in second cylinder. Drive hydraulic pump via fluid flow
620
Operate motor/generator in generating mode via hydraulic pump to generate electrical power during hydraulic fluid transfer. Transfer generated electrical power to power plant
End

FIG. 6

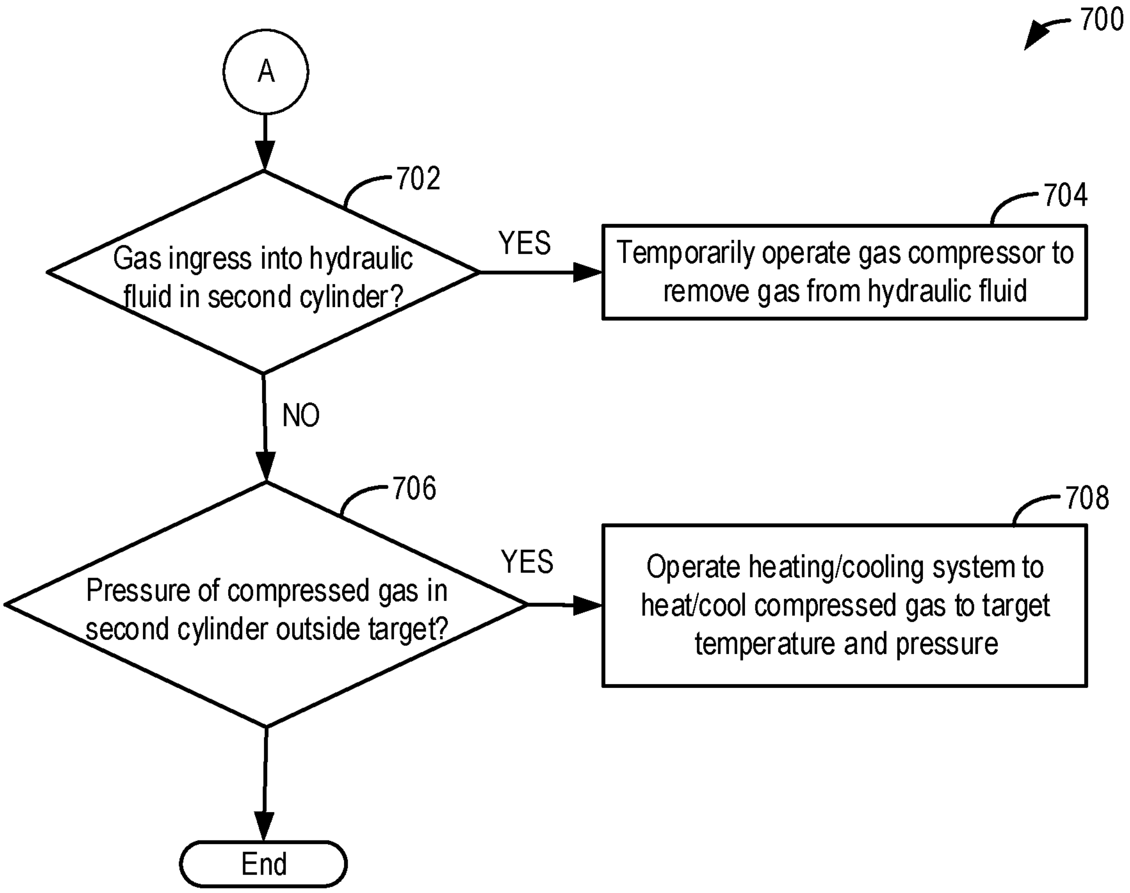
700
A
702
Gas ingress into hydraulic fluid in second cylinder?
YES
704
Temporarily operate gas compressor to remove gas from hydraulic fluid
NO
706
Pressure of compressed gas in second cylinder outside target?
YES
708
Operate heating/cooling system to heat/cool compressed gas to target temperature and pressure
End

