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(54) **CONTROL OF VARIABLE POWER SOURCE-COUPLED ELECTROLYSERS**

(57) There is provided a water electrolysis system for hydrogen generation, wherein an electrolyser is coupled to a variable power source through a control device. The control device is configured to control at least one operating parameter of the electrolyser to increase its lifetime. The at least one operating parameter includes an electrical operating point (state) of the electrolyser, wherein the control device regulates an output power of

the variable power source to match it to an electrical operating point (such as voltage and current) and input power to the electrolyser. The control device may comprise control units with modular configuration and hot-swap capabilities. The control device may comprise a state change smoothing method that produces operating parameter changes to bring the electrolyser from one state to another state.

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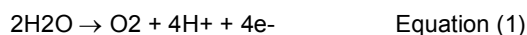
Description

BACKGROUND

[0001] The present disclosure relates to systems, devices, and methods for coupling between a variable power source and an electrolyser. Alternative spelling of "electrolyser" may be "electrolyzer".

[0002] Electrolysis of water, also known as electrochemical water splitting, is the process of using electricity to decompose water into oxygen and hydrogen gas by electrolysis. Hydrogen gas released in this way may be used as hydrogen fuel. Half-cell reactions of the water electrolysis in an acidic medium are shown in Equations (1) and (2) and half-cell reactions of the water electrolysis in an alkaline medium are shown in Equations (3) and (4) hereinbelow.

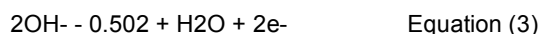
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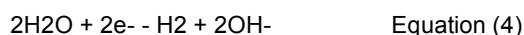
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[0003] The decomposition of water into hydrogen and oxygen at standard temperature and pressure may not be favorable in thermodynamic terms. Accordingly, power input may be required for the reaction to occur. Electrolysis of water allows distributed hydrogen production and the process may be compatible with a large number of existing renewable energy technologies (including, *inter alia*, solar, wind, biomass, hydro, tidal, wave, and geothermal technologies). Water electrolysis may be based on acidic or alkaline liquid electrolyte systems, as well as on a solid-state system incorporating polymer electrolyte membranes (PEMs), in which water flows through a solid acidic or alkaline medium. While efficiency of liquid electrolyte electrolyzers typically suffers from non-steady direct current (DC) voltage or current that are characteristic of many types of renewable energy sources, PEM electrolyzers may accept large power input variations, thus allowing direct integration with variable sources of power, such as photovoltaic (PV) solar and wind power. A solid oxide electrolyser cell (SOEC) may be combined with a renewable energy source. The SOEC may be based on a solid oxide fuel cell that uses a solid oxide or ceramic, an electrolyte, and runs in a regenerative mode.

BRIEF SUMMARY OF THE INVENTION

[0004] The following presents a simplified summary of disclosed aspects in order to provide a basic understanding of these aspects. This summary is not an extensive overview of the aspects. This summary is not intended to identify key or critical elements or to delineate the scope of the disclosure.

[0005] Aspects of the disclosure relate to water electrolysis systems for hydrogen generation including a variable power source, an electrolyser operatively connected to the variable power source, and a control device configured to control operating parameters of the electrolyser to increase its lifetime. The phrase operating parameter refers to a physical or electrical parameter that the electrolyser is operated at, such as a voltage, current, power, temperatures, pressures, flow rates, etc, and the control is performed by changing the value of the operating parameter. The control device is, *inter alia*, configured to regulate an output power of the variable power source to match it to an electrical operating point (state) of the electrolyser, wherein the electrical operating point may be selected to increase a lifetime of the electrolyser. Aspects further relate to devices useful with the system and methods of operating the system. As used herein the term match means substantially equivalent.

[0006] The electrolyser includes at least one electrode-membrane assembly (MEA), including a membrane positioned between a cathode and an anode. The cathode and the anode may include suitable catalysts, for example, a hydrogen evolution catalyst and an oxygen evolution catalyst, respectively. The electrodes may include a gas diffusion layer (GDL) that may be carbon-based. The membrane may be a polymer exchange membrane, such as a proton exchange mem-

brane or an anion exchange membrane. The electrolyser cell may include additional components, including current collectors and/or flow plates.

[0007] The components of the electrolyser may suffer from degradation during prolonged cycling. For example, the membrane may undergo chemical degradation that may be manifested, *inter alia*, in its reduced thickness. When the membrane becomes thinner, hydrogen and oxygen that are generated in the cathode and anode, respectively, may cross the membrane to the opposite side of the MEA, thereby decreasing hydrogen generation efficiency, and may even cause an explosion. As a result of chemical degradation and membrane thinning, probability of membrane perforation increases, which may lead to a short circuit. Cathode and anode catalysts may also suffer from chemical degradation, in particular when low catalyst loading is used and/or when the electrolyzer operates under non-constant current variations, leading to voltage losses. Bipolar plates may also experience chemical changes over operation time, e.g., due to corrosion, which increases interfacial contact resistance.

[0008] Renewable energy generation systems may be located in remote locations, such that electrolysers coupled to such systems may be sufficiently durable to avoid frequent replacements. Degradation of electrolyser components negatively affects hydrogen generation and the energy efficiency of water electrolysis process and increases the overall cost of hydrogen production of the renewable energy hydrogen system.

[0009] Performance of the electrolyser cell, as well as its degradation rate, depend, *inter alia*, on operating parameters of the electrolyser, including, for example, an input voltage, current density, temperature, and electrolyte or water flowrate. Operating parameters for increasing electrolyser lifetime may be different from these needed to improve the performance of the electrolyser. For example, at higher current densities which provide higher energy efficiency of the water splitting process, degradation of the OER catalyst may be higher than at lower current densities. For example, operating the electrolyser to minimize electrochemical stress on the membranes may be done by preventing sudden changes to the electrolyser current or voltage. For example, operating the cell at a high temperature may increase the amount of hydrogen generated by reducing overvoltage, but may cause a decrease over the lifetime of the electrolyser cell due to the deterioration of the membrane. Working at higher temperatures and/or at non-constant current values may also accelerate catalyst degradation.

[0010] Accordingly, in order to prolong the cycle life of the electrolyser, the operating parameters of an electrolyser that may be coupled to a variable power source, including its electrical operating point, may be controlled. The control device according to features of the disclosure herein may adjust a current density and/or voltage supplied by the variable power source to the electrolyser. The control device may control one or more of an operating temperature of the electrolyser, flowrate of electrolyte or water, and pressure of hydrogen and/or oxygen. The aforementioned operating parameters may be adjusted based on predetermined values that may be derived from calculations and/or empirical data (such as historically measured data) that correlate between the operating parameters and the lifetime of the electrolyser cell. The control device may perform real-time monitoring of at least one parameter related to electrolyser state-of-health (SOH), and select the operating parameters based on the measuring the at least one parameter. Parameters that may be monitored and used to evaluate electrolyser SOH may include, *inter alia*, cell voltage, when operated galvanostatically, internal cell resistance or impedance, electrolyte outlet temperature, electrolyte temperature gradient between the inlet and the outlet, and chemical composition of the outlet electrolyte. The control device may include a machine learning algorithm configured to analyze the performance of the electrolyser with respect to various operating parameters and to adjust the operating parameters based on the analyzed data of a plurality of such electrolysers. The control device may select the operating parameters of the electrolyser based on a predicted output power of the variable power source.

[0011] The control device may regulate output power of the variable power source to manage fast and slow power changes. In order to simplify the process of adjusting the output power to the electrical operating point of the electrolyser to prolong its lifetime, the power generated by the variable power source may first be smoothed to obtain a baseline power. For example, the control device may smooth fast power changes (e.g., power changes occurring over seconds) using an energy storage device such as a capacitor or secondary battery. For example, a rapid power surplus may be used to charge the storage device, and when the power falls below the target baseline, the storage device may be discharged to supplement the deficient power. Slow power changes (e.g., power changes occurring over minutes) may also be managed by a suitable energy storage system. The control device may be configured to export output power to the grid when there is excess power and to import power from the grid to provide the electrical operating point to the electrolyser when the combined output power of the variable power source and of the storage device does not suffice.

[0012] The process of aligning the SOH across multiple electrolysers may be termed "SOH balancing". The process balancing power between multiple electrolysers to produce a desired hydrogen production rate may be termed "power balancing". The control device and control units may be configured to provide SOH balancing and power balancing. Power balancing may be beneficial to align replacement times between multiple electrolysers at end of life to minimize hydrogen production down times during replacement.

[0013] Typically, a plurality of electrolyser cells may be stacked together to form an electrolyser stack. The control device may control the operating parameters of the entire stack. The system may include a plurality of electrolyser stacks. In such instances, the control device may control each of the stacks individually. The control device may shut

down one or more stacks, while other stacks continue to operate, for example, when the predicted power output is insufficient for operating all the stacks or when the SOH of one or more stacks indicates that they undergo rest or regeneration procedure. The control device may compare the SOH of each stack to the SOH of other stacks, and to select preferred operating parameters of each stack based on the comparison. For example, stacks having a better SOH may be operated at higher current densities, while stacks having an inferior SOH may be operated at lower current densities or not operated at all for a certain number of hours of system operation.

[0014] When controlling electrolyzers, each electrolyser may be operated in different operating parameters, electrical operating points, or states. These terms may be used interchangeably depending on the context of the term use. The states of an electrolyser may be defined in an operation manual of the electrolyser or determined empirically (during break in or operation). For example, the states of an electrolyser may be determined empirically during a break in period when the electrolyser is brought into continuous operation. Each state of operation of the electrolyser includes permitted ranges of the operating parameters, such as electrolyser current, voltage, temperatures, pressures, flow rates, etc. These ranges include upper and lower limits allowed for each operating parameter such that the electrolyser operation within these ranges is continuous or consistent. When a transition of the state of an electrolyser from one state to another state is performed, the operating parameters of the electrolyser may be controlled, such as voltage, current, temperature(s), pressure(s), flow rate(s), etc. A change that is continuous in the operating parameter being controlled, such as voltage, current, temperature, pressure, or flow, and changes smoothly from the first state to the second state may be used to perform the transition. To change the operating parameter smoothly from a first value to a second value, a sigmoid function may be used and the operating parameter adjusted digitally to follow that temporal change in the operating parameter. To change the operating parameter smoothly from a first value to a second value, a piece-wise smooth set of curves may be used. For example, a first time period may have an increasing slew rate of the operating parameter from zero to a certain predetermined value, a second time period of a linear increase in the operating parameter, and then a decreasing slew rate back to zero. The piece-wise smooth set of curves may also have a second order differential, such as an acceleration of the operating parameter that is in compliance with a predetermined threshold.

[0015] During operation of the electrolyser, a hydrogen production rate may be chosen to prolong an operating parameter of the electrolyser. For example, a hydrogen production rate may be chosen that prolongs lifetime, increases total hydrogen production, etc.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] A more complete understanding of the present invention and the advantages thereof may be acquired by referring to the following description in consideration of the accompanying drawings, in which like reference numbers indicate like features, and wherein:

FIGURE 1A illustrates a water electrolysis system including an electrolyser that is connected to a PV array through a control device, in accordance with some embodiments of the invention;

FIGURE 1B schematically illustrates a water electrolysis system including an electrolyser that is connected to a PV array through a control device, in accordance with some embodiments of the invention, wherein the PV array may be connected to an electric grid and a load;

FIGURE 2A schematically illustrates a water electrolysis system including a plurality of electrolyser stacks that are connected to a plurality of PV arrays through a control device, in accordance with some embodiments of the invention;

FIGURE 2B schematically illustrates a water electrolysis system including a plurality of electrolyser stacks that are connected to a plurality of power sources in series through a plurality of control units of a control device connected in series, in accordance with some embodiments of the invention;

FIGURE 2C schematically illustrates a water electrolysis system including a plurality of electrolyser stacks that are connected in series to a plurality of power sources through a plurality of control units of a control device connected in series and a plurality of optimizers connected in series, in accordance with some embodiments of the invention;

FIGURE 2D schematically illustrates a water electrolysis system including a plurality of an electrolyser stacks that are connected to a plurality of power sources through a plurality of control units of a control device connected in parallel and a plurality of optimizers connected in series, in accordance with some embodiments of the invention;

FIGURE 2E schematically illustrates a control unit for an electrolyser;

FIGURE 2F schematically illustrates a serial circuit for an operating parameter change of an electrolyser;

FIGURE 2G schematically illustrates a parallel circuit for an operating parameter change of an electrolyser;

5 FIGURE 3A schematically illustrates steps of a method for operating an electrolyser coupled to a variable power source, according to some embodiments of the invention;

FIGURE 3B schematically illustrates steps of a method for operating an electrolyser coupled to a variable power source, which includes monitoring at least one SOH-related parameter, according to some embodiments of the invention;

FIGURE 3C schematically illustrates steps of a method for operating a plurality of electrolysers coupled to a plurality of variable power sources, according to some embodiments of the invention;

15 FIGURE 4A schematically illustrates steps of a method for determining an operating parameter change of an electrolyser coupled to a variable power source, according to some embodiments of the invention;

FIGURE 4B schematically illustrates steps of a method for using an operating parameter change of an electrolyser coupled to a variable power source, according to some embodiments of the invention;

20 FIGURE 4C schematically illustrates steps of a method for implementing an operating state transition of an electrolyser coupled to a variable power source, according to some embodiments of the invention;

FIGURE 5A schematically illustrates a plot of applying a lag-free operating parameter change between two states of an electrolyser coupled to a variable power source, according to some embodiments of the invention;

Figure 5B schematically illustrates a plot of applying a lag-free operating parameter change process between multiple states of an electrolyser coupled to a variable power source, according to some embodiments of the invention;

30 FIGURE 6A schematically illustrates a plot of measuring a first lag of a first operating parameter change of an electrolyser coupled to a variable power source, according to some embodiments of the invention;

FIGURE 6B schematically illustrates a plot of measuring a second lag of a second operating parameter change of an electrolyser coupled to a variable power source, according to some embodiments of the invention;

35 FIGURE 6C schematically illustrates a plot of measuring a third lag of a third operating parameter change of an electrolyser coupled to a variable power source, according to some embodiments of the invention;

FIGURE 7 schematically illustrates a plot of measuring a lag of a fourth operating parameter change of an electrolyser coupled to a variable power source from a hot start, according to some embodiments of the invention;

FIGURE 8 schematically illustrates a plot of measuring a lag of an operating parameter change decrease (shutoff) of an electrolyser coupled to a variable power source, according to some embodiments of the invention; and

45 FIGURE 9 schematically illustrates plots of a lag of an operating parameter change of an electrolyser coupled to a variable power source when new and after extended use, according to some embodiments of the invention.

DETAILED DESCRIPTION OF THE INVENTION

50 **[0017]** Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs.

[0018] Disclosed are water electrolysis systems, devices, and methods for hydrogen generation including a variable power source; an electrolyser; and a control device, wherein the electrolyser may be operatively connected to the variable power source through the control device. Typically, when combining an electrolyser with a variable power source, economic efficiency of the entire process may be considered. For example, a cost-efficient hydrogen generating system may be designed such that even when a maximum output from a variable power source may be varied, the electrolyser may be operated at high efficiency by utilizing such maximum output.

[0019] A water electrolysis system may be powered by a variable power source. The water electrolysis system controls

parameters of the electrolyser and energy source operation in addition to economic efficiency of hydrogen generation or energy efficiency of the process. Operating parameters of the electrolyser, such as, but not limited to, current density or voltage, temperature, flowrate of the electrolyte or water, and hydrogen and/or oxygen pressure may significantly affect durability of the different components of the electrolyser, such as a membrane, electrodes, or flow plates, thereby decreasing the electrolyser lifetime or even causing a safety hazard. The control device may be configured to control at least one operating parameter of the electrolyser to increase its lifetime. Operating voltage or current of the electrolyser that receives its power directly from a variable power source depends directly on the power output of the power source. For example, abruptly decreasing the voltage or even shutting down the electrolyser due to insufficient power provided by the variable power source (that may be a result of partial shading caused by moving clouds in photovoltaic arrays or adverse weather parameters in wind turbines) may negatively affect the membrane, leading to its thinning or even perforation. It may be important to protect the electrolyser from rapid decrease of power. On the other hand, even when the variable power source works in optimal weather parameters and provides sufficient power to the electrolyser, operating the electrolyser at excessively high current densities may also destroy the membrane. The control device may be configured to control an electrical operating point of the electrolyser. In particular, the control device may be configured to regulate the output power of the variable power source to match it to a predetermined input current or voltage of the electrolyser. The predetermined input current or voltage may be selected to increase or decrease the lifetime of the electrolyser.

[0020] For example, when SOH balancing multiple electrolysers, the timing of multiple electrolysers end-of-life may be aligned to minimize hydrogen production down times during replacement of the electrolysers. SOH balancing of multiple electrolysers may also allow phasing out of old electrolysers so they may be replaced with new and more efficient electrolysers.

[0021] Power balancing between multiple electrolysers during operation may help align the timings for repairs and replacements. Power balancing between multiple electrolysers may allow aligning the power to each electrolyser to the power that each may accept for a given operational goal, such as maximising hydrogen production, maximizing lifetime, aligning repair timings, or aligning replacement timings.

[0022] The terms "electrical operating point," "target electrical operating point," and "preferred electrical operating point" as used herein interchangeably, refer to either one of an input voltage and current (or current density) of the electrolyser, wherein the relationship between the operating voltage and the resultant current or between the operating current (or current density) and the resultant voltage may be defined by a polarization (I-V) curve of the electrolyser.

[0023] The terms "current" and "current density" are used herein interchangeably, as it is understood that current density is the current that is normalized by a surface area of the electrolyser cell.

[0024] The term "lifetime," as used herein, may refer to a number of operating hours after which the electrolyser needs to be replaced or exhibits degraded performance which is below a threshold. The term "lifetime" may refer to a number of operating hours at which the electrolyser may be operated at its nominal voltage. The term "lifetime" may refer to a number of operating hours at which the electrolyser may be operated at its nominal current.

[0025] The term "to increase lifetime," as used herein, may refer to increasing the operating hours of the electrolyser by at least about 1%, wherein the electrolyser operates at parameters that are other than the nominal voltage or nominal current for at least a certain number of hours throughout its lifetime. The term "to increase lifetime" may refer to increasing the operating hours of the electrolyser by at least about 2%, at least about 5%, at least about 7%, at least about 10%, at least about 15%, or at least about 20%.

[0026] The term "nominal voltage," as used herein, refers to a voltage as provided by the electrolyser's manufacturer at which the electrolyser may be configured to operate. The nominal voltage typically corresponds to a voltage efficiency of about 70-80%.

[0027] The term "nominal current," as used herein, refers to a current density as provided by electrolyser's manufacturer, at which the electrolyser may be configured to operate.

[0028] The term "variable power source," as used herein, refers to sources of energy for which power generation may not be constant, for example because their power production ability depends on their environments. The variable power source may be a renewable energy source. Non-limiting examples of variable power sources that may be employed in a water electrolysis system include a photovoltaic (PV) power source, solar thermal energy (STE) power source, wind power source, tidal power source, a variable electrical grid, and wave power source. The photovoltaic power generation may be intermittent because the power generated is proportional to the ambient light. Wind power generation depends on the force of the wind that may not be constant. Tidal power varies with the ebb and flow of the tide and wave power depends on the force of the waves which can vary widely. An electrical grid may be variable when a fixed grid power (such as limited by a main circuit breaker) is shared between the electrolyser and other variable loads. The remaining grid power is therefor variable and may be considered a variable power source. The electrolyser may be operated from the remaining variable grid power. While many of the examples herein of variable power sources use PV systems in the examples, it is understood that the devices, systems, and methods described herein apply to any variable power source,

[0029] The variable power source may be a PV power source. The term "PV power source," as used herein, may refer

to a single PV panel or a combination of PV panels (also termed herein "PV array," unless the context indicates otherwise. The term "PV power source" may encompass a PV panel operatively attached to a converter module such as a direct current (DC)-to-DC converter, also termed herein "optimizer" or "power optimizer". The term "PV panel," as used herein, includes any of one or more solar cells, cells of multiple semiconductor junctions, solar cells connected in different ways (such as serial, parallel, serial/parallel), of thin film and/or bulk material, and/or of different materials. When multiple PV panels are used, they may be operated at their maximum power point (MPP), by using, e.g., the converter module.

[0030] Reference is now made to FIGURE 1A which schematically illustrates water electrolysis system 101, according to some embodiments of the disclosure herein. System 101 includes variable power source (such as PV array 103), electrolyser 105, and control device 107, which operatively connects between variable power source 103 and electrolyser 105. Control device 107 may be configured to control at least one operating parameter of electrolyser 105 to increase its lifetime, wherein the at least one operating parameter comprises an electrical operating point of electrolyser 105. Control device 107 regulates an output power of variable power source 103 to match it to an electrical operating point of electrolyser 105.

[0031] The water electrolysis system may be an off-grid system that employs solar energy for generating hydrogen from water. Such a system may be used, e.g., as a refueling system for fuel cell-based vehicles. The generated hydrogen may be collected and transported to be used at a different location. The water electrolysis system as described herein may be operatively connected to at least one of an electric grid and electric load, wherein the variable power source may provide power for residential or commercial uses, in parallel to powering the electrolyser to generate hydrogen. A grid-connected system may receive power from the utility grid to supplement the power provided by the variable power source, when needed. The variable power source may be operatively connected to at least one of the grid and the load. The electrolyser may be operatively connected to the grid. The connected may be implemented by means of the control device.