FIG. 7

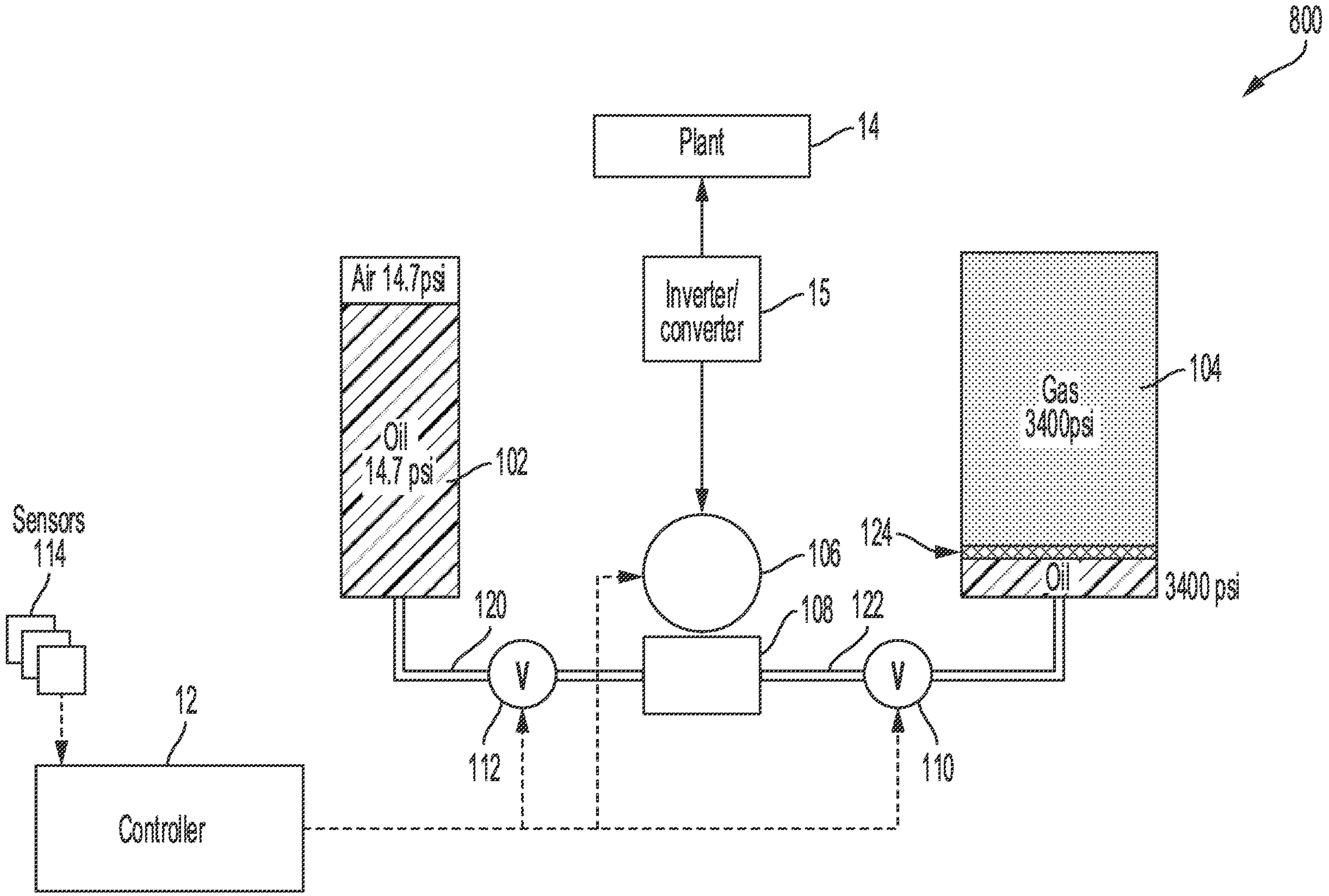
800
Plant
14
Inverter/
converter
15
Air 14.7psi
Oil
14.7 psi
102
Gas
3400psi
104
124
Oil
3400 psi
106
108
120
122
V
V
112
110
Sensors
114
12
Controller

FIG. 8

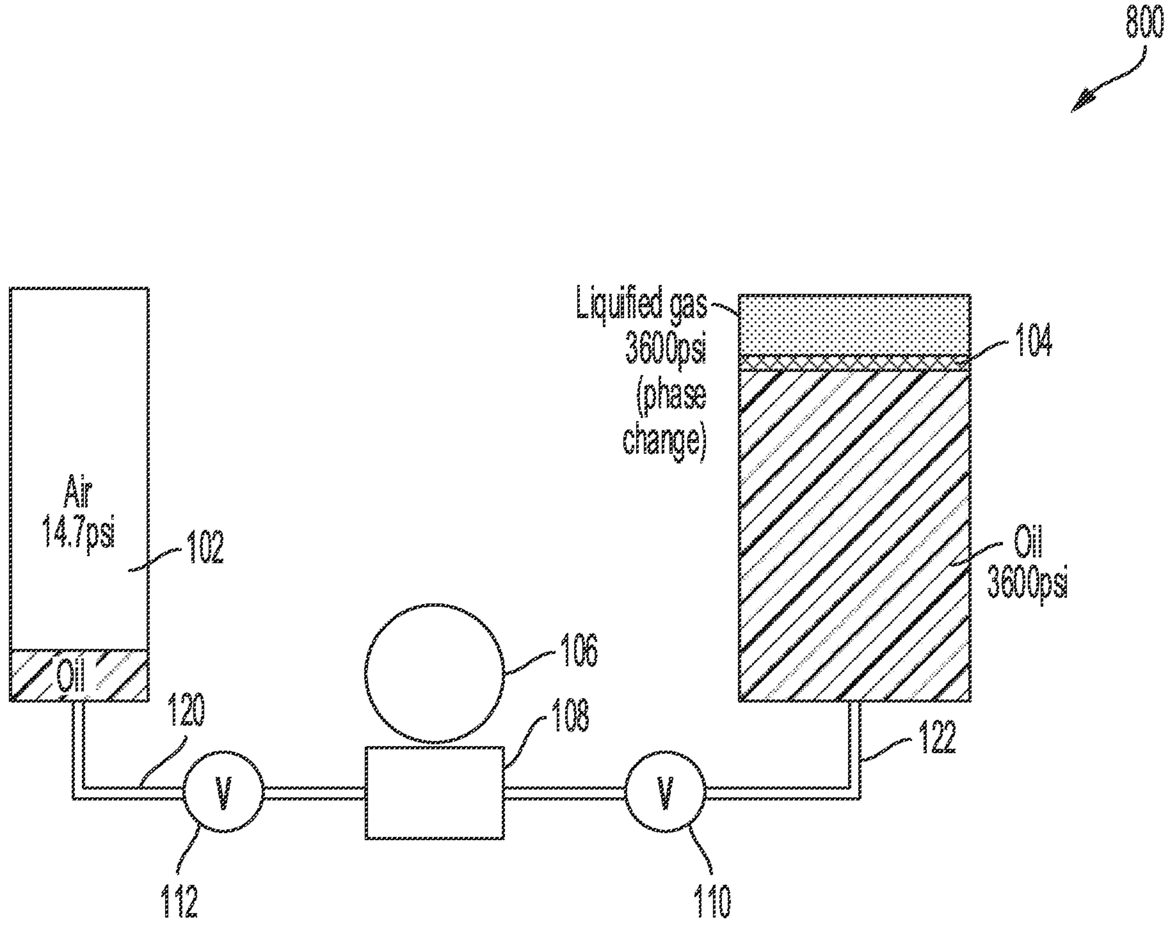
800
Air
14.7psi
102
Oil
120
112
106
108
Liquified gas
3600psi
(phase
change)
104
Oil
3600psi
122
V
V
110