[0032] The terms "electric grid" and "grid," as used herein interchangeably, refer to a source of alternating current (AC) power.

[0033] The terms "electric load" and "load," as used herein interchangeably, relate to any device or group of devices that may be capable of absorbing electric power from the variable power source.

[0034] The water electrolysis system may include any type of electrolyser, such as but not limited to, a polymer electrolyte membrane water electrolyser, a liquid electrolyte electrolyser, and a solid oxide electrolyser cell (SOEC). The electrolyser may be selected from a proton-exchange membrane water electrolyser and anion-exchange membrane water electrolyser.

[0035] A preferred electrical operating point level may be selected to suppress degradation of one or more components of the electrolyser. The electrolyser typically includes at least one electrolyser cell containing a cathode and anode that are separated by a membrane or a separator (depending on the electrolyser technology used). A separator may be used along with a liquid alkaline or acidic electrolyte in alkaline water electrolyzers and acid water electrolyzers, respectively. The separator may be a porous, thin film that allows passage of the electrolyte ions therethrough, while being electrically insulating, thereby avoiding electrical shorts between the electrodes. The separator may be configured to prevent the crossover of oxygen and hydrogen that are generated at the anode and cathode, respectively, to avoid reduction in hydrogen generation efficiency and prevent a potential safety risk.

[0036] A membrane, such as a polymer electrolyte membrane (PEM) may be employed in solid-state systems having solid polymer electrolyte (SPE) that may be responsible for the conduction of protons, separation of product gases, and electrical insulation of the electrodes. For example, a proton exchange membrane that conducts protons may be used in a proton-exchange membrane water electrolyser and an anion exchange membrane that conducts anions may be employed in an anion-exchange membrane water electrolyser. The use of the polymer electrolyte membrane may be hindered by hydrogen and oxygen crossover that may result from a chemical degradation of the membrane caused by radical attack and subsequent membrane thinning and loss of functional groups. Severity of the membrane degradation may depend on the number of operating hours of the electrolyser, as well as certain operating parameters of the electrolyser, such as working at a high current density.

[0037] The cathode and the anode of the electrolyser may be in a form of a metallic electrode or may contain a catalyst configured to catalyze the hydrogen evolution reaction and the oxygen evolution reaction, respectively. The catalyst and suitable additives may be applied to an electrically conductive support such as a metallic mesh or a gas diffusion layer having a carbon paper or cloth. Alternatively, the catalyst may be applied directly onto the membrane. Non-optimal operating parameters of the electrolyser may accelerate degradation of the cathode and/or the anode, thereby decreasing the electrolyser lifetime. For example, in low-temperature alkaline electrolysis, maintaining operation at a minimum cell potential may reduce degradation of the electrodes.

[0038] The electrolyser cell may include a current collector for conducting electrons to or from the cathode and anode and a flow plate for the flow of the electrolyte and/or water. These additional components may also experience degradation, depending on the operating parameters of the electrolyser.

[0039] A control device of the water electrolysis system may mitigate degradation of different components of the

electrolyser by controlling the operating parameters of the electrolyser. The controlling may be performed by using a control device that comprises at least one energy storage device. The energy storage device may be selected from a capacitor, battery, flow battery, fuel cell, flywheel, and any combination thereof. Preferably, the control device includes at least one of a capacitor and a battery. Non-limiting examples of suitable capacitors include an electric double layer capacitor, farad capacitor, surface mount capacitor, single layer capacitor, ceramic capacitor, and a tantalum capacitor. The term "electric double layer," as used herein, is meant to encompass any one of a double layer capacitor, electrochemical capacitor, supercapacitor, and ultracapacitor. Non-limiting examples of suitable batteries include a lithium-ion battery, lithium polymer battery, lithium sulfur battery, lithium air battery, sodium ion battery, magnesium ion battery, sodium ion battery, potassium ion battery, aluminum ion battery, nickel-metal hydride battery, nickel cadmium battery, and lead-acid battery.

[0040] A control device may comprise at least one energy storage device that may be a fast-charging energy storage device. The term "fast charging," as used herein, when referring to a battery denotes a battery that has a charge rate of 3C or greater, wherein C is the total battery capacity per hour. The fast-charging device may be selected from an electric double-layer capacitor and a lithium-ion battery.

[0041] A control device may comprise at least one energy storage device that may be a high-capacity energy storage device, such as, e.g., a battery having a capacity of 1 A/hour or greater.

[0042] The control device may comprise at least one fast-charging energy storage device and at least one high-capacity energy storage device. The fast-charging energy storage device may assist in regulating the output power of the variable power source to mitigate fast output changes (in the range of seconds) during the operation of the electrolyser to provide the electrical operating point, e.g., to prevent fluctuations of the operation voltage or current of the electrolyser, which may negatively affect the electrolyser lifetime. The high-capacity energy storage device may assist in regulating the output power of the variable power source to mitigate its slow changes (in the range of minutes) to provide the electrical operating point. For example, the high-capacity energy storage device may be discharged to provide power to the electrolyser to maintain the desired operation voltage or current without the need to decrease the voltage or current to non-optimal values or shut down the electrolyser, when the output power of the variable power source becomes insufficient. The high-capacity energy storage device may also be charged to store the excess output power of the variable power source to match the output power provided to the electrolyser to the electrical operating point of the electrolyser.

[0043] The one or more energy storage devices may be used to store sufficient energy from variable power sources until enough energy is available to operate electrolysers with power one or more energy storage devices for sufficient time and sufficient power to optimize an operational goal of the system. For example, a low-power PV system (such as a 5 kW PV system providing power for 5 hours each day) may provide energy to a large energy storage device (such as a 500 kWh battery system) over a period of 20 days, and subsequent to that electrolysers are operated at a high-power rate (such as 10 kW) for a time period shorter than the storage period (such as a continuous operation time of 2 days).

[0044] The operation of the one or more energy storage devices of the control device to effectively control the at least one operating parameter of the electrolyser may be enabled by suitable circuitry, one or more sensors and/or one or more power conversion devices. For example, the control device may include a controller, a sensor configured to sense parameters related to the output power of the variable power source (such as current and voltage) and report a sensed and/or calculated power to the controller, and an electrical power converter, configured to convert at least a portion of the output power of the variable power source into a preferred electrical operating point of the electrolyser. The controller may execute an algorithm configured to automatically carry out various steps in the operation of the control device, including setting the preferred electrical operating point and the at least one portion of the output power. The controller may include a readable memory such as a digital memory or the like for storing data (such as parameters and/or commands, for example, code for implementing the algorithm). Additionally, the controller may include and/or execute a machine learning algorithm configured to process and analyze the stored data.

[0045] The output power of the variable storage device may be divided into a first portion and a second portion. For example, when the output power of the variable power source is higher than the electrical operating point of the electrolyser, the at least one portion of the power may be the first portion that may be converted by the electrical power converter and supplied to the electrolyser after the electrical operating point is set by the controller. The controller may be configured to enable transition of a second portion of the output power of the variable power source to at least one of the energy storage device, grid and load. When the output power of the variable power source is not significantly higher than the electrical operating point of the electrolyser, the electrical power converter may be configured to convert the entire output power of the variable power source into the electrical operating point of the electrolyser. The controller may be configured to enable transition of a power from at least one of the energy storage device and the grid to the electrolyser in addition to the power supplied thereto by the variable power source through the electrical power converter, e.g., when the output power is substantially equal or lower than the electrical operating point of the electrolyser.

[0046] The term "electrical power converter" as used herein refers to voltage-control or current-control alternating current (AC)-to-DC or DC-to-DC converters, for example, buck converters, boost converters, buck-boost converters,

full-bridge converters, flyback converters, half-bridge converters, full-bridge converters, or any other circuit for electrical power conversion/inversion known in the art. An electrical power converter may comprise a DC-to-DC converter that may switch between a current control mode and a voltage control mode. An electrical power converter may comprise a DC-to-DC converter and an AC-to-DC converter.

[0047] The control device may include one or more AC-to-DC converters or DC-to-AC inverters, e.g., for connecting the variable power source to the grid, or the load and/or for connecting the electrolyser to the grid. The control device may include an DC-to-DC converter for connecting the variable power source to the load, when the load is DC-operated load. The electrolyser may include a DC-to-AC connection for connecting to the grid. The control device may include one or more power optimizers configured to maximize the PV array output power by tracking continuously the maximum power point which depends on PV panels temperature and on irradiance values.

[0048] Monitoring the operation of the electrolysers, power sources, power from a grid, power to loads, and power to an energy storage device, may provide patterns for predicting future power needs of load and electrolysers, and allow controlling the electrolysers to and energy storage devices to account for future predicted changes to the available electrical power sources and load requirements. For example, when a known load will be needed in the future, power may be saved to the energy storage devices and provided to the loads when needed, allowing the electrolysers to continue operating at preferred operating parameters.

[0049] Reference is now made to FIGURE 1B which schematically illustrates water electrolysis system **201**, according to some embodiments of the invention. System **201** includes variable power source (such as PV array **203**), electrolyser **205**, and control device **207**, which connects electrolyser **205** to variable power source **203**. Control device **207** includes energy storage device **209** and additional electronic components. Control device **207** may connect variable power source **203** to electric grid **211** and electric load **213**. Control device **207** may be configured to split the output power of variable power source **203** between electrolyser **205** and at least one of energy storage device **209**, electric grid **211** and load **213**, when the output power of variable power source **203** is higher than the electrical operating point of electrolyser **205**, thereby matching the output power to the electrical operating point of electrolyser **205**. Control device **207** may be configured to facilitate delivery of a power from at least one of energy storage device **209** and electric grid **211** to electrolyser **205** in addition to the output power of variable power source **203**, when the output power of variable power source **203** is lower than the electrical operating point of electrolyser **205**, thereby matching the output power to the electrical operating point of electrolyser **205**. Control device **207** may include sensors **215**, such as current sensors, voltage sensors, temperature sensors, pressure sensors, and power sensors. Control device **207** may include switches and a power bus **216** to allow connecting and disconnecting multiple electrolysers in series or parallel as needed. Control device **207** may include a controller or control circuit **217**, that performs the management of the electrolyser operating parameters and states of operation. Control device **207** may include a converter **219**, such as a DC-DC converter to convert a DC power source to be used by a DC electrolyser, or an alternating current (AC)-DC converter to convert an AC power source to be used by a DC electrolyser.

[0050] As mentioned hereinabove, controlling the electrical operating point of the electrolyser may include controlling at least one of an operating voltage and operating current of the electrolyser. The electrolyser may be operated at steady state conditions (such as at a constant voltage or constant current). Alternatively, the electrolyser may be operated in an alternate electrolysis mode that utilizes a pulsed direct current or voltage. Accordingly, in addition to controlling an amplitude of the operating current or voltage, when working at steady state conditions, additional features of the electrolyser electrical operating point may be controlled. For example, by utilizing conventional pulse width modulation (PMW), multiple dependent variables may be altered, including a type of a waveform, a duty cycle, and a frequency. Additionally, the operating current or voltage may be changed linearly versus time in cyclical phases. Controlling at least one of the operating voltage and operating current of the electrolyser may comprise controlling at least one of an amplitude of the operating voltage or operating current, a rate at which the operating voltage or operating current is changed, a type of a waveform of the operating voltage or operating current, a duty cycle of the waveform, and a frequency of the waveform. For example, the current and/or voltage may be controlled to minimize electrochemical stress on the electrolyser membranes.

[0051] Control over said features of the operating current or voltage may be performed by the controller, the electrical power converter and, optionally, the energy storage device. The controller may set the amplitude, waveform type, duty cycle, and frequency and the electrical power converter may receive the at least one portion of the output power of the variable power device and convert it into the electrical operating point of the electrolyser based on the instructions provided by the controller. The energy storage device may enable controlling the rate at which the operating voltage or operating current is changed by storing excess output power when the operating current or voltage need to be decreased and by supplying additional power when the operating current or voltage need to be increased.

[0052] The control device of the water electrolysis system may be configured to control the at least one operating parameter of the electrolyser based on a predicted output power of the variable power source. The predicted output power may be calculated, e.g., by using machine learning algorithms and detectable parameters that affect energy output. For example, when using a PV power source, the predicted output power may be based on the lighting intensity

that depends, *inter alia*, on time of day and weather conditions. Wind turbine efficiency may also be predicted based on weather data.

[0053] Even when the current output power of the variable power source allows operating the electrolyser at certain operating parameters, e.g., at a relatively high current density, thereby increasing hydrogen generation efficiency, said operating parameters may be adjusted based on the predicted output power in order to enhance the electrolyser lifetime, resulting in decreased hydrogen production. For example, when the output power of a PV array is expected to decline in the evening, controlling the at least one operating parameter of the electrolyser may include a preemptive slow decrease of the operating current or voltage to gradually shut down the electrolyser before the nightfall instead of an abrupt shutdown caused by an actual diminishing of the output power. The control device may gradually decrease the operating current or voltage to operate the electrolyser at up to about 10% of the current efficiency during nighttime or when adverse weather conditions are expected. The power for operating the electrolyser may be provided by the energy storage device. While being inefficient in terms of hydrogen generation, operating the electrolyser at very low currents may enhance its lifetime. Accordingly, by using the predicted output power of the variable power source, adjustment of the operating parameters of the electrolyser may advantageously be done before such change may be required by the actual state of the output power, thereby diminishing or even eliminating situations at which the electrolyser works at non-optimal conditions that negatively affect its durability.

[0054] The control device of the water electrolysis system may control additional operating parameters of the electrolyser, such as, but not limited to, an operating temperature of the electrolyser, flowrate of the electrolyte or water, pressure of hydrogen and/or oxygen, and any combination thereof.

[0055] Temperature may be an important operating parameter, especially for PEM electrolysers, that may affect efficiency and durability of the electrolyser. High operating temperatures and current densities within PEM electrolysers may cause accelerated aging of membrane and electrodes. High temperatures may also lead to increased crossover of hydrogen and oxygen. The term "operating temperature of the electrolyser," as used herein, refers to a temperature that may be controlled, e.g., the temperature of the electrolyte or water that flows into the electrolyser cell, as opposed to the temperature of the electrolyte or water that flows from the electrolyser and which may be affected by the processes taking place within the electrolyser.

[0056] The flowrate of the electrolyte or water and gas pressure or composition at the cathode and the anode may also affect durability of the electrolyser. For example, as the electrolyte or water flowrate may control the electrolyser temperature, its effect on the durability may be similar to that of temperature.

[0057] The additional operating parameter may affect the electrical operating point of the electrolyser. For example, operating the electrolyser at higher current densities increases the temperature of the electrolyser, thereby accelerating degradation of the various components of the electrolyser. When operating the electrolyser at a higher temperature is specified, the current density of the electrolyser may be decreased in order to reduce the negative effect on its lifetime. The control device may thus be configured to regulate the output power of the variable power source to match it to the electrical operating point of the electrolyser in view of said additional operating parameter. For example, the controller may be configured to set the operating current or voltage and operating temperature of the electrolyser, wherein the operating current or voltage depend on the operating temperature, and as such, regulating the output power of the variable power source may be also dependent on the operating temperature of the electrolyser.

[0058] The control device may include a sensor configured to measure the at least one additional operating parameter, including the operating temperature of the electrolyser, flowrate of the electrolyte or water, and pressure of hydrogen and/or oxygen. Non-limiting examples of a suitable sensor include a thermocouple, infrared sensor, thin film thermal sensor, flowmeter, pressure transducer, and any combination thereof. The sensor may be used to control said additional operating parameter. The control device may include means for controlling said at least one additional operating parameter, such as, a water cycle and/or a heat exchanger.

[0059] Control over the at least one operating parameter of the electrolyser to increase its lifetime, including the electrical operating point of the electrolyser and the additional operating parameters listed hereinabove, may be based on a predetermined value of the operating parameter. The control device, and in particular, the controller, may include a look-up table that may be used by the controller to set the operating parameter.

[0060] The predetermined value may be derived from a model correlating between the at least one operating parameter and the electrolyser lifetime. The predetermined value may be derived from a model correlating between a combination of different operating parameters and the electrolyser lifetime. For example, the model may correlate between the at least one operating parameter and degradation of one or more components of the electrolyser, such as but not limited to, a membrane, separator, cathode, anode, current collector, or flow plate. The model may correlate between the operating current or voltage, the operating temperature of the electrolyser and the durability of the membrane.

[0061] Additionally or alternatively, the predetermined value may be derived from an empirical/measured data correlating between the at least one operating parameter and the electrolyser lifetime. For example, the empirical/measured data may correlate between the at least one operating parameter and a degradation of one or more components of the electrolyser. Various types of tests may be performed in order to establish a connection between a certain operation

condition of the electrolyser and degradation of a certain component. A non-limiting example of a suitable test includes an accelerated aging test that allows to evaluate the long-term effect of various operating parameters on electrolyser degradation, while the test may be performed for a relatively short period of time.

[0062] Additionally or alternatively, the predetermined value may be derived from data obtained from a plurality of electrolyzers of the same kind that have been previously or currently used in the water electrolysis system. The machine learning algorithm of the controller may be configured to analyze said data to assess a correlation between the at least one operating parameter and the electrolyser lifetime and to provide the predetermined value of the at least one operating parameter based on said correlation.

[0063] The data obtained from the plurality of electrolyzers may include one or more operating parameters, as listed hereinabove, as measured by the control device throughout the water electrolysis system operation.

[0064] The predetermined value may be configured to allow operating the electrolyser for a predefined number of hours at a predefined percentage of a nominal power. It may be established based on the model, empirical/measured data or machine learning algorithm that in order to ensure that the electrolyser operates for a certain number of hours before it has to be replaced, a certain operating parameter of the electrolyser may be set at said predetermined value for a certain period of its operation lifetime. For example, it may be predetermined that an electrolyser of a specific type may be operated at a first current density and/or first voltage and at a first temperature when operated between 0 hours of operation and 100 hours of operation and at a second current density and/or second voltage and at a second temperature when operated between 100 hours of operation and 300 hours of operation, and so forth.

[0065] The control device may perform real-time monitoring of at least one parameter related to electrolyser state-of-health (SOH), and control the at least one operating parameter based on said parameter.

[0066] The terms "monitoring," "sensing," "assessing," and "measuring" are used herein interchangeably.

[0067] The term state-of-health related parameter as used herein refers to a figure of merit of the condition of an electrochemical device, such as an electrolyser, or a combination of electrochemical devices, such as an electrolyser stack, compared to its ideal condition, e.g., its initial condition as provided by a manufacturer, prior to operation by the user. State-of-health of the electrochemical device may be determined based on various electrochemical parameters, such as, but not limited to, resistance, impedance, conductance, capacity, voltage, current, and ability to accept or draw power. Additional parameters related to physical or chemical condition of electrolyser components may also be used to assess its SOH. Non-limiting examples of suitable SOH-related parameters that may be monitored by the control device include an electrolyser voltage, when operated galvanostatically; electrolyser current, when operated potentiostatically; internal cell resistance or impedance; temperature of the electrolyte; conductivity of the electrolyte; chemical composition of the electrolyte and any combination thereof. For example, high operation voltage may indicate a loss in performance that may be a sign of electrolyser degradation. Low operating voltage on the other hand may result from hydrogen or oxygen crossover that may be enabled by membrane thinning. Excessively high temperature of the electrolyser may be a sign of high ohmic losses due to electrolyser degradation. Membrane constituents found in the electrolyte or water that flows from the outlet of the electrolyser may serve as an indication of decomposition of the membrane or separator, such as fluoride ions from a fluoropolymer-based PEM.

[0068] When referring to the temperature of the electrolyser (as opposed to the operating temperature of the electrolyser), it may include any one of a temperature of the electrolyte that flows from an outlet of the electrolyser, a gradient of the temperature of the electrolyser between an inlet and the outlet of the electrolyser, and a temperature of the electrolyte within the membrane or the separator.

[0069] The control device may include at least one device configured to measure the SOH-related parameter. For example, the temperature may be measured by one or more of a thermocouple, infrared sensor, and thin film thermal sensor. The electrolyser voltage (when operated galvanostatically) and/or the electrolyser current (when operated potentiostatically) may be assessed by one or more of a polarization curve (I-V curve), dynamic hydrogen electrode (DHE) combined with a PEM strip, hydrogen reference electrode (HRE), and solid electrolyte connection. The internal cell resistance or impedance may be assessed by one or more of a polarization curve (I-V curve), dynamic hydrogen electrode (DHE) combined with a PEM strip, hydrogen reference electrode (HRE), solid electrolyte connection, and electrochemical impedance spectroscopy (EIS). The chemical composition of the electrolyte may be assessed by using a fluoride selective electrode.

[0070] Controlling the at least one operating parameter of the electrolyser may be based on a correlation between a predetermined value of the operating parameter and the SOH-related parameter of the electrolyser. The predetermined value may be derived from a model correlating between the at least one operating parameter and the SOH-related parameter. The predetermined value may be derived from an empirical/measured data correlating between the at least one operating parameter and the SOH-related parameter.

[0071] The predetermined value may be configured to allow operating the electrolyser at a predefined percentage of a nominal power without significantly affecting the measured SOH-related parameter. The term "without significantly affecting" as used herein, may refer to a change in the SOH-related parameter that may be less than about 1%. The term "without significantly affecting" may refer to a change in the SOH-related parameter that may be less than about

5%. The term "without significantly affecting" may refer to a change in the SOH-related parameter that may be less than about 10%. It may be established based on the model or empirical/measured data that in order to ensure that the electrolyser operates without significantly affecting its lifetime as expressed by the measured SOH-related parameter, a certain operating parameter of the electrolyser may be set at said predetermined value for the measured SOH-related parameter. For example, it may be predetermined that an electrolyser of a specific type may be operated at a first current density and/or first voltage and at a first temperature when the measured SOH-related parameter is X and at a second current density and/or second voltage and at a second temperature when the measured SOH-related parameter is more than 10% higher or lower than X. As such, constant monitoring of the SOH-related parameter may be required in order to establish when the at least one operating parameter needs to be adjusted.