FIG. 9

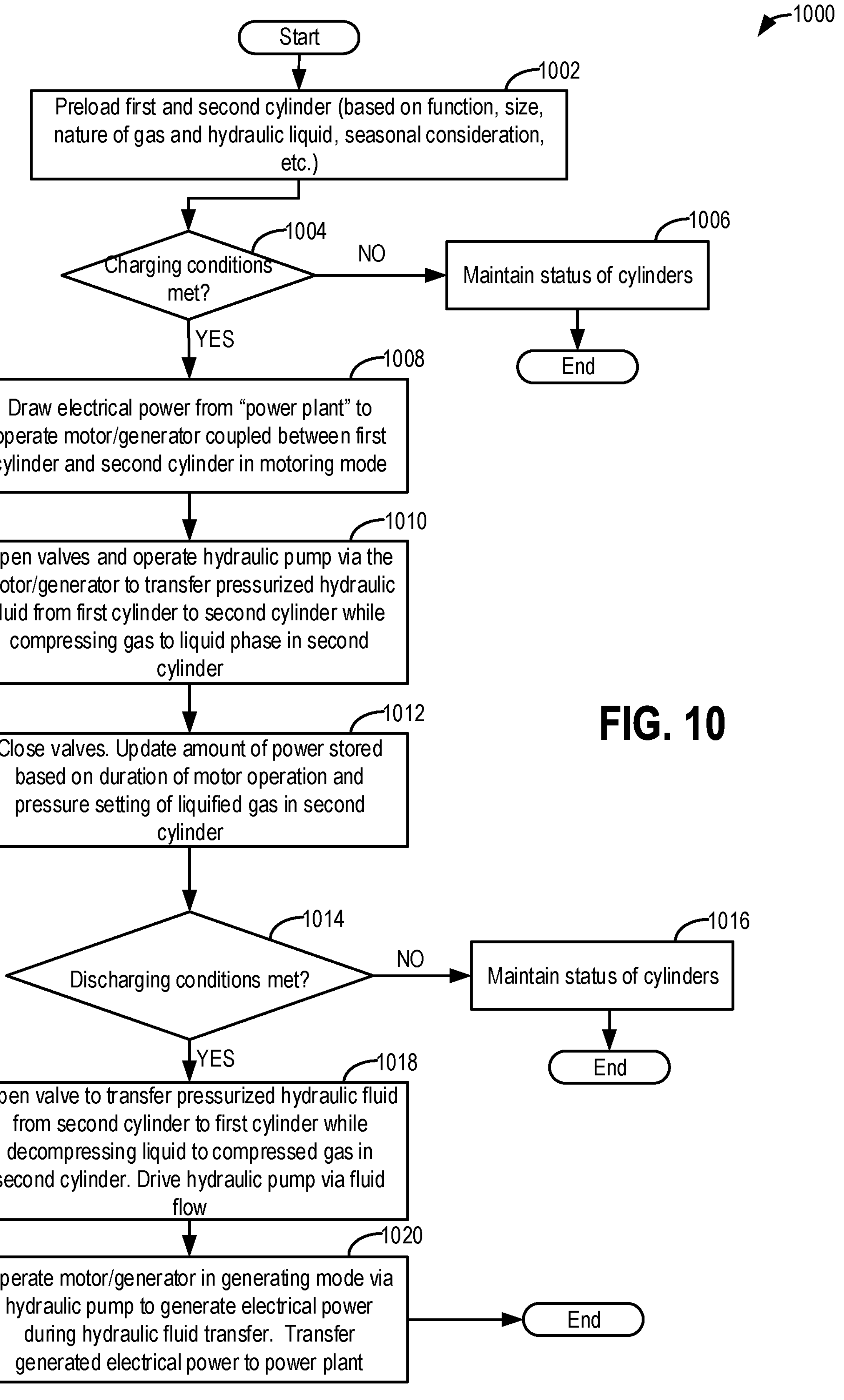
1000
Start
1002
Preload first and second cylinder (based on function, size, nature of gas and hydraulic liquid, seasonal consideration, etc.)
1004
Charging conditions met?
NO
1006
Maintain status of cylinders
End
YES
1008
Draw electrical power from "power plant" to operate motor/generator coupled between first cylinder and second cylinder in motoring mode
1010
Open valves and operate hydraulic pump via the motor/generator to transfer pressurized hydraulic fluid from first cylinder to second cylinder while compressing gas to liquid phase in second cylinder
1012
Close valves. Update amount of power stored based on duration of motor operation and pressure setting of liquified gas in second cylinder
1014
Discharging conditions met?
NO
1016
Maintain status of cylinders
End
YES
1018
Open valve to transfer pressurized hydraulic fluid from second cylinder to first cylinder while decompressing liquid to compressed gas in second cylinder. Drive hydraulic pump via fluid flow
1020
Operate motor/generator in generating mode via hydraulic pump to generate electrical power during hydraulic fluid transfer. Transfer generated electrical power to power plant
End

FIG. 10

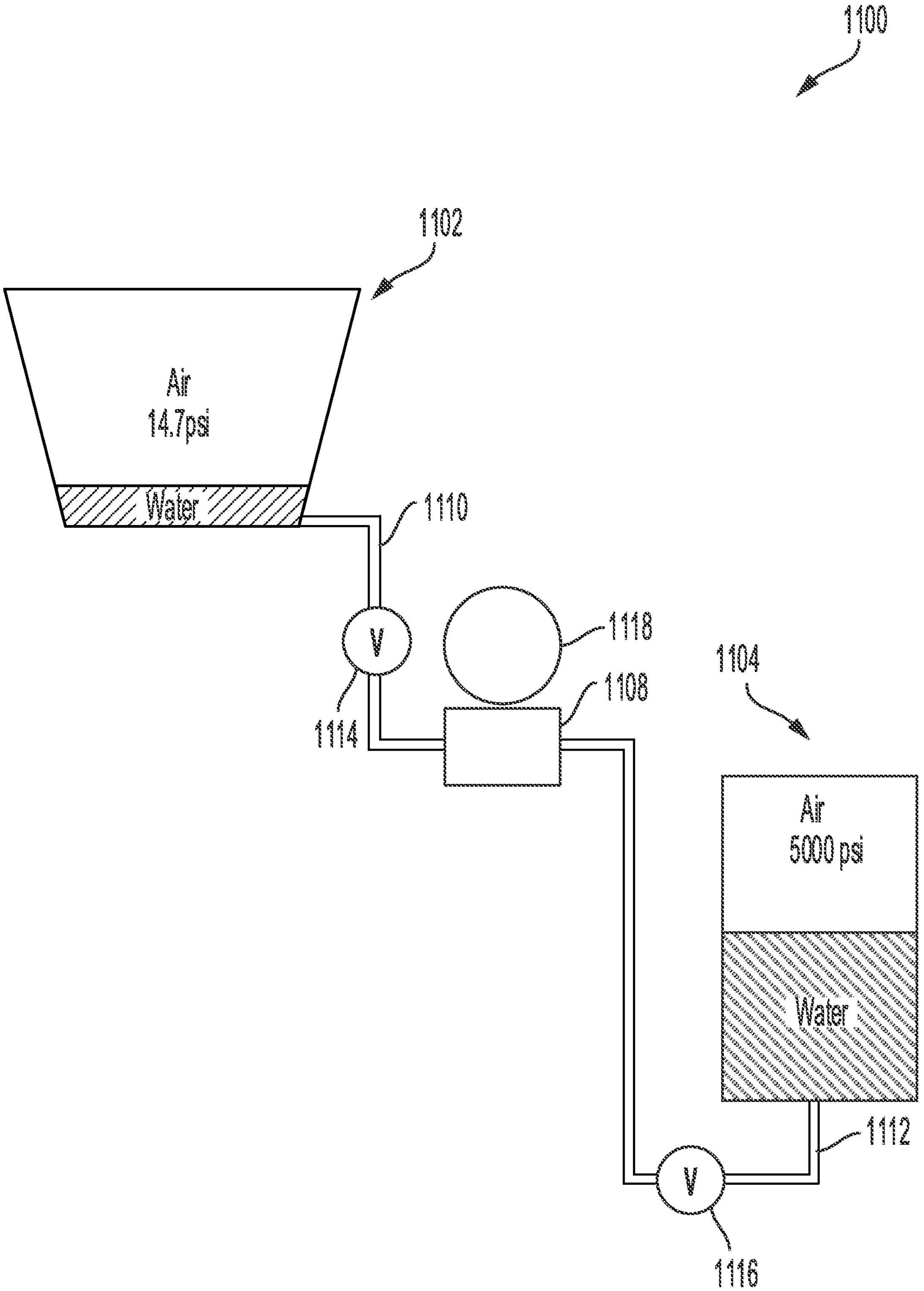
1100
1102
Air
14.7psi
Water
1110
1118
1104
1108
1114
Air
5000 psi
Water
1112
V
V
1116