[0072] The machine learning algorithm of the control device may be configured to analyze the data obtained from a plurality of electrolysers of the same kind that have been previously employed in the water electrolysis system to assess a correlation between the at least one operating parameter and the SOH-related parameter of said plurality of electrolysers. Controlling the at least one operating parameter may be based on a measured value of the SOH-related parameter and the analysis of said correlation. The machine learning algorithm may be configured to analyze the previous operating data of the current electrolyser to assess a correlation between the at least one operating parameter and the SOH-related parameter of said electrolyser. The machine learning algorithm may include a feedback loop, wherein the at least one operating parameter affects the SOH-related parameter and wherein the at least one operating parameter may be adjusted based on the measured value of the SOH-related parameter.

[0073] The data obtained from the plurality of electrolysers may include one or more operating parameters and SOH-related parameters, as listed hereinabove, as measured by the control device throughout the water electrolysis system operation.

[0074] The control device may be configured to repeatedly monitor the SOH-related parameter and to subsequently control the at least one operating parameter. The control device may be configured to continuously monitor the SOH-related parameter.

[0075] For example, the electrolyser may be operated in a galvanostatic mode and the control device may monitor the voltage of the electrolyser throughout its operation, wherein current may be the at least one operating parameter of the electrolyser and voltage may be the SOH-related parameter of the electrolyser. The control device may therefore repeatedly adjust the current based on the measured voltage. Alternatively, the electrolyser may be operated in a potentiostatic mode and the control device may monitor the current of the electrolyser throughout its operation. In another example, the electrolyser may be operated in a potentiostatic mode and the control device may monitor the temperature of the electrolyte or water that flows from the electrolyser outlet throughout its operation. Voltage may be the at least one operating parameter of the electrolyser and temperature may be the SOH-related parameter of the electrolyser, such that the voltage may be repeatedly adjusted based on the measured temperature.

[0076] The machine learning algorithm may be configured to analyze the SOH-related parameter to detect degradation of a specific component of the one or more components of the electrolyser. The control device may be configured to adjust the at least one operating parameter to increase lifetime of the specific component of said one or more components.

[0077] For example, the electrical operating point of the electrolyser may be selected to increase a lifetime of the membrane. The electrical operating point may comprise an operating current or voltage that allow to operate the electrolyser at a constant current or voltage providing up to about 75% of the current efficiency.

[0078] For example, lifetime may be increased by closing down electrolysers at certain intervals for certain amounts of time. For example, lifetime may be increased by reducing the hydrogen production of electrolysers at certain intervals for certain amounts of time.

[0079] For example, the electrical operating point may be selected to increase a lifetime of at least one of the cathode and the anode. The electrical operating point may comprise reducing the operating voltage or operating current to operate the electrolyser at about 0% to about 10% of the current efficiency.

[0080] In yet another example, the electrical operating point may include zero operating voltage or operating current, when the output power of the variable power source and the power of the energy storage device is lower than the electrical operating point or when the SOH-related parameter falls or rises beyond a critical value. Said critical value may be related to a thinning of the membrane.

[0081] Controlling the at least one operating parameter may include lowering the operating current or temporarily shutting down the electrolyser, when the SOH-related parameter falls or rises beyond a critical value. The SOH-related parameter may be an electrolyser voltage that rises above the critical value. The critical value may be related to one or more of a cathode deactivation, anode deactivation, and reduction in ionic conductivity of the membrane or separator.

[0082] The term "critical value," may refer to a value on a relative scale, wherein higher values mean better SOH. The electrical operating point may include zero operating voltage or operating current, when the SOH-related parameter falls beyond the critical value.

[0083] The water electrolysis system may include a plurality of electrolyser (or electrolyser cells) that are stacked together to form an electrolyser stack. Preferably, the control device controls the operating parameters of the stack as

a whole.

[0084] The water electrolysis system may include a plurality of electrolyser stacks. There may be provided a water electrolysis system for hydrogen generation, the system including a plurality of variable power sources, a plurality of electrolyser stacks, and a control device, wherein at least a portion the electrolyser stacks are operatively connected to variable power sources through the control device, wherein the control device may be configured to control at least one operating parameter of the plurality of electrolyser stacks to increase their lifetime, wherein the at least one operating parameter comprises an electrical operating point of the electrolyser stack, wherein the control device regulates an output power of the plurality of variable power sources to match it to an electrical operating point of the plurality of electrolyser stacks.

[0085] Each electrolyser stack may be operatively connected to its corresponding variable power source through the control device. The control device may regulate an output power of each variable power source to match it to an electrical operating point of its corresponding electrolyser stack.

[0086] The plurality of variable power sources may be arranged in a series and/or parallel electrical connection to provide the output power to the plurality of electrolyser stacks. The control device may change the type of the electrical connection arrangement (series or parallel) to match the output power of the plurality of variable power sources to the electrical operating point of the plurality of electrolysers.

[0087] The control device may include the energy storage device, controller, sensor, and electrical power converter, as detailed hereinabove. In order to control each electrolyser stack individually, the control device may include a plurality of control units, wherein each control unit comprises a controller, sensor and electrical power converter. The variable power sources may be individually connected to their corresponding electrolyser control units through such unit. The control device may be configured to individually regulate the output power of the plurality of the variable power sources to match it to the electrical operating point of the plurality of the corresponding electrolyser stacks.

[0088] The control device having a plurality of control units, wherein each control unit comprises the controller, sensor and electrical power converter, may include one or more energy storage devices, wherein the one or more energy storage devices may be employed by the plurality of the control units to store and release power when needed. Each control unit may include an individual energy storage device, such that the energy storage device may be used solely by a control unit and its respective variable power source-electrolyser stack pair. Control units may be modular and allow hot-swap capabilities within the control device to reduce down time due to maintenance and maintain hydrogen production.

[0089] The plurality of variable power sources may be operatively connected to at least one of an electric grid and load. The control device may connect the plurality of variable power sources to the electric grid and/or load. The control device may include an AC-to-DC converter or a DC-to-AC inverter.

[0090] Controlling the at least one operating parameter of the electrolyser stack may be based on a predetermined value of the operation parameter, as explained in detail hereinabove. Preferably, when stacks including multiple electrolyser cells are involved, said predetermined value may be derived from a machine learning analysis of the previously operated electrolyser stacks of the same system, rather than from a model or empirical/measured data, which are more suitable for single cells.

[0091] Controlling the at least one operating parameter may be based on the real-time monitoring of a state-of-health (SOH)-related parameter of the electrolyser stack by the control device, as explained in detail hereinabove. While said SOH-related parameters may vary among different electrolyser cells within the stack, a single value of the SOH-related parameter may be assigned to the stack, e.g., an average value of SOH-related parameters of each cell.

[0092] The control device may shut down one or more stacks, while other stacks continue to operate, for example, when the predicted power output may be insufficient for operating all the stacks or when the SOH of said one or more stacks indicates that they undergo rest or regeneration procedure. The machine learning algorithm of the control device may be configured to compare SOH of different electrolyser stacks, and to select the operating parameters of each electrolyser stack based on said comparison. When there is a significant difference between SOH of different electrolyser stacks, electrolyser stacks with better SOH may be operated at higher current densities, while stacks with inferior SOH may be operated at lower current densities or not operated at all for a certain period of time or until the difference between the SOH of different stacks becomes less significant. The control device may therefore not only assist in prolonging the lifetime of the individual electrolyser stacks but also harmonize the operation of the entire water electrolysis system in terms of durability of its electrolyser stacks.

[0093] Reference is now made to FIGURE 2A that schematically illustrates water electrolysis system **301** according to some embodiments of the invention. System **301** includes a plurality of variable power sources (PV arrays) **303a**, **303b**, **303c**, **303d**, and **303e**. Variable power sources **303a**, **303b**, **303c**, **303d**, and **303e** may be electrically connected therebetween in series and/or in parallel. System **301** may include a plurality of electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e**. Electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e** may also be electrically connected therebetween in series and/or in parallel. Electrolyser stacks are operatively connected to variable power sources through control device **307**. Control device **307** may regulate an output power of variable power sources (PV arrays) **303a**, **303b**, **303c**, **303d**, and **303e** to match it to an electrical operating point of electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e**. For

example, control device **307** may regulate an output power of variable power source **303a** to match it an electrical operating point of electrolyser stack **305a**, an output power of variable power source **303b** to match it an electrical operating point of electrolyser stack **305b**, an output power of variable power source **303c** to match it an electrical operating point of electrolyser stack **305c**, an output power of variable power source **303d** to match it an electrical operating point of electrolyser stack **305d**, and an output power of variable power source **303e** to match it an electrical operating point of electrolyser stack **305e**. Alternatively, the control device may regulate the output power of the PV arrays by combining the output power of variable power sources **303a**, **303b**, **303c**, **303d**, and **303e** that are connected in series and/or in parallel and then splitting it to match to the electrical operating point of electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e**.

[0094] Control device **307** may control at least one operating parameter of each one of electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e** independently, to prolong the lifetime of each electrolyser stack. Control device **307** may be configured to monitor a SOH-related parameter of each one of electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e**. Control device **307** may include a controller **307a**, switches **307b**, a power bus **307c**, power devices **307d**, sensors **307e**, and electrical energy storage devices **307f**.

[0095] The output power of variable power sources **303a**, **303b**, **303c**, **303d**, and **303e** may be split evenly between electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e**. Alternatively, the output power of variable power sources **303a**, **303b**, **303c**, **303d**, and **303e** may be split unevenly between electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e**, depending on the electrical operating point of each stack. For example, some electrolyser stacks may be operated at a lower current density or lower voltage and other electrolyser stacks may be operated at a higher current density or higher voltage. The output power may be delivered to only a portion of electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e**, while the remaining stacks may be shut down, e.g., in view of the measured SOH-related parameter of these stacks and/or when the output power (or predicted output power) of variable power sources **303a**, **303b**, **303c**, **303d**, and **303e** may be significantly lower than the electrical operating point of the plurality of electrolyser stacks **305a**, **305b**, **305c**, **305d**, and **305e**.

[0096] Reference is now made to FIGURE 2B that schematically illustrates water electrolysis system **401** according to some embodiments of the invention. System **401** may include a plurality of variable power sources **403a**, **403b**, **403c**, **403d**, and **403e**. System **401** may include a plurality of electrolyser stacks **405a**, **405b**, **405c**, **405d**, and **405e**. System **401** may include control device **407** that includes a plurality of control units **407a**, **407b**, **407c**, **407d**, and **407e**. Variable power sources **403a**, **403b**, **403c**, **403d**, and **403e** are electrically connected therebetween in series. Electrolyser stack **405a** may be operatively connected to the plurality of variable power sources through control unit **407a** of control device **407**. Similarly, electrolyser stack **405b** may be operatively connected to the plurality of variable power sources through control unit **407b**, electrolyser stack **405c** may be operatively connected to the plurality of variable power sources through control unit **407c**, electrolyser stack **405d** may be operatively connected to the plurality of variable power sources through control unit **407d**, and electrolyser stack **405e** may be operatively connected to the plurality of variable power sources through control unit **407e** of control device **407**. Electrolyser stacks **405a**, **405b**, **405c**, **405d**, and **405e** may be electrically connected therebetween in series via control units **407a**, **407b**, **407c**, **407d**, and **407e**. Each control unit may individually control the output power of the plurality of variable power sources to match the electrical operating point of its corresponding electrolyser stack.

[0097] Reference is now made to FIGURE 2C that schematically illustrates water electrolysis system **501** according to some embodiments of the invention. System **501** includes a plurality of variable power sources **503a**, **503b**, **503c**, **503d**, and **503e**. System **501** may include a plurality of electrolyser stacks **505a**, **505b**, **505c**, **505d**, and **505e**. System **501** may include control device **507** that includes a plurality of control units **507a**, **507b**, **507c**, **507d**, and **507e**, and a plurality of optimizers **509a**, **509b**, **509c**, **509d**, and **509e**. Variable power source **503a** may be operatively connected to optimizer **509a** of control device **507** that may be configured to maximize the output power of power source **503a**. Likewise, variable power source **503b** may be operatively connected to optimizer **509b**, variable power source **503c** may be operatively connected to optimizer **509c**, variable power source **503d** may be operatively connected to optimizer **509d**, and variable power source **503e** may be operatively connected to optimizer **509e**. Optimizers **509a**, **509b**, **509c**, **509d**, and **509e** may be electrically connected therebetween in series. Electrolyser stack **505a** may be operatively connected to the plurality of variable power sources through control unit **507a** of control device **507**. Similarly, electrolyser stack **505b** may be operatively connected to the plurality of variable power sources through control unit **507b**, electrolyser stack **505c** may be operatively connected to the plurality of variable power sources through control unit **507c**, electrolyser stack **505d** may be operatively connected to the plurality of variable power sources through control unit **507d**, and electrolyser stack **505e** may be operatively connected to the plurality of variable power sources through control unit **507e** of control device **507**. Control units **507a**, **507b**, **507c**, **507d**, and **507e** may be electrically connected therebetween in series. Each optimizer may individually control its corresponding variable power source to provide maximum output power and each control unit may individually control the electrical operating point of its corresponding electrolyser stack to regulate the output power of the plurality of variable power sources to match it to the electrical operating point of the particular electrolyser stack.

[0098] Reference is now made to FIGURE 2D that schematically illustrates water electrolysis system **511** according to some embodiments of the invention. System **511** includes a plurality of variable power sources **503a**, **503b**, **503c**, **503d**, and **503e**. System **511** may include a plurality of electrolyser stacks **505a**, **505b**, **505c**, **505d**, and **505e**. System **511** may include control device **519** and a plurality of control units **517a**, **517b**, **517c**, **517d**, and **517e**, and a plurality of optimizers **509a**, **509b**, **509c**, **509d**, and **509e**. Variable power source **503a** may be operatively connected to optimizer **509a** of control device **507** that may be configured to maximize the output power of power source **503a**. Likewise, variable power source **503b** may be operatively connected to optimizer **509b**, variable power source **503c** may be operatively connected to optimizer **509c**, variable power source **503d** may be operatively connected to optimizer **509d**, and variable power source **503e** may be operatively connected to optimizer **509e**. Optimizers **509a**, **509b**, **509c**, **509d**, and **509e** may be electrically connected therebetween in series to an input of control device **519**. Electrolyser stack **505a** may be operatively connected to the plurality of variable power sources through control unit **517a** of control device **519**. Similarly, electrolyser stack **505b** may be operatively connected to the plurality of variable power sources through control unit **517b**, electrolyser stack **505c** may be operatively connected to the plurality of variable power sources through control unit **517c**, electrolyser stack **505d** may be operatively connected to the plurality of variable power sources through control unit **517d**, and electrolyser stack **505e** may be operatively connected to the plurality of variable power sources through control unit **517e** of control device **519**. Control units **517a**, **517b**, **517c**, **517d**, and **517e** may be electrically connected therebetween in parallel to an output of control device **519**. Each optimizer may individually control its corresponding variable power source to provide maximum output power and each control unit may individually control the electrical operating point of its corresponding electrolyser stack to regulate the output power of the plurality of variable power sources to match it to the electrical operating point of the particular electrolyser stack. Control device **519** may include a controller **519a**, switches **519b**, a power bus **519c**, power devices **519d**, sensors **519e**, fast electrical energy storage devices **519f**, and high-capacity electrical energy storage devices **519g**.

[0099] Reference is now made to FIGURE 2E that schematically illustrates water electrolysis system **521** according to some embodiments of the invention. A control device may include one or more control units **527**. Control unit **527** be configured to operatively connect an electrolyser **525** to a variable power source **523**. The control unit **527** may comprise a control circuit **531**; a switching circuit **532**; a data storage repository **533**; one or more energy storage devices **534**; sensor(s) **535**; an electrical power converter **536**; and a communication circuit **537**. The electrical power converter **536** may be configured to convert a first portion of the output power of the variable power source into an electrical operating point of the electrolyser stack. The control circuit **531** may be configured to set the electrical operating point and the first portion of the output power. The control unit **527** may be configured to control at least one operating parameter of the electrolyser to increase its lifetime, where the at least one operating parameter comprises the electrical operating point of the electrolyser stack. Sensor(s) **535** may be configured to sense the output power of the variable power source and report a sensed power to controller of the control circuit **531**. Sensor(s) **535** may be configured to sense the temperature, pressure, flow rate, current, voltage, and power to ancillary equipment (pumps, heat exchanges, compressors, etc.).

[0100] The control device may include one or more sensors configured to measure an operating parameter of the electrolyser, such as an operating temperature of the electrolyser, flowrate of the electrolyte or water, and pressure of hydrogen and/or oxygen. Non-limiting examples of a suitable sensor include a thermocouple, infrared sensor, thin film thermal sensor, flowmeter, pressure transducer, and any combination thereof. The sensor may be used to control said additional operating parameter. The control device may include means for controlling an operating parameter, such as, a water cycle and/or a heat exchanger.

[0101] The control device may include at least one device configured to measure a SOH-related parameter of the electrolyser, such as, but not limited to voltage, current, internal cell resistance or impedance, temperature of the electrolyte, conductivity of the electrolyte, chemical composition of the electrolyte and any combination thereof. Non-limiting examples of suitable device include thermocouple, infrared sensor, thin film thermal sensor, potentiostat, amperemeter, dynamic hydrogen electrode (DHE) combined with a PEM strip, hydrogen reference electrode (HRE), solid electrolyte connection, fluoride selective electrode, and any combination thereof.

[0102] Reference is now made to FIGURE 2F that schematically illustrates a water electrolysis system **540** according to some embodiments of the invention. Water electrolysis system **540** may include an impedance control circuit **543** in series between the outputs **541a** and **541b** of a power source **541** and the inputs **542a** and **542b** of an electrolyser stack **542**. The impedance control circuit **543** may include active and passive components, such as comparators, op amps, inductors, resistors, capacitors. For example, active components may be configured to control the impedance when a operating parameters are in certain ranges. The impedance control circuit **543** may be configured to set limits on changes to the current received by the electrolyser stack **542**, such as by using one or more inductors connected in series with switches, where different impedances are connected based on the voltage of the electrolyser.

[0103] Reference is now made to FIGURE 2G that schematically illustrates a water electrolysis system **550** according to some embodiments of the invention. Water electrolysis system **550** may include an impedance control circuit **553** in series between the outputs **551a** and **551b** of a power source **551** and the inputs **552a** and **552b** of an electrolyser stack **552**. The impedance control circuit **553** may include active and passive components, such as comparators, op amps,

inductors, resistors, capacitors. The impedance control circuit **553** may be configured to set limits on changes to the current received by the electrolyser stack **552**, such as by using one or more inductors connected in series with switches, where different impedances are connected based on the voltage of the electrolyser.

[0104] A method for operating an electrolyser coupled to a variable power source is disclosed. The method includes controlling at least one operating parameter of the electrolyser to increase its lifetime, wherein the at least one operating parameter includes an electrical operating point of the electrolyser and the method includes regulating an output power of the variable power source to match it to an electrical operating point of the electrolyser.

[0105] Reference is now made to FIGURE 3A which schematically illustrates steps of an exemplary method **600** for operating an electrolyser coupled to a variable power source, according to some embodiments of the invention. Step **601** includes comparing the output power of the variable power source with the electrical operating point of the electrolyser. The output power may be an actual measured power or a predicted power. The electrical operating point may be based on a predetermined value.

[0106] When the output power of the variable power source is higher than the electrical operating point in step **601**, step **603** may be performed that includes evaluating whether the output power is substantially higher than the electrical operating point. When the output power is not substantially higher than the electrical operating point in step **603**, steps **605** and/or **607** may be performed. Step **605** includes using a DC-to-DC converter to match the output power of the variable power source to the electrical operating point of the electrolyser. Step **607** includes charging a fast-charging energy storage device to store the excess power to match the output power of the variable power source to the electrical operating point of the electrolyser. When the output power is substantially higher than the electrical operating point in step **603**, a high-capacity energy storage device may be used to store the excess power and match the output power of the variable power source to the electrical operating point of the electrolyser (step **609a**). The excess output power may be delivered to at least one of an electric grid (step **609b**) and a load (step **609c**). Parameters other than the amount of excess power may also be used to choose between one or more of the DC-to-DC converter, fast-charging energy storage device, high-capacity energy storage device, electrical grid and load.

[0107] When the output power of the variable power source is lower than the electrical operating point in step **601**, steps **611** or **613** may be performed. Step **611** includes shutting down the electrolyser. The electrolyser may be shut down for a certain period of time. Step **613** includes drawing additional power to match the output power to the electrical operating point. Depending on the on-grid/off-grid location of the variable power source and the electrolyser, and/or the capacity and grid power cost) the additional power may be supplied by the high-capacity energy storage device (step **615a**) or drawn from the electric grid (step **615b**). Selection of step **611** or step **613** may also be made based on the same considerations. For example, when the amount of additional power is high and the grid power is expensive, step **611** (such as shutting down the electrolyser for a certain period of time) may be performed. In instances, where the amount of additional power is low and the grid power is expensive, steps **613** and **615a** may be chosen, wherein the additional power is supplied by the high-capacity energy storage device. When the amount of additional power is high and the grid power is cheap, steps **613** and **615b** may be performed, wherein the additional power is drawn from the electric grid.

[0108] It is to be emphasized that matching the output power to the electrical operating point may include controlling one or more of the operating current or voltage of the electrolyser, a rate at which the operating voltage or operating current is changed, a type of a waveform of the operating voltage or operating current, a duty cycle of the waveform, and a frequency of the waveform. Accordingly, Step **601** may include evaluating the output power of the variable power source to check whether one or more of the above operating parameters may be satisfied.

[0109] Reference is now made to FIGURE 3B which schematically illustrates steps of an exemplary method **700** for operating an electrolyser coupled to a variable power source, according to some embodiments of the invention. Step **701** includes measuring a SOH-parameter of the electrolyser to establish its electrical operating point. Step **702** includes comparing the output power of the variable power source with the electrical operating point of the electrolyser. The output power may be an actual measured power or a predicted power.

[0110] When the output power of the variable power source is higher than the electrical operating point in step **702**, step **703** may be performed that includes evaluating whether the output power is substantially higher than the electrical operating point. When the output power is not substantially higher than the electrical operating point in step **703**, steps **705** and/or **707** may be performed. Step **705** includes using a DC-to-DC converter to match the output power of the variable power source to the electrical operating point of the electrolyser. Step **707** includes charging a fast-charging energy storage device to store the excess power to match the output power of the variable power source to the electrical operating point of the electrolyser. When the output power is substantially higher than the electrical operating point in step **703**, a high-capacity energy storage device may be used to store the excess power and match the output power of the variable power source to the electrical operating point of the electrolyser (step **709a**). The excess output power may be delivered to at least one of an electric grid (step **709b**) and a load (step **709c**).

[0111] When the output power of the variable power source is lower than the electrical operating point in step **702**, step **710** is performed, which includes evaluating the SOH-related parameter. When the SOH of the electrolyser is

considered to be bad, step **711** may be performed, including shutting down the electrolyser. When the SOH of the electrolyser is considered to be good, step **713** may be performed, which includes drawing additional power to match the output power to the electrical operating point. The additional power may be supplied by the high-capacity energy storage device (step **715a**) or drawn from the electric grid (step **715b**).

[0112] Reference is now made to FIGURE 3C which schematically illustrates steps of an exemplary method **800** for operating a plurality of electrolyser stacks coupled to a plurality of variable power sources, according to some embodiments of the invention. Step **801** includes measuring a SOH-parameter of each electrolyser stack to establish its electrical operating point. When the measured SOH-related parameter of some stacks is below a critical value as at step **802**, step **802a** is performed, which includes shutting down these stacks. Stacks which SOH below the critical value may be considered as having the electrical operating point of 0 Watt (or current density of 0 Amp/cm²).

[0113] Step **803** includes comparing the output power of the plurality of variable power sources with the electrical operating point of the electrolyser. The plurality of variable power sources may be electrically connected in series and/or in parallel. The output power may be an actual measured power of the plurality of variable power sources or a predicted power.

[0114] When the output power of the plurality of variable power sources is higher than the total electrical operating point (for stacks which SOH-related parameter is above the critical value) in step **803**, step **804** may be performed that includes evaluating whether the output power of the plurality of variable power sources is substantially higher than the total electrical operating point of the plurality of electrolyser stacks. When the output power is not substantially higher than the electrical operating point in step **804**, steps **805** and/or **807** may be performed. Step **805** includes using a DC-to-DC converter to match the output power of the variable power source to the electrical operating point of the electrolyser. Step **807** includes charging a fast-charging energy storage device to store the excess power to match the output power of the plurality of variable power sources to the total electrical operating point of the plurality of electrolyser stacks. When the output power is substantially higher than the electrical operating point in step **804**, one or more high-capacity energy storage device may be used to store the excess power and match the output power of the plurality of variable power sources to the total electrical operating point of the plurality of electrolyser stacks (step **809a**). The excess output power may be delivered to at least one of an electric grid (step **809b**) and a load (step **809c**).

[0115] When the output power of the plurality of variable power sources is lower than the total electrical operating point in step **803**, step **810** is performed, which includes comparing the SOH-related parameters of different electrolyser stacks. Depending on said comparison steps **811** or **813** may be performed. Step **811** includes shutting down one or more electrolyser stacks which have inferior SOH. For example, when the SOH of an electrolyser stack is above the critical value and the output power is higher than the total electrical operating point, the method includes delivering an adjusted output power from the variable power sources to said stack (such as operating the electrolyser stack). However, when the output power is lower than the total electrical operating point, the method may include shutting down electrolyser stacks with inferior SOH and supplying the adjusted output power only to stacks with better SOH (step **813**). The insufficient output power may be supplemented by drawing additional power from the high-capacity energy storage device (step **815a**) or drawn from the electric grid (step **815b**). Following the output power adjustment, in step **817**, power may be split between the remaining electrolyser stacks, wherein the operating parameters of each electrolyser, such as operating current or voltage, rate of change of the operating voltage or operating current type of a waveform of the operating voltage or operating current, duty cycle of the waveform, or frequency of the waveform are set based on the measured SOH-related parameter. As used herein, the rate of change of an operating parameter, is the first derivative over time of that operating parameter, and may be termed the first order rate of change. As used herein, the second order rate of change of an operating parameter, is the second derivative over time of that operating parameter, and may be termed the acceleration of the operating parameter.

[0116] During operational control of an electrolyser, the operating parameters may be changed. In general, when the operating parameters of an electrolyser are changed from first state to a second state, such as during startup, shutdown, or production level change, the operating parameters, such as voltage or current are changed. To improve the operation of the electrolyser, such as for increased hydrogen production rate, increased lifetime hydrogen production, increased longevity, decreased maintenance intervals, decreased mean times between failures, and increase reliability, the operational parameters of the electrolyser may be monitored using sensors to prevent electrochemical stress to the electrolyser that may decrease performance. The electrochemical stress may be correlated with a delay or time lag in response to the change in operational parameters, and by monitoring the operational parameters and computing a value associated with the lag, transitions that decrease the lag may be recorded and the electrolyser operated. For example, when a current control converter applies a current change to transition from one state to another state of the electrolyser, the current change may be controlled to reach an operational goal such as prolonging lifetime or maximizing hydrogen production. These may be termed "permitted changes" may be used to improve the operation over the lifetime of the electrolyser. As used herein the term "IV values" refers to current or voltage values used to control the changes in operating parameters or states of the electrolyser. The terms "IV values", "operating parameters", "operating conditions", "electrical operating point", and "operating point" may refer to the at least some values of operating controls of the

electrolyser at a given time, and "IV value changes", "permitted changes" may refer to the time evolution of values of operating controls of the electrolyser over a time period. Operating controls of the electrolyser may include electrolyser voltage, electrolyser current (voltage and current define power), operation of ancillary equipment (voltage, current, or power), pressure(s), temperature(s), flow rate(s), etc. The devices, methods, and systems described herein may apply

to any of these operating controls that are used to operate an electrolyser, but specific attention is made to electrolyser voltage and current. It is understood that these techniques and devices can be used for any of the other operating controls (such as operation of ancillary equipment -voltage, current, or power, pressures, temperatures, flow rates, etc). **[0117]** As used herein, electrolyser operational "states" mean specific electrical operating point settings or setpoint. Electrolyser operational states may include a range of hydrogen production states with production rates from 5 percent of full rated power or voltage to full rated power or voltage. In some cases, an overpower range may be beneficial for the maintenance, operation, or optimal end of life management. Cold start describes the transition from cold state to operational state. Hot start describes preheating and pressurising the electrolyser using ancillary equipment (such as heaters, compressors, etc) to optimal turn on transitions to operational state. Open circuit voltage (OCV) states may be based on a lower heating value (LHV)-OCV state and a higher heating value (HHV) state.

[0118] Transitions between these states, or within the range of operational states, may involve several portions to perform each transition with minimal electrochemical degradation. For example, a current-controlled electrolyser may transition from a first state to a second state with a low amount of degradation by accelerating a slew rate of the supply current so that the voltage lag behind the current is minimal. A slew rate may then be chosen that minimizes degradation by remaining below a threshold determined during a break in period performed before entering operation, such as doing a calibration of the electrolyser's permitted changes. Once the current and voltage are aligned with the target state of the transition, a deceleration of the current may be performed before reaching the electrical operating point. The acceleration, slew rate, and deceleration may be defined using values and mathematical formula that allow for a smooth and continuous transition. The transition in the controlled parameter (such as voltage, current, or power) is continuous, and the first differential is continuous to ensure smooth transitions from one state to another. Additionally, a slew rate threshold (first differential) and acceleration threshold (second differential) may be determined during break in to minimize the operational parameter lag. For example, during a transition the operational parameter lag may be modelled as a lag of the voltage behind the current according to an exponential relationship such as the formula of Equation (5):

$$y = y_0 + A_1(1 - e^{-x/t_1})$$

Equation (5)

Besides the lag, an operational parameter drift may be exhibited during operation and over the lifetime of the electrolyser. Linear models may be used to quantify these drifts, that may be associated with a long-term degradation of the anode or cathode layers.

[0119] The following figures show example disclosures of the devices and methods that may implement the method of smooth state transitions described herein.

[0120] Reference is now made to FIGURE 4A, which schematically illustrates steps of a method **900** for testing an operating parameter change of an electrolyser coupled to a variable power source, according to some embodiments of the invention. An operating parameter change, such as a current or voltage (IV) change, is received as at step **901**, such as a command or message sent from a processor. An initial state of an electrolyser is retrieved and recorded as at step **902**. The IV change is applied to the electrolyser, and the resulting response of the electrolyser is monitored using sensors as at step **903**. The sensors may monitor a second parameter of the electrolyser, such as voltage, current, temperature, power, power to ancillary devices (such as devices used for heating or cooling the electrolyser), pressure, water flow, and hydrogen production. The monitored second parameter is used to compute a lag as at step **904** in the response of the second parameter over time, such as over seconds or minutes. The lag is a measure between the actual response recorded by a data logger, and an expected response. An expected response may be a response that is being targeted during operation, such as a linear response between voltage and current. The lag may be quantified by area between two curves, or fitting a model to the measured data and using resulting fitted coefficients of the model. For example, a linear model or exponential as described herein.

[0121] For example, the second parameter is monitored for 1 second to 60 minutes, or any subrange therebetween, such as using a data logger or a data recorder. The monitoring is continued till the response of the second parameter is linear. The computed lag of the second parameter is compared to a threshold as at step **905** and when the lag within the permitted range, the initial state and transition are stored as a permitted change as at step **906**. When the lag is not within the permitted range, the initial state and a decreased change is stored as at step **907** to be tested in a future iteration of method **900**.

[0122] Repeated iterations of method **900** are performed for multiple initial states, permitted changes are found by computing the lag as described herein, and the permitted changes. The recordings of permitted operational parameter

changes may be used to control the electrolyser, and the permitted operational parameter changes may be monitored and updated as needed similarly to the break in calibration.

[0123] Reference is now made to FIGURE 4B, which schematically illustrates steps of method **920** for using a lag-free operating parameter change of an electrolyser coupled to a variable power source, according to some embodiments of the invention. A command or request for a transition from a first state to a second state is received as at step **921**. An initial state of the electrolyser is retrieved by receiving values from sensors configured to monitor the operating parameters as at **922**, and a final state is estimated based on the initial state and requested transition. Permitted changes in the range between the initial and final states are retrieved as at step **923**. A piecewise smoothed IV change is computed based on the permitted changes as at step **924**. The smoother IV change is applied to the electrolyser as at step **925**, and the operating parameters are monitored using the sensors. A lag is computed as at step **926**, and the lag is compared to a threshold as at step **927**. When the lag is compliant with the threshold, a successful transition is stored in a log as at step **928**. When the lag is not compliant with the threshold as at step **929**, the permitted IV change is decreased and stored in the permitted changes, along with the initial state and a flag that the decreased IV change has not been tested for compliance with the threshold. The next time this transition is requested from this initial state, the decreased change may be applied, and the lag computed again as in method **900** of FIGURE 4A.

[0124] Reference is now made to FIGURE 4C, which schematically illustrates steps of a method **940** for implementing an operating state transition of an electrolyser coupled to a variable power source, according to some embodiments of the invention. A request for a transition from an initial state to a final state may be determined as at step **941**, such as by a higher logical function of a control device for changing the operation of multiple electrolysers under the constraints of a given predicted power availability. According to a state machine of the specific electrolysers being controlled, intermediate states are checked between the initial and final states as at step **942**. When intermediate states don't exist, a single step transition is performed as at step **943b**. When intermediate states exist, for each intermediate state the permitted changes are retrieved from a data storage repository as at step **943a**, and a smoothed IV change is computed between each state change over the transition as at step **944**. The smoothed IV changes for all steps are combined into a complete change process as at step **945**, and the complete change process is applied to the electrolyser as at step **946**.

[0125] Reference is now made to FIGURE 5A, which schematically illustrates a plot **1004** of an operating parameter change versus time between two states **S1** and **S2** of an electrolyser coupled to a variable power source, according to some embodiments of the invention. For example, the plot **1004** may be determined according to methods **900** and **920**. During a transition between an initial operating state **S1** and a final operating state **S2** of an electrolyser, the smoothed changes in current or voltage control may have three time periods: period **1001**, period **1002**, and period **1003**. During period **1001** (up till time **1001a**), a slew rate **1006** of the IV curve **1004** may increase from zero at the start of the change to a slew rate value of **1006v** at the end of period **1001**. The slew rate value **1006v** may be lower than a threshold slew rate value **1006t** to benefit from a decreased degradation of the electrolyser. For example, the slew rate **1006** may increase linearly during region **1001**. For example, the slew rate **1006** may increase according to a parabolic function during region **1001**. For example, the slew rate **1006** may increase according to a circular function during region **1001**. For example, the slew rate **1006** may increase according to a elliptical function during region **1001**. For example, the slew rate **1006** may increase according to a sigmoidal function during region **1001**. For example, the slew rate **1006** may increase according to a logistical function during region **1001**. For example, the slew rate **1006** may increase according to a spline function during region **1001**. For example, the slew rate **1006** may increase according to a hyperbolic function during region **1001**. For example, the slew rate **1006** may increase exponentially during region **1001**. For example, the slew rate **1006** may increase quadratically during region **1001**. For example, the slew rate **1006** may increase according may be monotonically increasing. This will ensure a smooth transition from state **S1** to a slew rate value **1006v**, which can be maintained over period **1002** (up to time **1002a**). During the third period **1003**, the slew rate is lowered again to zero so that the electrolyser will be at state **S2** at time **1003a**, with new IV parameter value **1008**.

[0126] When smoothing the operating parameter curve to a spline function, such as a cubic spline function, constraints for beginning and ending rates of value changes and control points may be used that provide a change from the first state to the last state with a continuous value change, a rate of change threshold, and a second differential threshold as described herein.

[0127] An absolute value of an acceleration (second order differential) plot over time **1007** may reach a value of **1007v**, which is below a threshold value of the acceleration **1007t**. Limiting the acceleration below **1007t** may further decrease degradation of the electrolyser.

[0128] Reference is now made to FIGURE 5B, which schematically illustrates a plot **1010** of applying an operating parameter change process between states **S11**, **S12**, **S13**, and **S14** of an electrolyser coupled to a variable power source, according to some embodiments of the invention. For example, the plot **1004** may be determined according to methods **900**, **920** and **940**. When a request for transition from state **S11** to state **S14** is checked for in permitted changes, and it is determined that there are intermediate steps **S12** and **S13** in between, the IV changes may include seven time periods **1011**, **1012**, **1013**, **1014**, **1015**, **1016**, and **1017**. During period **1001** the slew rate may increase from zero to the

permitted slew rate of period **1012** starting at time **T1** and IV value **P1**. During period 1012, IV values are increased to **P2** at time **T2**, and state **S2** is passed during period 1013 and the slew rate is decreased to the permitted slew rate during period 1014 starting at IV value **P3** at time **T3**. In this example the permitted slew rate during period 1014 is lower than during period 1012, but other examples may illustrate different permitted slew rates and permitted acceleration values between the other example states, some changes increasing and some decreasing the slew rate. At the time **T4** the IV value is **P4**, and the slew rate is increased during period 1015 to IV value **P5** at time **T5**. State **S13** is passed during period 1015. In other examples, delays may be implemented at specific states when determined by the permitted changes. Once the slew rate reaches the permitted slew rate during period 1016, the IV value increases to **P6** at time **T6**. During period 1017, the slew rate is decreased to zero at time **T7** and IV value **P7** and the electrolyser will be at state **S14**. As specified above, slew rate changes may follow different functions that are continuous and monotonically increasing. Discontinuities in the IV value or slew rate may increase electrolyser degradation.

[0129] Reference is now made to FIGURE 6A, which schematically illustrates computing a first lag of a first operating parameter change **1101** versus time of an electrolyser coupled to a variable power source, according to some embodiments of the invention. In this example, a linear correlation is performed on the ending portion of plot **1101**. A lag is measured as the area between the extrapolated trendline of correlation **1102** and the values of plot **1101** and may be measured by subtracting the values **1101** from **1102**. In this example, the value of the area **1103** is 0.130 volt-seconds. In this example, the expected response is the linear trendline and the lag is the area between the trendline (expected response) and the actual measurements. The initial state of the electrolyser was at standard operating parameters (such as pressure, temperature, etc) and a starting voltage of 1.4 volts when the current was increased using a step function to illustrate the lag.

[0130] Reference is now made to FIGURE 6B, which schematically illustrates computing a second lag of a second operating parameter change **1111** of an electrolyser coupled to a variable power source, according to some embodiments of the invention. In this example, a linear correlation is performed on the ending portion of plot **1111**. A lag is measured as the area between the extrapolated trendline of correlation **1112** and the values of plot **1111** and may be measured by subtracting the values **1111** from **1112**. In this example, the value of the area **1113** is 0.0224 volt-seconds. The initial state of the electrolyser was at standard operating parameters (such as pressure, temperature, etc) and a starting voltage of 1.55 volts when the current was increased using a step function to illustrate the lag.

[0131] Reference is now made to FIGURE 6C, which schematically illustrates computing a third lag of a third operating parameter change **1121** of an electrolyser coupled to a variable power source, according to some embodiments of the invention. In this example, a linear correlation is performed on the ending portion of plot **1121**. A lag is measured as the area between the extrapolated trendline of correlation **1122** and the values of plot **1121** and may be measured by subtracting the values **1121** from **1122**. In this example, the value of the area **1123** is 0.0140 volt-seconds. The initial state of the electrolyser was at standard operating parameters (such as pressure, temperature, etc) and a starting voltage of 1.68 volts when the current was increased using a step function to illustrate the lag.

[0132] Reference is now made to FIGURE 7, which schematically illustrates computing a lag of a fourth operating parameter change **1130** of an electrolyser coupled to a variable power source from a hot start, according to some embodiments of the invention. In this example, the electrolyser undergoes several different operational parameters during time periods **1131**, **1132**, and **1133**. During period **1131**, plot **1130** asymptotically increases until time **1131a**. During period **1132**, plot **1130** exponentially increases until time **1132a**. During period **1133**, plot **1130** asymptotically increases until the transition is completed. As in the examples of FIGURES 6A to 6C, a linear correlation is performed on the ending portion of plot **1130**. A lag is measured as the area between the extrapolated trendline of correlation **1132** and the values of plot **1130** and may be measured by subtracting the values **1130** from **1132**. In this example, the value of the area **1133** is 13.5volt-seconds. The initial state of the electrolyser was at standard operating parameters (such as pressure, temperature, etc) and a starting voltage of zero volts (hot start) when the current was increased using a step function to illustrate the lag. For example, when the plot of Figure 5B is applied as a current waveform to the electrolyser (instead of a step function) the response of the voltage of the electrolyser will have similar shape, indicating very low lag. By aligning fitting the voltage to the current and measuring the distance between them, the lag can be computed as the area between the two curves. By plotting the voltage against the current, a linear correlation would indicate no lag, but the further the plot is from linearity, the more the lag. A measure of linearity of the IV plot may be used to compute the lag, and a current change profile that is more linear will produce less stress on the electrolyser.

[0133] Reference is now made to FIGURE 8, which schematically illustrates computing a lag of an operating parameter change decrease (shutoff) **1141** of an electrolyser coupled to a variable power source, according to some embodiments of the invention. As in the examples of FIGURES 6A to 7, a linear correlation is performed on the ending portion of plot **1141**. A lag is measured as the area **1142** between the extrapolated trendline of correlation **1143** and the values of plot **1141** and may be measured by subtracting the values **1141** from **1143**. The initial state of the electrolyser was at standard operating parameters (such as pressure, temperature, etc) and a starting voltage of 1.845 volts when the current was stopped using a step function to illustrate the lag.

[0134] Reference is now made to FIGURE 9, which schematically illustrates computing a lags of operating parameter

changes when new **1151** and after extended use **1161** of an electrolyser coupled to a variable power source, according to some embodiments of the invention. As in the examples of FIGURES 6A to 8, a linear correlation is performed on the ending portion of plot **1151** or **1161**. A lag is measured as the area **1152** or **1162** between the extrapolated trendline of correlation **1153** or **1163** and the values of plot **1141** or **1161** and may be measured by subtracting the values **1151** or **1161** from **1153** or **1163**. The initial state of the electrolyser was at standard operating parameters (such as pressure, temperature, etc) and a starting voltage of 1.48 volts for **1151** or 1.72 volts for **1161** when the current was increased using a step function to illustrate the lag. Plots **1151** and **1161** were also fitted to a bi-exponential function:

$$y = y_0 + A_1(1 - e^{-x/t_1}) + A_2(1 - e^{-x/t_2})$$

Equation (6)

and the resulting coefficients that were computed by fitting the data to the model are in Table 1.