FIG. 11

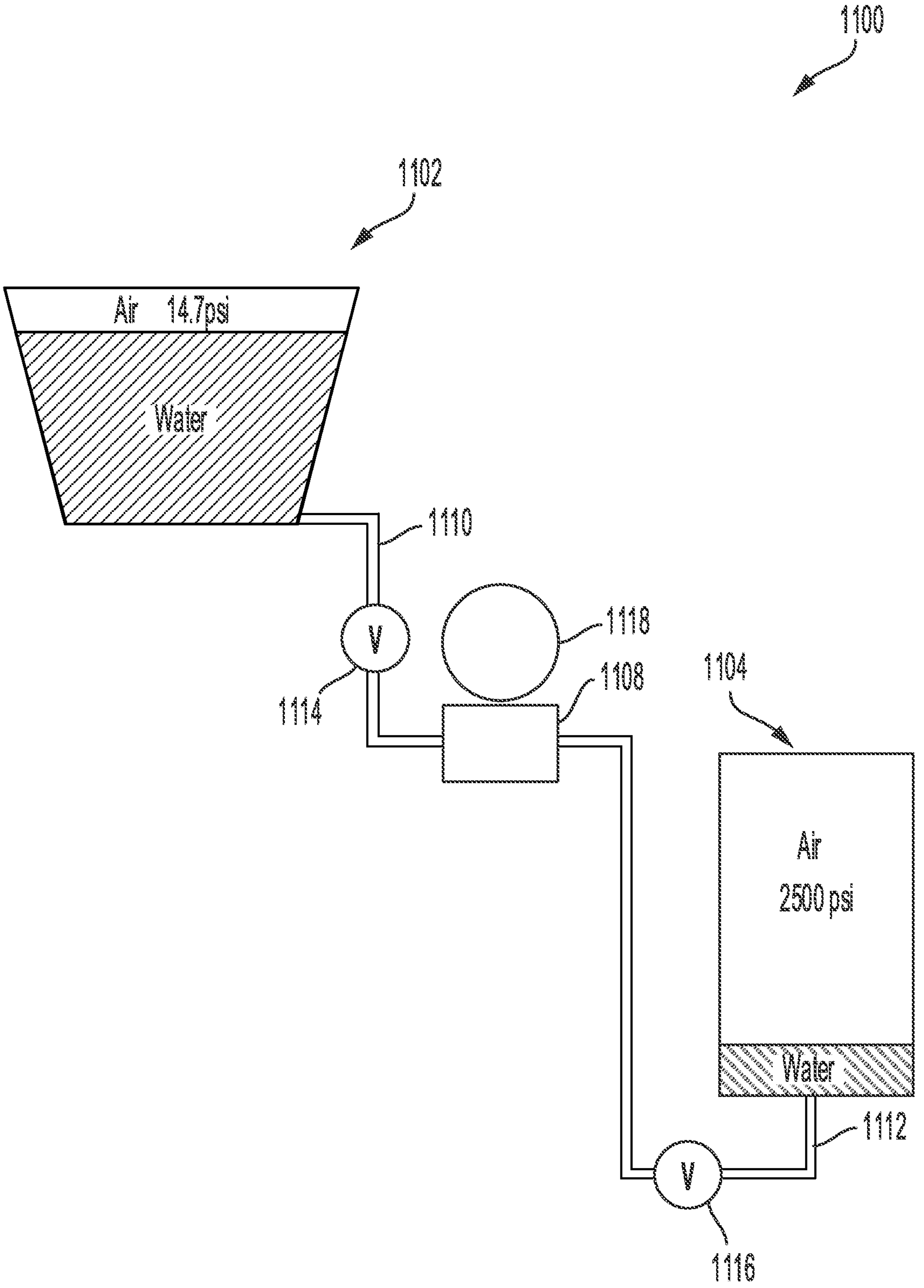
1100
1102
Air 14.7psi
Water
1110
1118
V
1114
1108
1104
Air
2500 psi
Water
1112
V
1116

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/024045

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - F02C 6/16; F15B 1/02; H02J 15/00 (2020.01)
CPC - H02J 15/00; F02C 6/16; F15B 1/02; F15B 1/024 (2020.05)

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)
see Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
see Search History document

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2011/0219760 A1 (MCBRIDE et al) 15 September 2011 (15.09.2011) entire document	1, 3, 11, 15, 16, 19, 20 --- 2, 9, 13, 14, 17, 18
Y	US 2010/0003545 A1 (HORNE et al) 07 January 2010 (07.01.2010) entire document	2
Y	US 2011/0296822 A1 (BOLLINGER et al) 08 December 2011 (08.12.2011) entire document	9
Y	US 2011/0167814 A1 (HAYNES) 14 July 2011 (14.07.2011) entire document	13, 14, 17, 18

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	"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
"A" document defining the general state of the art which is not considered to be of particular relevance	
"D" document cited by the applicant in the international application	"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
"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)	"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
"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	"&" document member of the same patent family

Date of the actual completion of the international search 05 June 2020	Date of mailing of the international search report 22 JUN 2020
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver Telephone No. PCT Helpdesk: 571-272-4300