Table 1: bi-exponential fit coefficients for plots **1151** and **1161**.

	y_0	A_1	t_1	A_2	t_2
Plot 1151	1.633	0.0205	94	0.138	1.752
Plot 1161	1.795	0.0481	154	0.144	2.07

where y_0 is a y-intercept of the model in Equation (6), A_1 and t_1 are the parameters of the first exponent, and A_2 and t_2 are the parameters of the second exponent. The parameter t_2 reflects the time constant of the fast exponential rise. Plot **1151** is fitted to a faster time constant (lower t_2 value) indicating less lag during new cycles, and plot **1161** is fit shows more lag (higher t_2 value) after extended use. An area **1152** between plot **1151** and a fitted linear model to the second half of **1151** has an area of 0.63 volt-seconds. An area **1162** between plot **1161** and a fitted linear model to the second half of **1161** has an area of 1.15 volt-seconds, indicating more lag relative to plot **1151**. In this example of fitting the measured data to the expected response of Equation (6), the metric to measure the lag may be t_2 , or the decay time of the second exponent.

[0135] Similarly, other examples of computing the lag may be performed by fitting an exponent to any of plots **1101**, **1111**, **1121**, or **1131** and using the time constant as the metric. Similarly, another example of computing the lag may be by fitting the sum of two exponents to the any of plots **1101**, **1111**, **1121**, or **1131** and using the faster of the two time constants (lower value) as the value of the lag. Similarly, another example of computing the lag may be by fitting a line to any of plots **1101**, **1111**, **1121**, or **1131** starting after an initial subperiod (such as starting after between 1 and 10 percent of the total IV change time) and goodness of the linear fit as the value of the lag. Similarly, another example of computing the lag may be by fitting an n-th order polynomial function to any of plots **1101**, **1111**, **1121**, or **1131** starting after an initial subperiod (such as starting after between 1 and 10 percent of the total IV change time) and goodness of the linear fit as the value of the lag. When the value of the lag increases with increasing electrolyser stress, the lag value of an permitted IV change will be below a threshold value. When the value of the lag decreases with increasing electrolyser stress, the lag value of an permitted IV change will be above a threshold value.

[0136] As used herein and in the appended claims the singular forms "a," "an," and "the" include plural references unless the content clearly dictates otherwise. Thus, for example, reference to "an energy storage device" includes a plurality of such energy storage devices and equivalents thereof known to those skilled in the art, and so forth. It may be noted that the term "and" or the term "or" is generally employed in its sense including "and/or" unless the content clearly dictates otherwise.

[0137] As used herein, the term "plurality" means more than one.

[0138] As used herein, the term "about," when referring to a measurable value such as an amount, a temporal duration, and the like, is meant to encompass variations of +/-10%, more preferably +/-5%, even more preferably +/-1%, and still more preferably +/-0.1% from the specified value, as such variations are appropriate to perform the disclosed methods.

[0139] Following are clauses of this disclosure:

Clause 1. A system comprising:

a variable power source;

an electrolyser; and

a control device,

wherein the electrolyser is operatively connected to the variable power source through the control device, and wherein the control device is configured to control at least one operating parameter of the electrolyser, wherein

the at least one operating parameter comprises at least one of a current, a voltage, and an input power supplied to the electrolyser, each of the current, voltage, and input power within respective permitted ranges for a state of operation of the electrolyser, wherein the control device regulates an output power of the variable power source to match the input power supplied to the electrolyser.

Clause 2. The system of clause 1, wherein the control device further comprises:

a controller;
an electrical power converter, configured to convert a first portion of the output power of the variable power source and supply the first portion to the electrolyser; and
a sensor configured to sense the output power of the variable power source,
wherein the controller is configured to:

monitor sensor values of the sensor, and
set the voltage or current of the first portion according to the sensor values and the permitted ranges.

Clause 3. The system of clauses 1 or 2, wherein the system is operatively connected to at least one of an electric grid and a load.

Clause 4. The system of any preceding clause, wherein the control device comprises an energy storage device.

Clause 5. The system of clause 4, wherein the energy storage device comprises at least one fast-charging energy storage device and at least one high-capacity energy storage device.

Clause 6. The system of any of clauses 3-5, wherein the control device is configured to split the output power of the variable power source between the electrolyser and at least one of the energy storage device, the electric grid, and the load, when the output power of the variable power source is higher than the permitted range of the input power to the electrolyser, thereby matching the output power to the input power to the electrolyser.

Clause 7. The system of any of clauses 3-6, wherein the control device is configured to facilitate delivery of a power from at least one of the energy storage device and electric grid to the electrolyser in addition to the output power of the variable power source, when the output power of the variable power source is lower than the input power to the electrolyser, thereby matching the output power to the input power to the electrolyser.

Clause 8. The system of any preceding clause, wherein the electrolyser comprises a cathode, an anode, and a membrane or separator positioned between the cathode and the anode, wherein the membrane and the separator are configured to electrically insulate the cathode from the anode and configured to enable passage of an electrolyte or water ions therethrough.

Clause 9. The system of any preceding clause, wherein the at least one operating parameter is further selected from the group consisting of an operating temperature of the electrolyser, flowrate of the electrolyte or water, pressure of hydrogen and/or oxygen, and any combination thereof.

Clause 10. The system of any preceding clause, wherein controlling the at least one operating parameter is based on a predetermined value of the operation parameter.

Clause 11. The system of clause 10, wherein the predetermined value is derived from a model correlating between the at least one operating parameter and the electrolyser lifetime.

Clause 12. The system of clauses 10 or 11, wherein the predetermined value is derived from measured data correlating between the at least one operating parameter and the electrolyser lifetime.

Clause 13. The system of any of clauses 10-12, wherein the control device comprises a machine learning algorithm configured to analyze a correlation between the at least one operating parameter and the electrolyser lifetime, and wherein the predetermined value is derived from analyzed data of a plurality of electrolysers.

Clause 14. The system of any preceding clause, wherein controlling the at least one operating parameter is based on a real-time monitoring of a state-of-health (SOH)-related parameter of the electrolyser by the control device.

Clause 15. The system of clause 14, wherein the SOH-related parameter is selected from the group consisting of an electrolyser voltage, when operated galvanostatically; electrolyser current, when operated potentiostatically; internal cell resistance or impedance; temperature of electrolyte; conductivity of electrolyte; chemical composition of electrolyte, and any combination thereof.

Clause 16. The system of clauses 14 or 15, wherein a machine learning algorithm is configured to analyze a correlation between the at least one operating parameter and the SOH-related parameter of a plurality of previously operated electrolysers, and wherein controlling the at least one operating parameter is based on a current value of the SOH-related parameter and an analysis of said correlation.

Clause 17. The system of any preceding clause, wherein the electrolyser is selected from the group consisting of a polymer electrolyte membrane water electrolyser, a liquid electrolyte electrolyser, and a solid oxide electrolyser cell.

Clause 18. The system of any of clauses 1-16, wherein the electrolyser is selected from a proton-exchange membrane water electrolyser and anion-exchange membrane water electrolyser.

Clause 19. The system of any preceding clause, wherein the variable power source is selected from the group consisting of a photovoltaic (PV) power source, solar thermal energy (STE) power source, wind power source, tidal power source, a variable electrical grid and wave power source.

Clause 20. A method for operating an electrolyser coupled to a variable power source, the method comprising controlling at least one operating parameter of the electrolyser to increase its lifetime, wherein the at least one operating parameter comprises a state of operation of the electrolyser and the method comprises regulating an output power of the variable power source to match it to the input power to the electrolyser.

Clause 21. A system comprising:

- a plurality of variable power sources;
- a plurality of electrolyser stacks; and
- a control device,

wherein at least a portion the electrolyser stacks are operatively connected to their corresponding variable power sources through the control device, wherein the control device is configured to control at least one operating parameter of the plurality of electrolyser stacks, wherein the at least one operating parameter comprises at least one of a current, a voltage, and an input power supplied to the plurality of electrolyser stacks, each of the current, voltage, and input power within respective permitted ranges for a state of operation of the plurality of electrolyser stacks, wherein the control device regulates an output power of the plurality of variable power sources to match it to the input power to the plurality of electrolyser stacks.

Clause 22. The system of clause 21, wherein the input power to the plurality of electrolyser stacks is balanced between the the plurality of electrolyser stacks to enable the plurality of electrolyser stacks to reach a replacement or end-of-life condition.

Clause 23. The system of clauses 21 or 22, wherein the input power to the plurality of electrolyser stacks is balanced between the the plurality of electrolyser stacks to increase a total hydrogen production rate of the plurality of electrolyser stacks.

Clause 24. The system of any of clauses 21-23, wherein the input power to the plurality of electrolyser stacks is balanced between the the plurality of electrolyser stacks to operate the plurality of electrolyser stacks at an increased efficiency.

Clause 25. The system of any of clauses 21-24, wherein the input power to the plurality of electrolyser stacks is balanced between the the plurality of electrolyser stacks to operate the plurality of electrolyser stacks at an increased lifetime.

Clause 26. The system of any of clauses 21-25, wherein the input power to the plurality of electrolyser stacks is controlled based on a predicted availability of a future output power.

Clause 27. A control device for operatively connecting an electrolyser to a variable power source, the control device

comprising:

one or more energy storage devices;
 a controller;
 5 a sensor configured to sense output power of the variable power source and report a sensed power to the controller; and
 an electrical power converter, configured to convert a first portion of the output power of the variable power source into an input power to an electrolyser stack, wherein the controller is configured to set the state of operation of the electrolyser stack and the first portion of the output power,
 10 wherein the control device is configured to control at least one operating parameter change of the electrolyser stack .

Clause 28. The control device of clause 27, wherein the controller is configured to change an operating parameter of the electrolyser continuously.

Clause 29. The control device of clauses 27 or 28, wherein the controller is configured to change an operating parameter of the electrolyser with a rate of change below a threshold rate of change.

Clause 30. The control device of any of clauses 27-29, wherein the controller is configured to change an operating parameter of the electrolyser with a second order rate of change below a threshold second order rate of change.

Clause 31. The control device of any of clauses 27-30, wherein the controller is configured to change an operating parameter of the electrolyser smoothly.

Clause 32. A method comprising:

receiving a notice to perform a change an operating parameter of an electrolyser;
 retrieve and store an initial state of the electrolyser;
 apply the change to the electrolyser;
 30 monitor a second operating parameter of the electrolyser;
 compute a value of the monitored second operating parameter reflecting an expected response of the second operating parameter;
 when the value indicates that the monitored second operating parameter complies with the expected response, store the initial state and the change in a permitted change table; and
 35 when the value indicates that the monitored second operating parameter doesn't comply with the expected response, send a notification to decrease a second change at the initial state.

Clause 33. A method comprising:

receiving a notice to perform a change an operating parameter of an electrolyser;
 retrieve an initial state of the electrolyser;
 estimate intermediate states and final state based on the change and the initial state;
 for each state of the intermediate states and final state:

retrieval a table of permitted changes for each of the intermediate states and the final state, and
 compute a smoothed change between a previous state and the next state, and
 apply the smoothed change to the electrolyser.

Clause 34. The method of clause 33, further comprising actions to:

monitor a second operating parameter of the electrolyser;
 compute a value of the monitored second operating parameter reflecting an expected response of the second operating parameter;
 when the value indicates that the monitored second operating parameter complies with the expected response, store the initial state and the change in a permitted change table; and
 55 when the value indicates that the monitored second operating parameter doesn't comply with the expected response, send a notification to decrease a second change at the initial state.

Clause 35. A device for operating an electrolyser connected to a variable power source, the device comprising a control circuit, where the control circuit is configured to apply a change to an operating parameter of the electrolyser, wherein the change comprises a continuous change in the operating parameter value, wherein the change comprises a rate of change less than a threshold rate of change, wherein the change comprises a second order rate of change less than a threshold second order rate of change.

Clause 36. The device of clause 35, wherein the rate of change is continuous.

Clause 37. The device of clauses 35 or 36, wherein the control circuit comprises a controller or a processor and a repository connected to the control circuit, wherein the repository comprises controller or processor instructions configured to apply the change to the electrolyser.

Clause 38. The device of any of clauses 35-37, wherein the control circuit comprises active components and passive components configured to apply the change to the electrolyser.

Clause 39. The device of any of clauses 35-37, wherein the control circuit comprises passive components configured to apply the change to the electrolyser.

Clause 40. The devices of clauses 38 or 39, wherein the passive components comprise an inductor or a capacitor.

Clause 41. The device of any of clauses 38-40, wherein the passive components are in series between the variable power source and the electrolyser.

Clause 42. The device of any of clause 38-41, wherein the passive components are in parallel between the variable power source and the electrolyser.

Clause 43. The device of any of clauses 35-42, wherein the change comprises a voltagecontrolled change.

Clause 44. The device of any of clauses 35-43, wherein the change comprises a current-controlled change.

Clause 45. The device of any of clauses 35-44, wherein the change, at least in part, follows at least part of a linear function, a parabolic function, a circular function, an elliptical function, a sigmoidal function, a logistical function, a hyperbolic function, an exponential function, a spline function, a polynomial function, or a quadratic function.

Clause 46. The device of any of clauses 35-45, wherein the change comprises steps, wherein the steps are determined by a digital to analog converter and an amplification circuit of a power converter, wherein the device comprises the digital to analog converter, the amplification circuit, and the power converter.

[0140] While the present invention has been particularly described, persons skilled in the art may appreciate that many variations and modifications may be made. Therefore, the invention is not to be construed as restricted to the particularly described examples and illustrations, and the scope and concept of the invention may be more readily understood by reference to the claims, which follow.

Claims

1. A method comprising:

receiving a notice to perform a change an operating parameter of an electrolyser;
 retrieve and store an initial state of the electrolyser;
 apply the change to the electrolyser;
 monitor a second operating parameter of the electrolyser;
 compute a value of the monitored second operating parameter reflecting an expected response of the second operating parameter;
 when the value indicates that the monitored second operating parameter complies with the expected response, store the initial state and the change in a permitted change table; and
 when the value indicates that the monitored second operating parameter does not comply with the expected response, store the initial state and a decreased second change.

2. A method comprising:

determining a transition of an operating parameter of an electrolyser;
 retrieving an initial state of the electrolyser;
 5 estimating intermediate states and final state based on the transition and the initial state;
 for each state of the intermediate states and final state:

retrieving a table of permitted changes for each of the intermediate states and the final state, and
 computing a smoothed change between a previous state and the next state, and
 10 applying the smoothed change to the electrolyser.

3. The method of claim 2, further comprising actions to:

monitor a second operating parameter of the electrolyser;
 15 compute a value of the monitored second operating parameter reflecting an expected response of the second
 operating parameter;
 when the value indicates that the monitored second operating parameter complies with the expected response,
 store the initial state and the change in a permitted change table; and
 when the value indicates that the monitored second operating parameter does not comply with the expected
 20 response, send a notification to decrease a second change at the initial state.

4. A device for operating an electrolyser connected to a variable power source, the device comprising a control circuit, where the control circuit is configured to apply a change to an operating parameter of the electrolyser, wherein the change comprises a continuous change in the operating parameter value, wherein the change comprises a rate of change less than a threshold rate of change, wherein the change comprises a second order rate of change less than a threshold second order rate of change.

5. The device of claim 4, wherein the rate of change is continuous.

6. The device of any one of claims 4 to 5, wherein the control circuit comprises a controller or a processor and a repository connected to the control circuit, wherein the repository comprises controller or processor instructions configured to apply the change to the electrolyser.

7. The device of any one of claims 4 to 6, wherein the control circuit comprises active components and passive components configured to apply the change to the electrolyser.

8. The device of any one of claims 4 to 7, wherein the control circuit comprises passive components configured to apply the change to the electrolyser.

9. The device of claim 8, wherein the passive components comprise an inductor or a capacitor.

10. The device of claim 8, wherein the passive components are in series between the variable power source and the electrolyser.

11. The device of claim 8, wherein the passive components are in parallel between the variable power source and the electrolyser.

12. The device of any one of claims 4 to 11, wherein the change comprises a voltage-controlled change.

13. The device of any one of claims 4 to 12, wherein the change comprises a current-controlled change.

14. The device of any one of claims 4 to 13, wherein the change, at least in part, follows at least part of a linear function, a parabolic function, a circular function, an elliptical function, a sigmoidal function, a logistical function, a hyperbolic function, an exponential function, a spline function, a polynomial function, or a quadratic function.

15. The device of any one of claims 4 to 14, wherein the change comprises steps, wherein the steps are determined by a digital to analog converter and an amplification circuit of a power converter, wherein the device comprises the digital to analog converter, the amplification circuit, and the power converter.

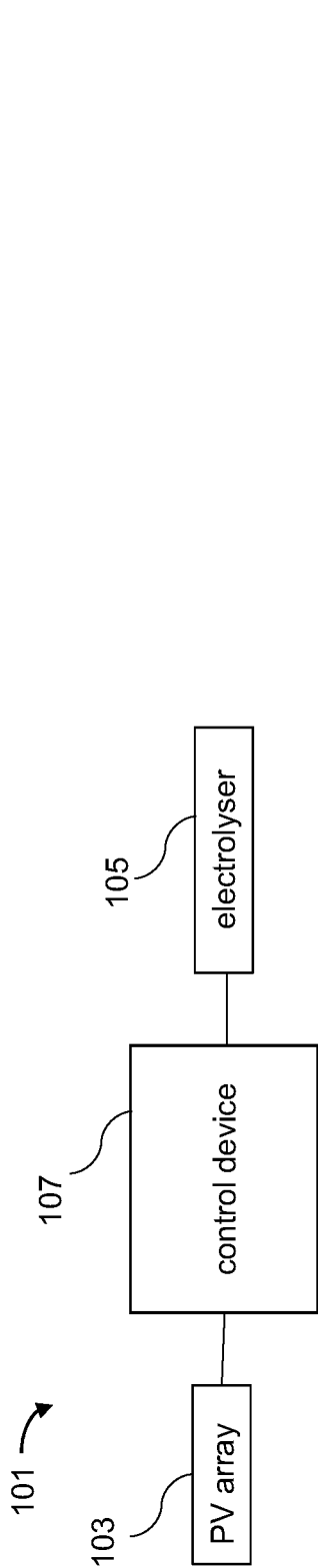


FIGURE 1A

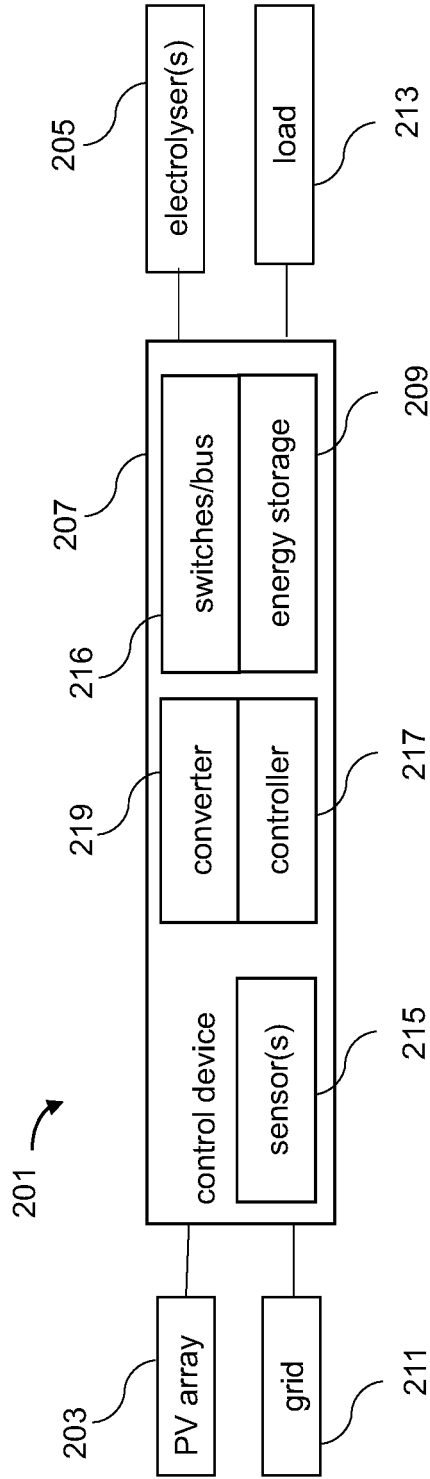


FIGURE 1B

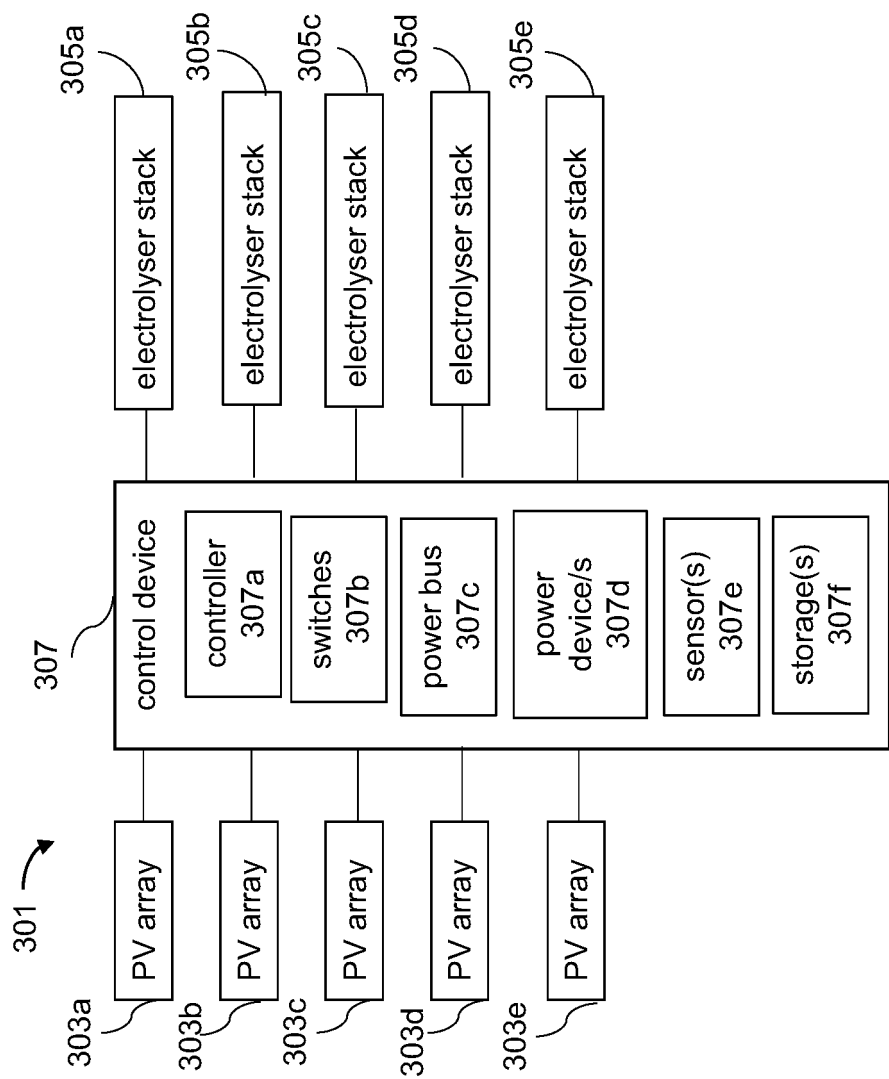


FIGURE 2A

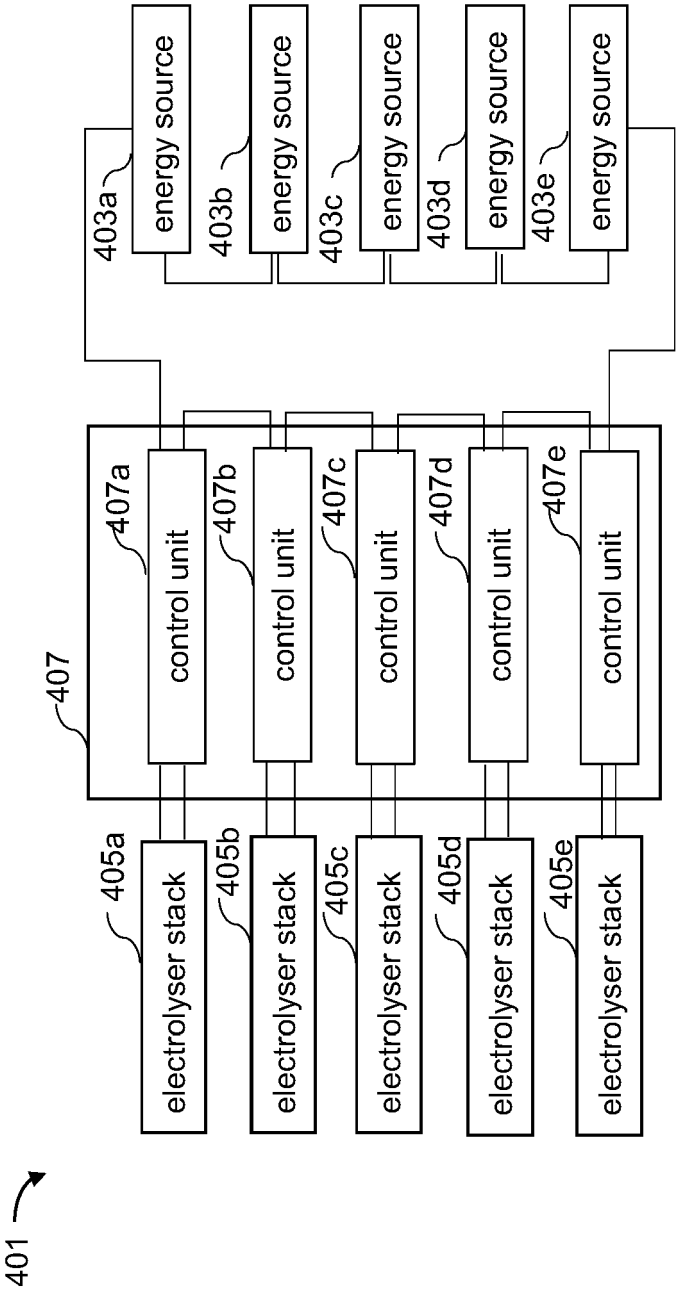


FIGURE 2B

501 →

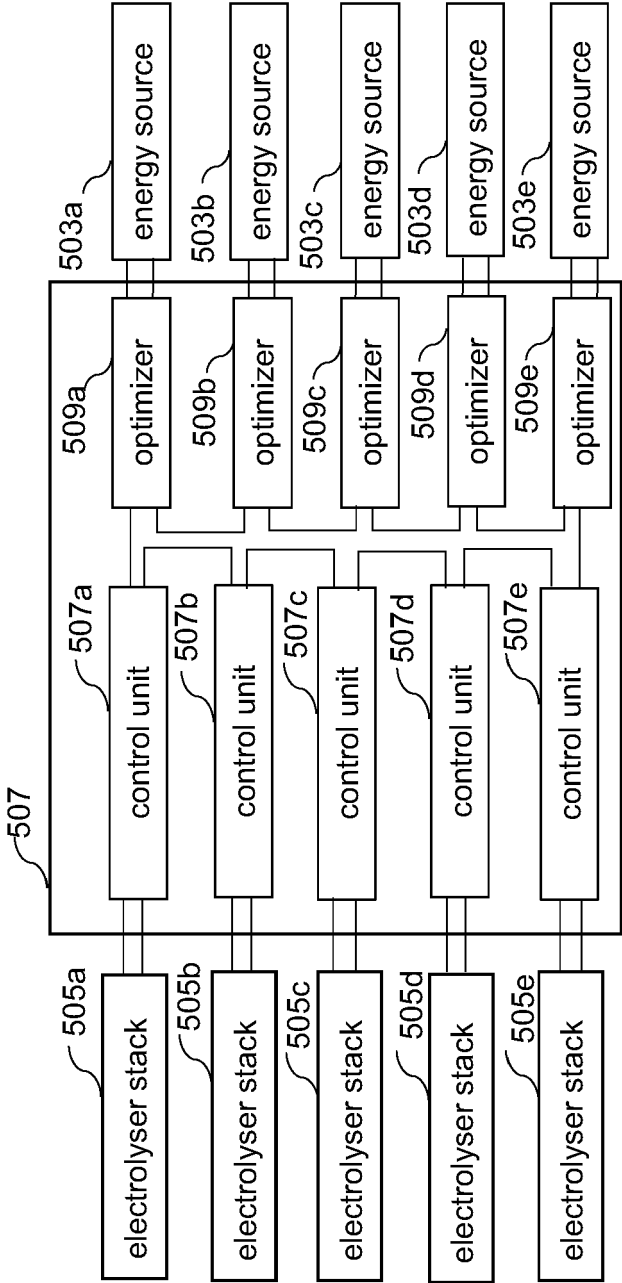


FIGURE 2C

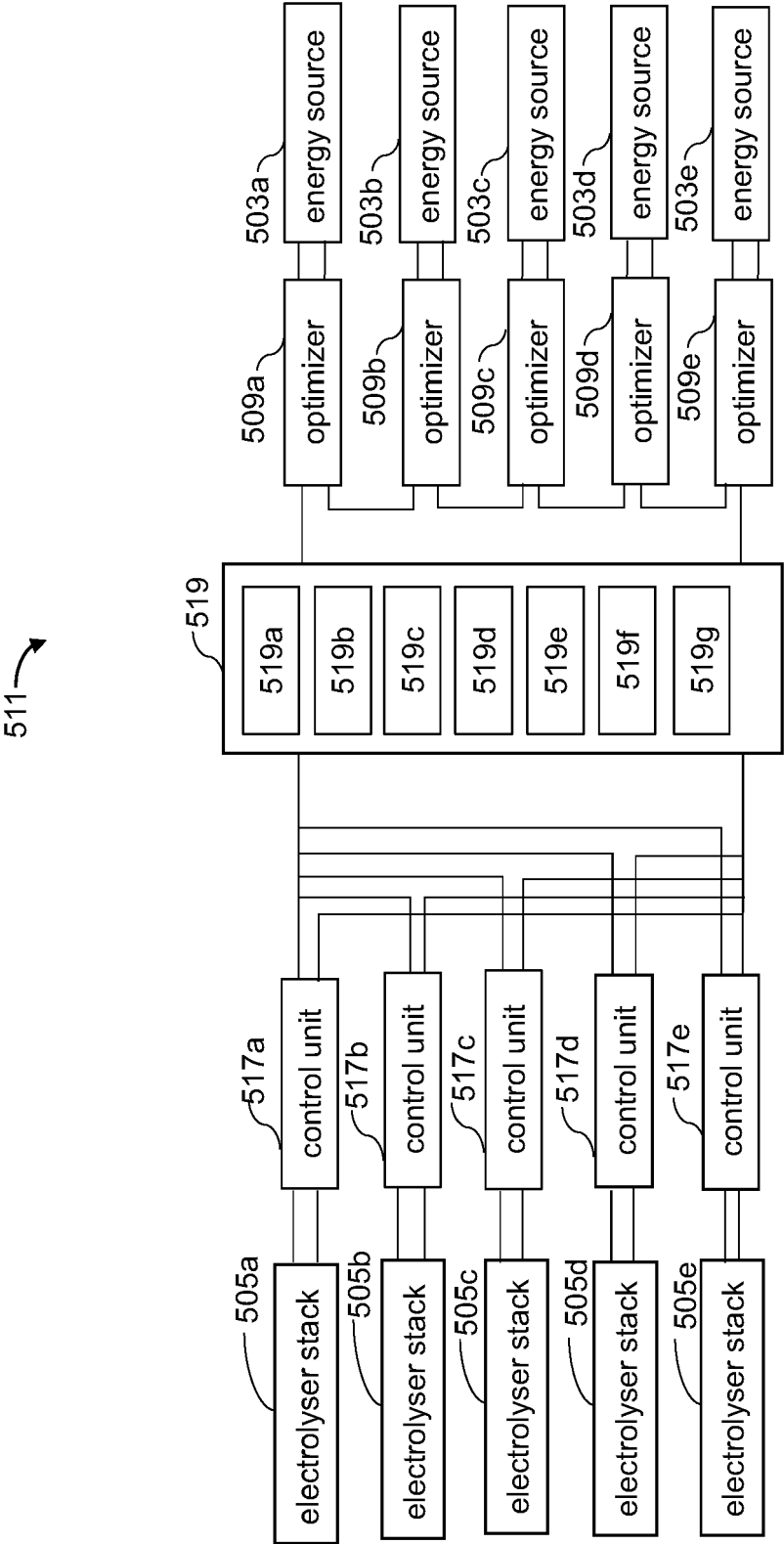


FIGURE 2D

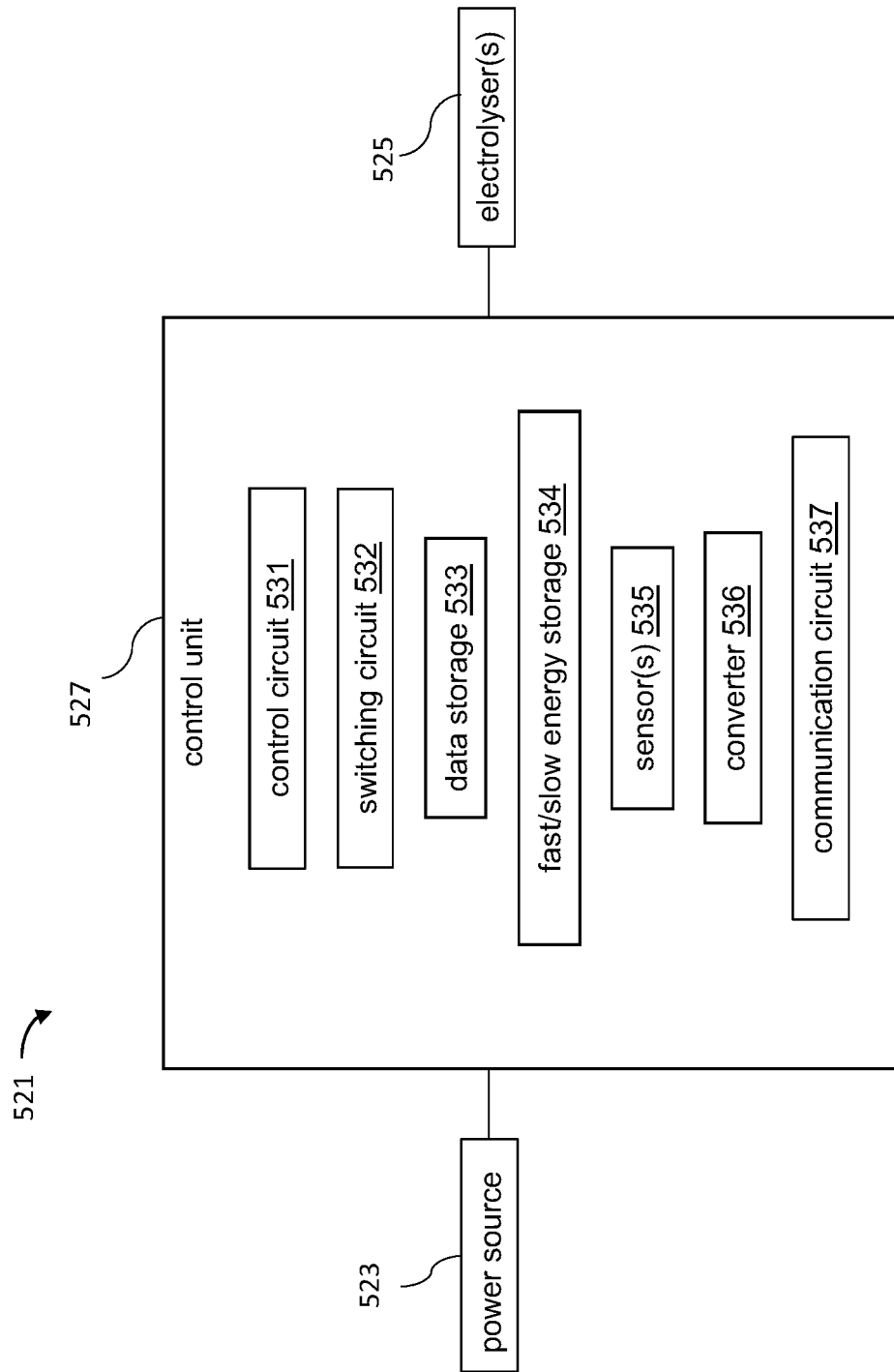


FIGURE 2E

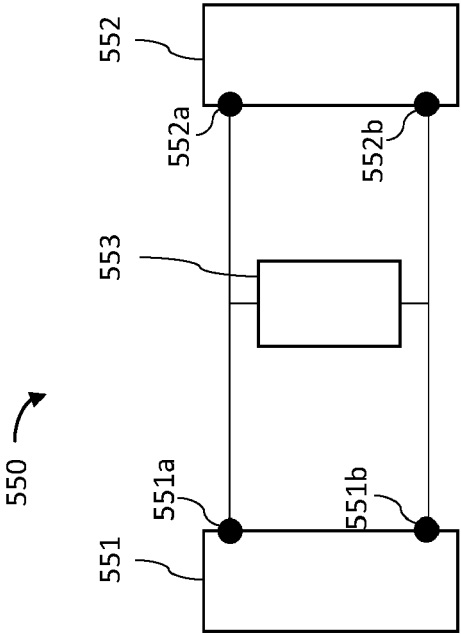


FIGURE 2G

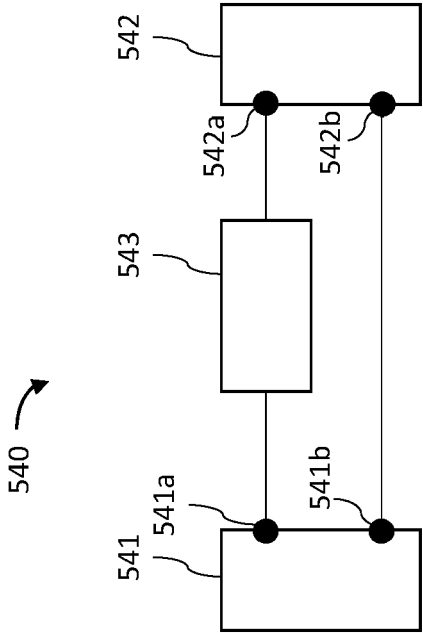


FIGURE 2F

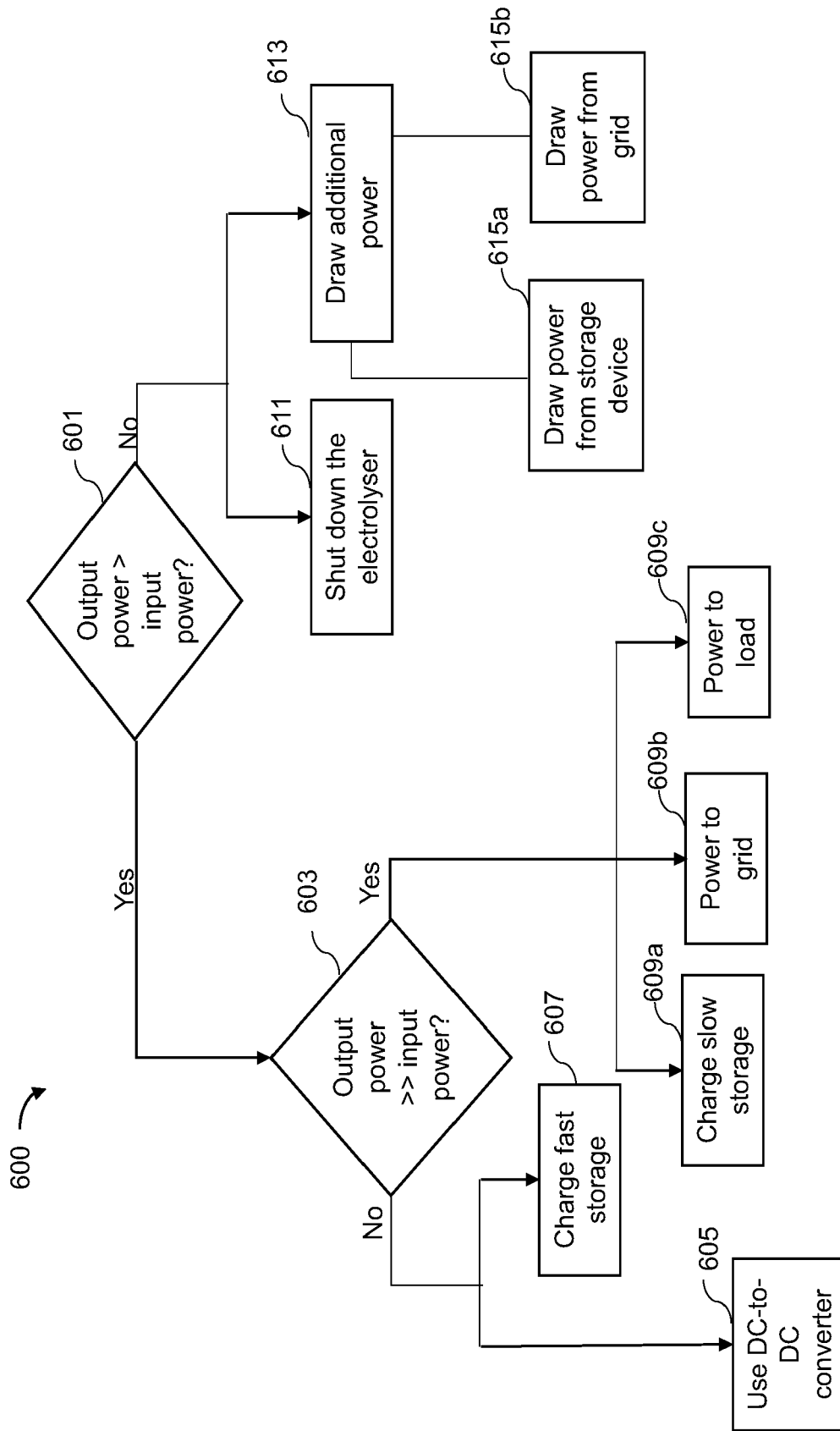


FIGURE 3A

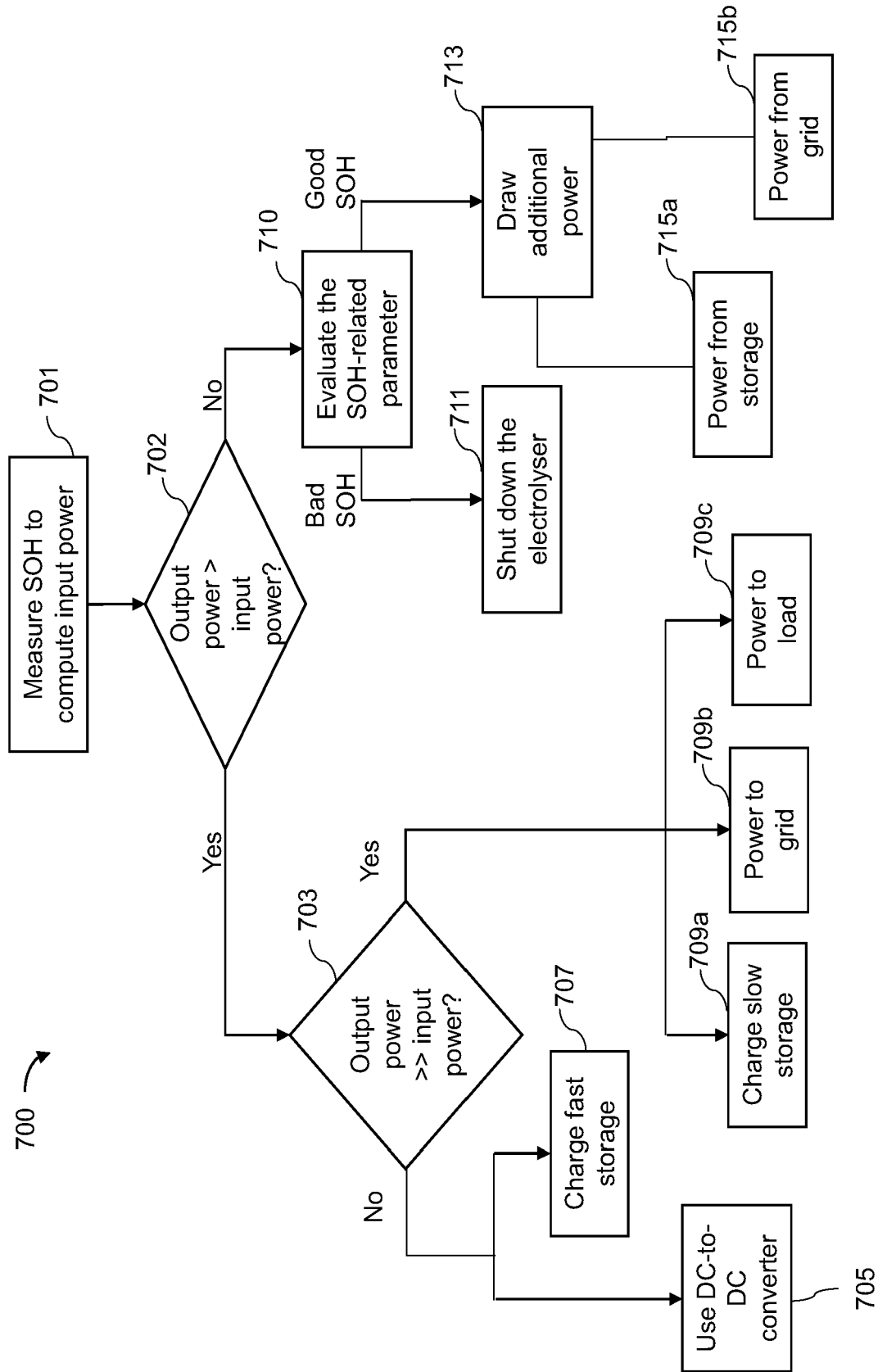


FIGURE 3B

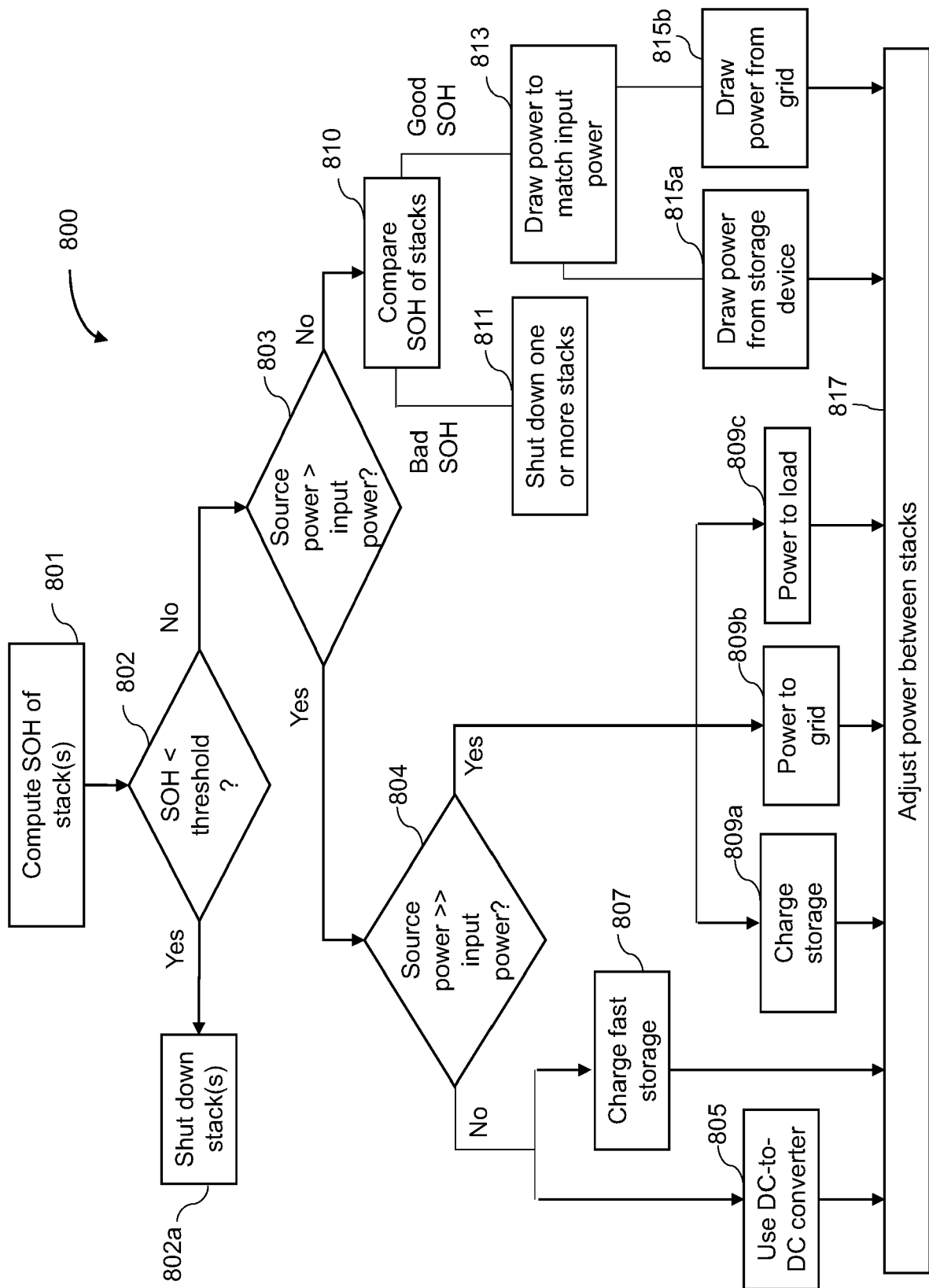


FIGURE 3C

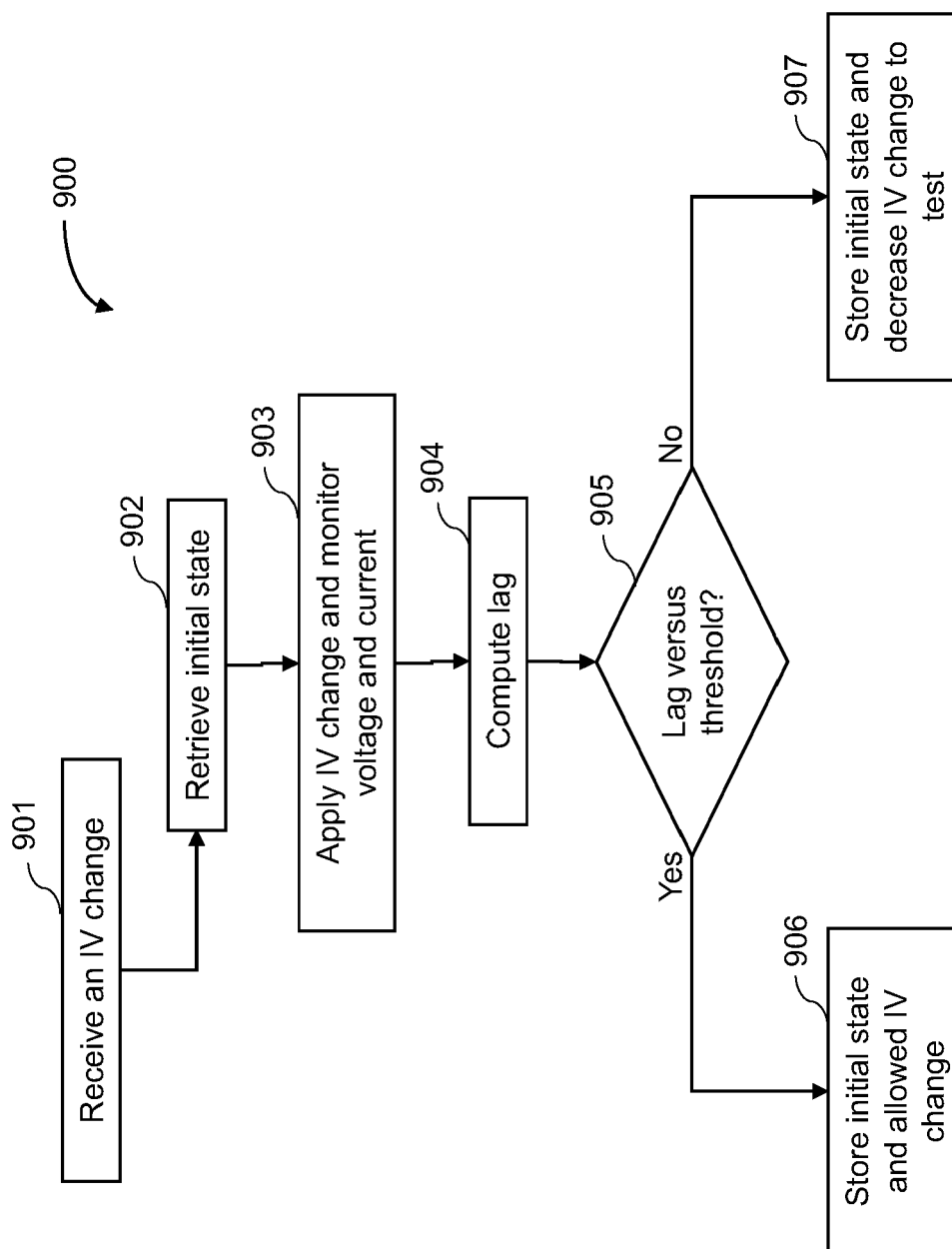


FIGURE 4A

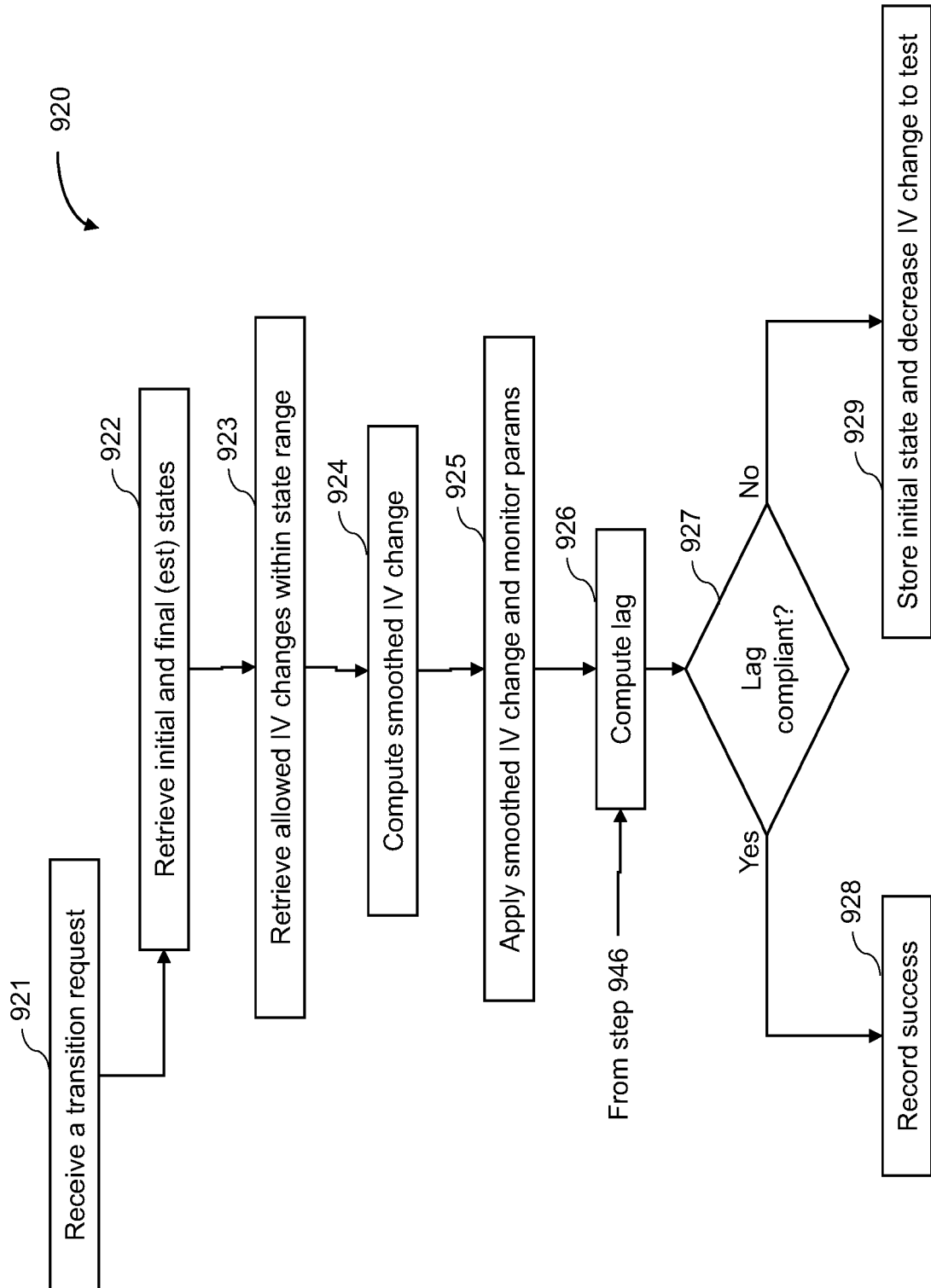


FIGURE 4B

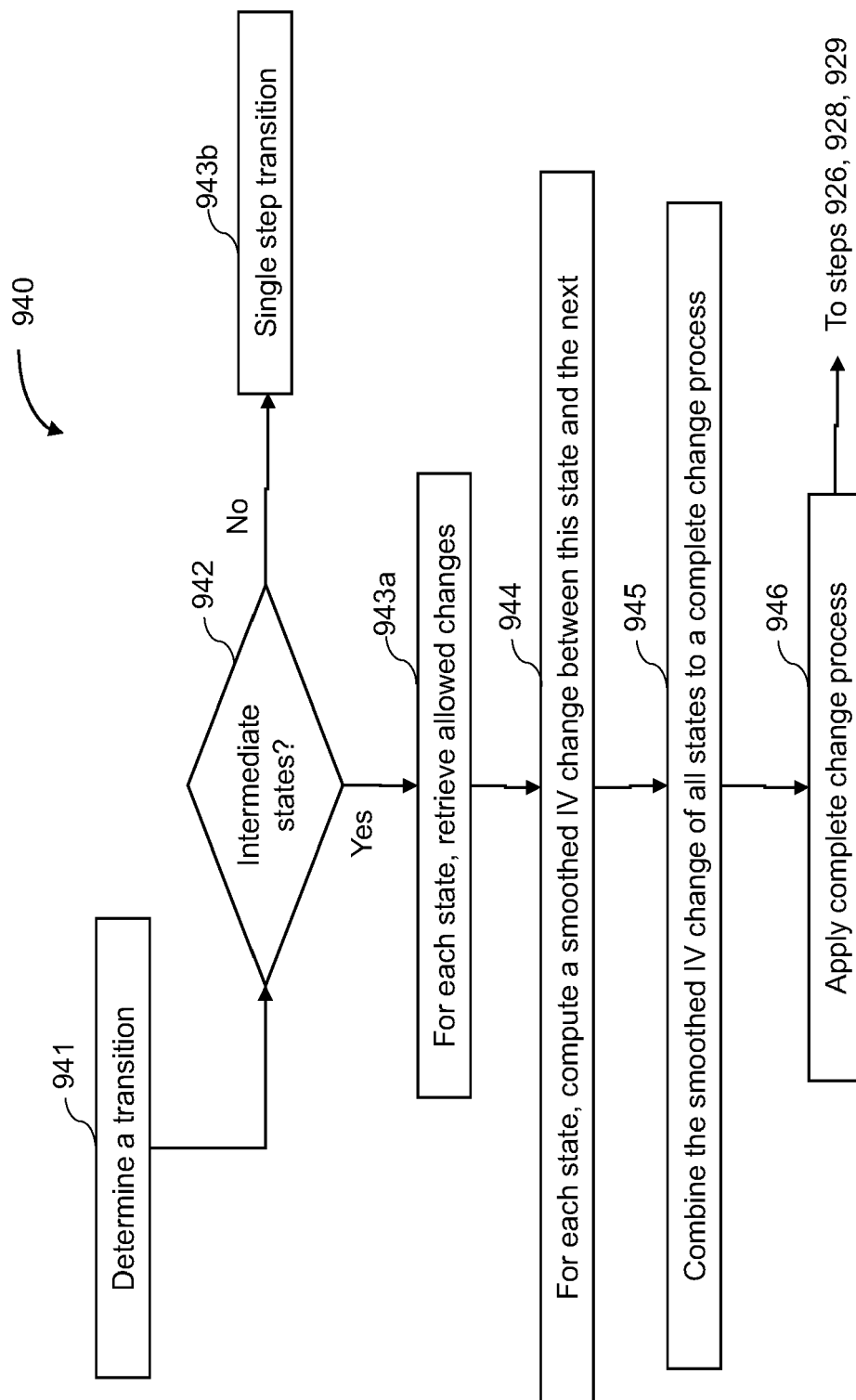


FIGURE 4C

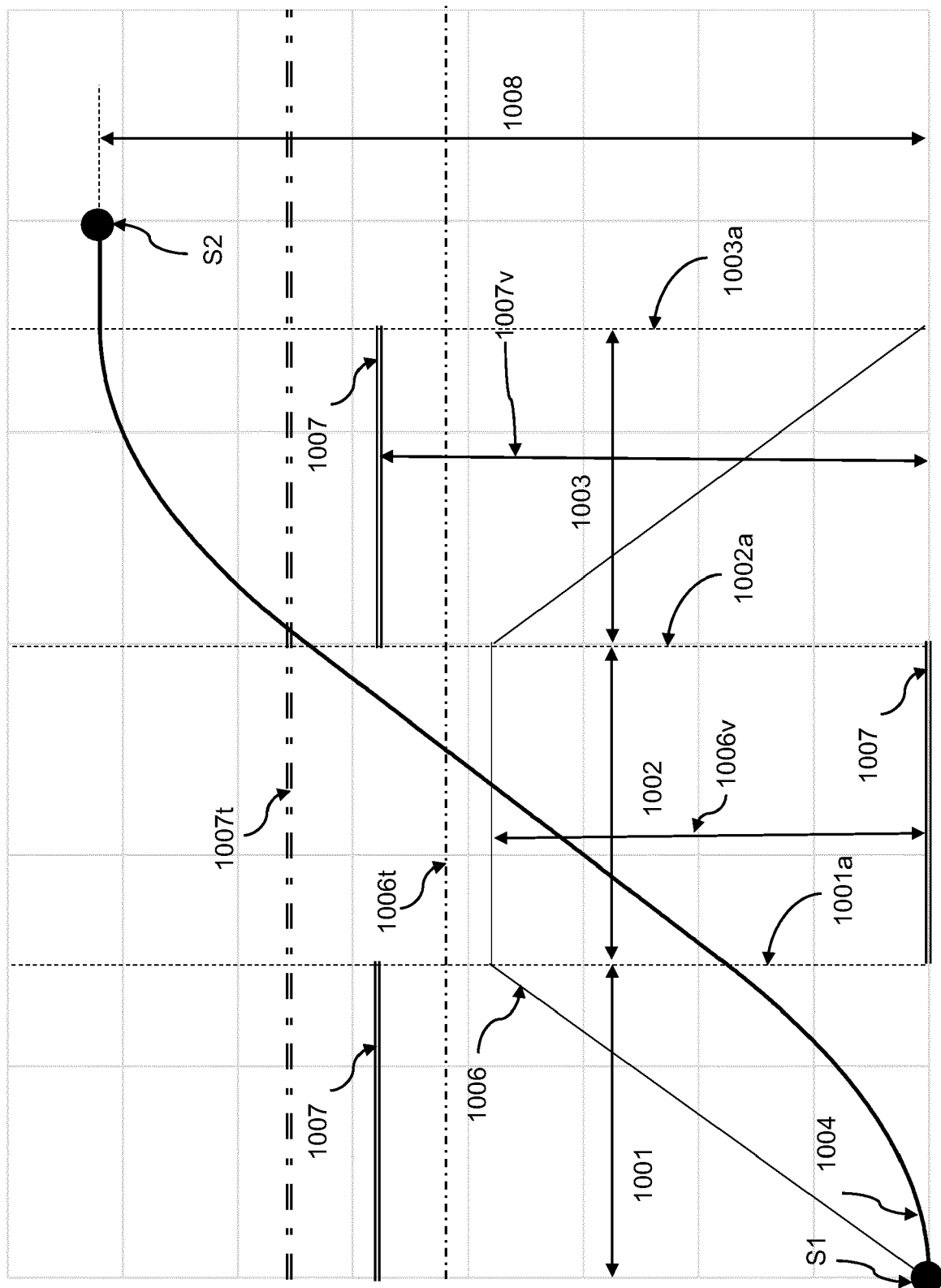


FIGURE 5A

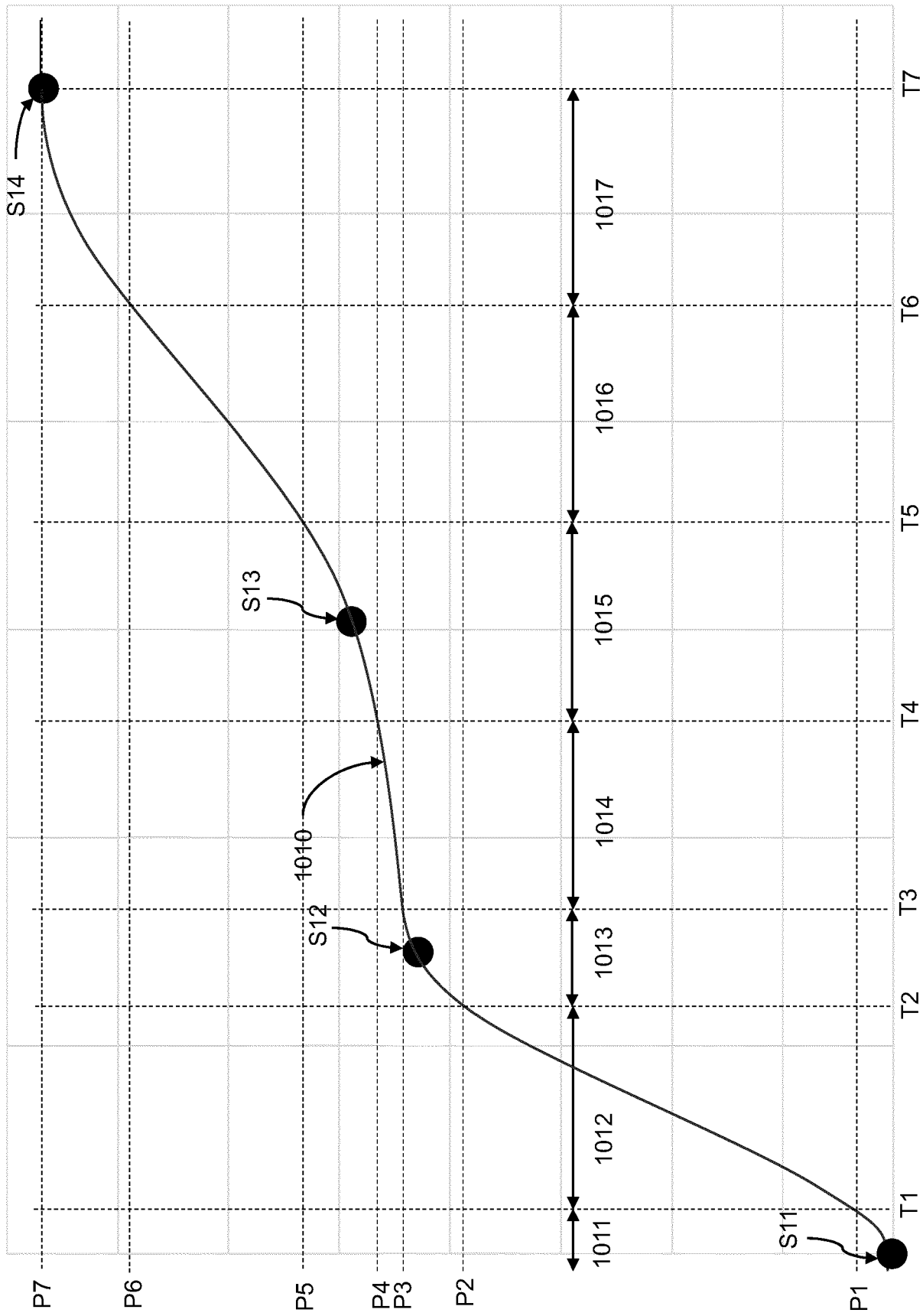


FIGURE 5B

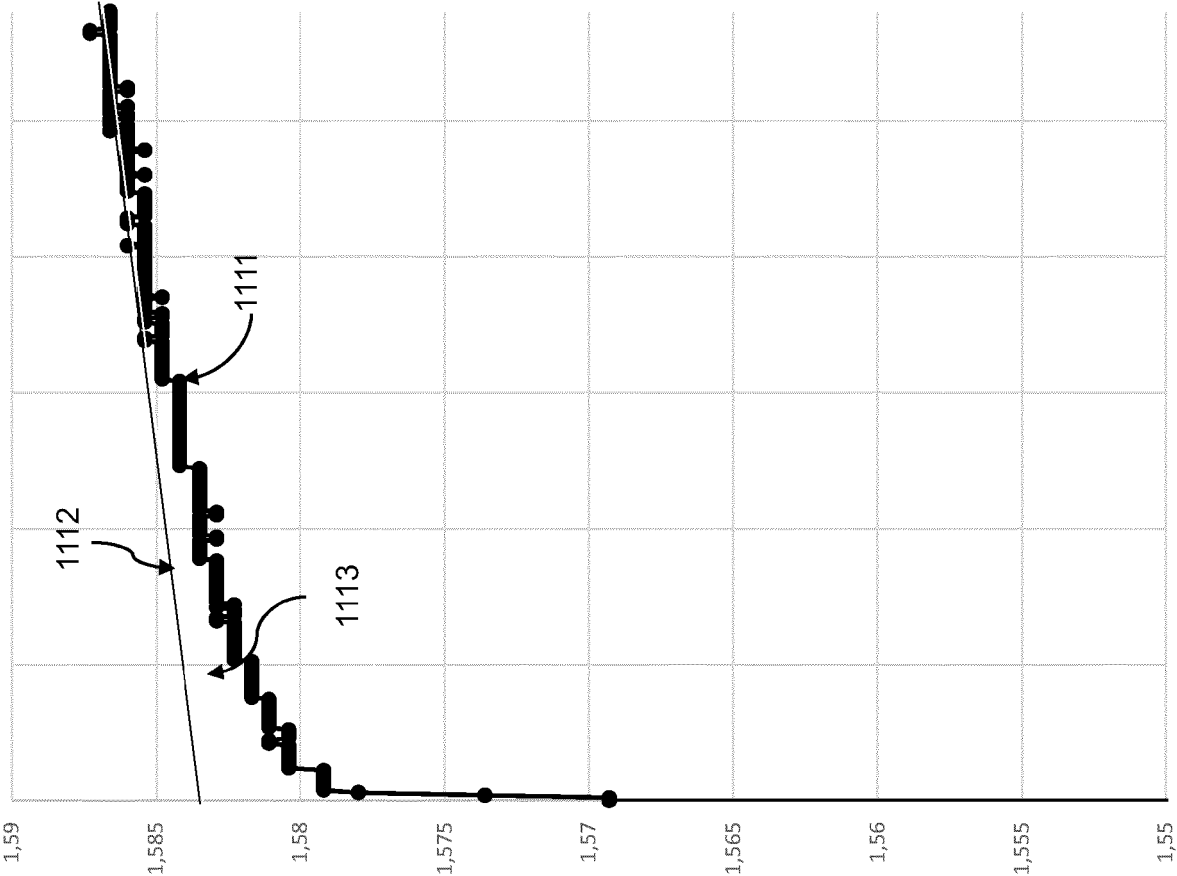


FIGURE 6B

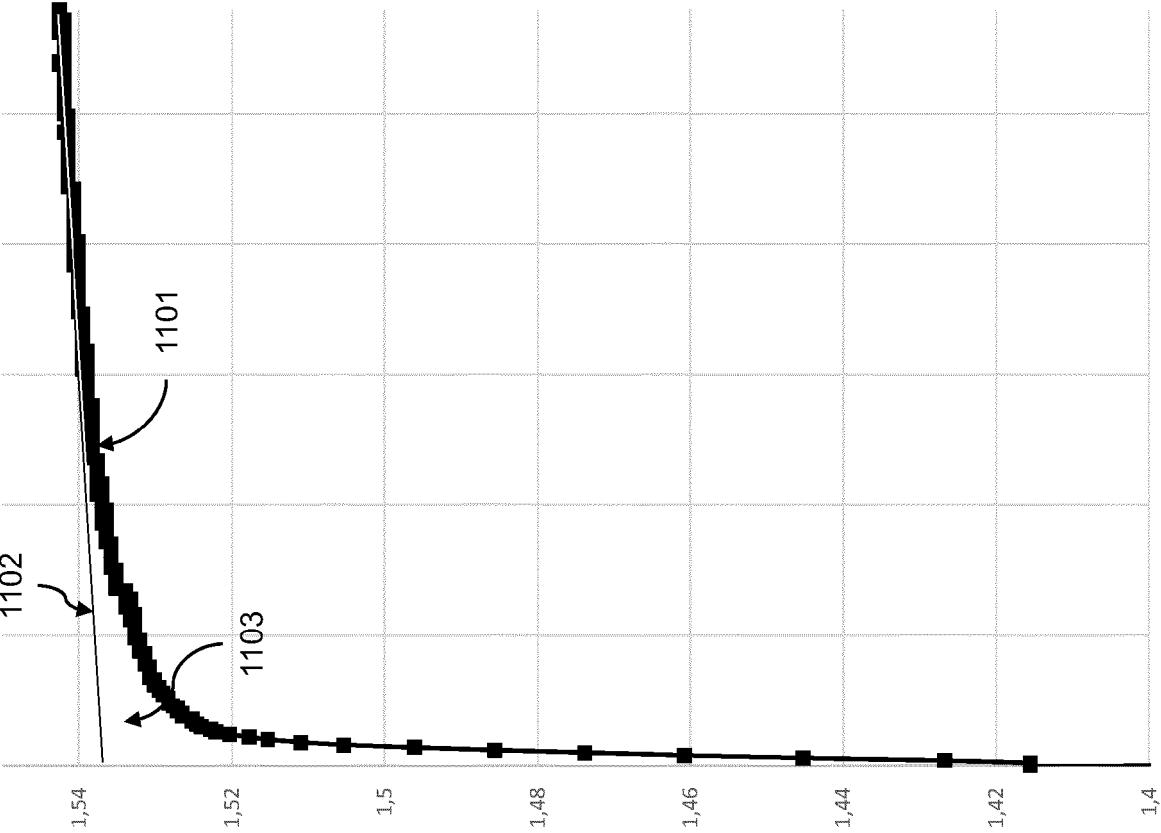


FIGURE 6A

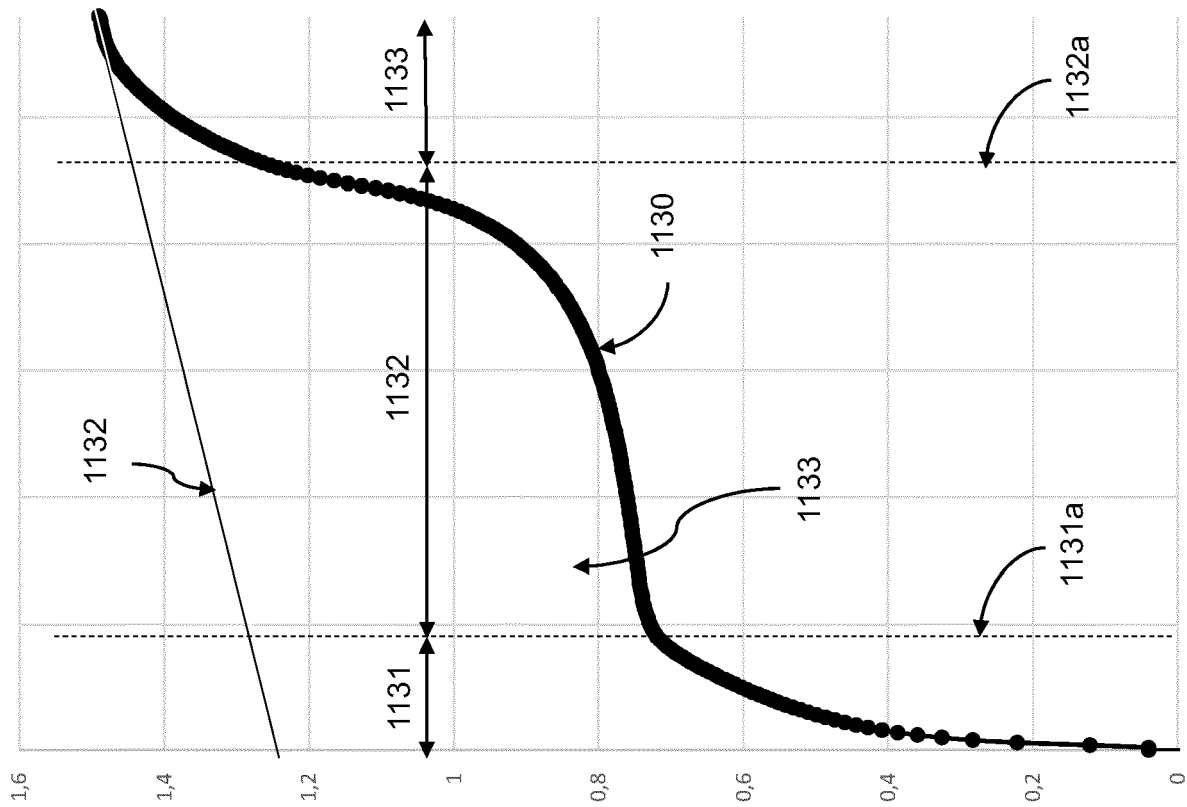


FIGURE 7

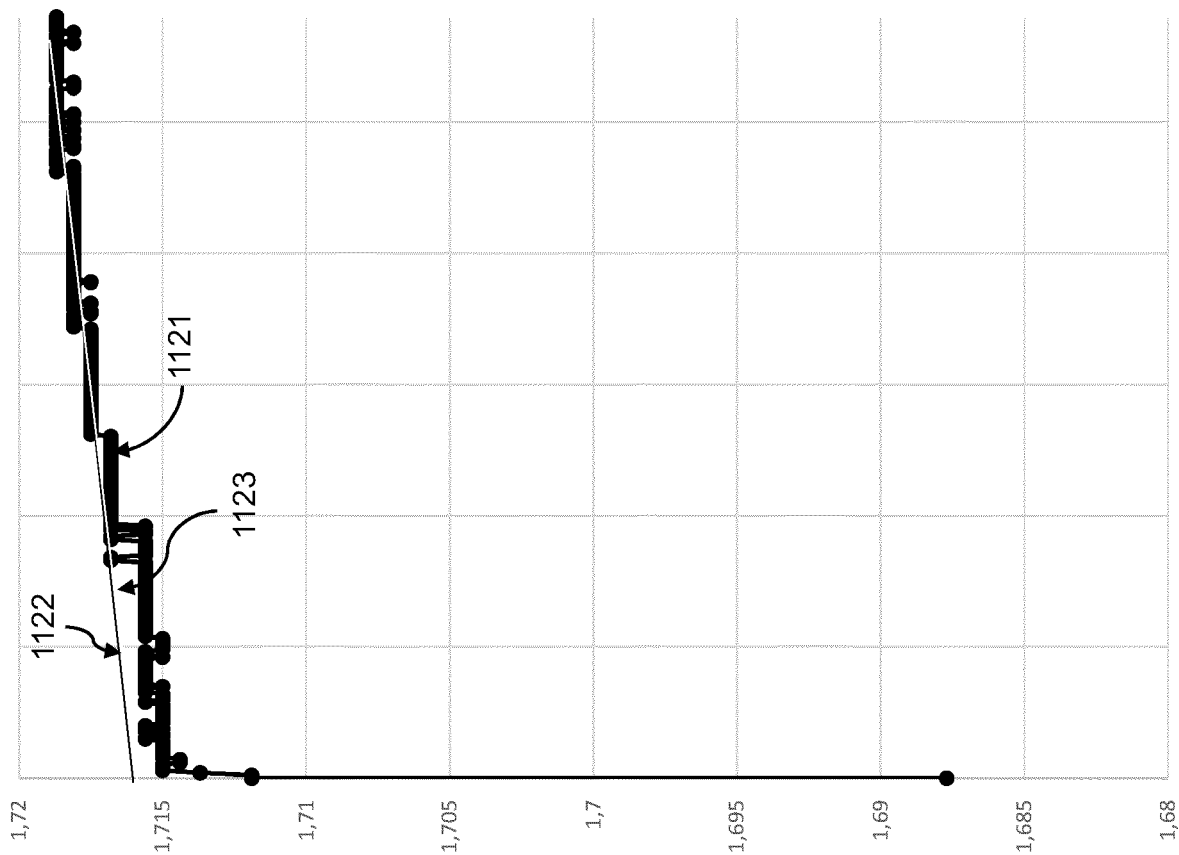


FIGURE 6C

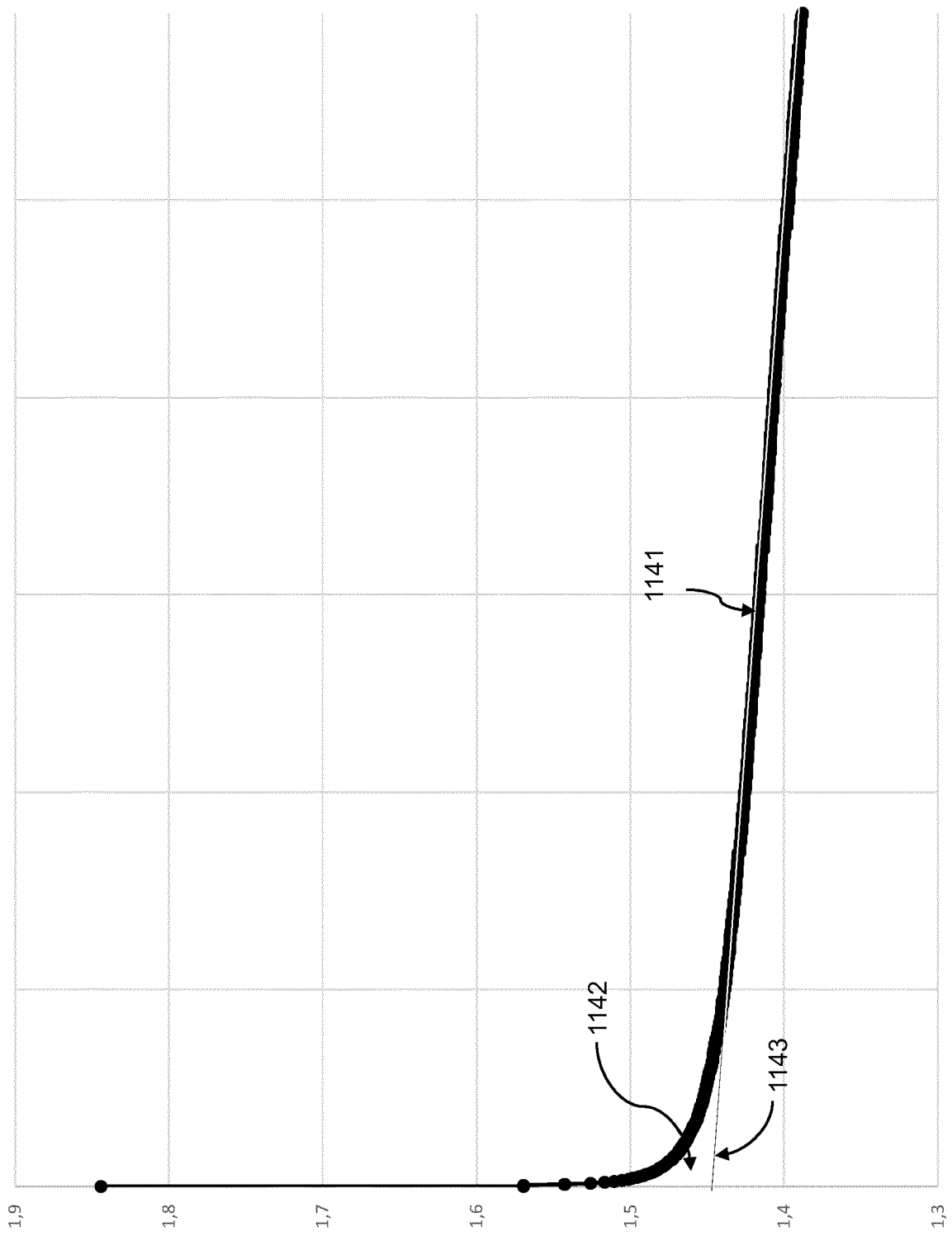


FIGURE 8

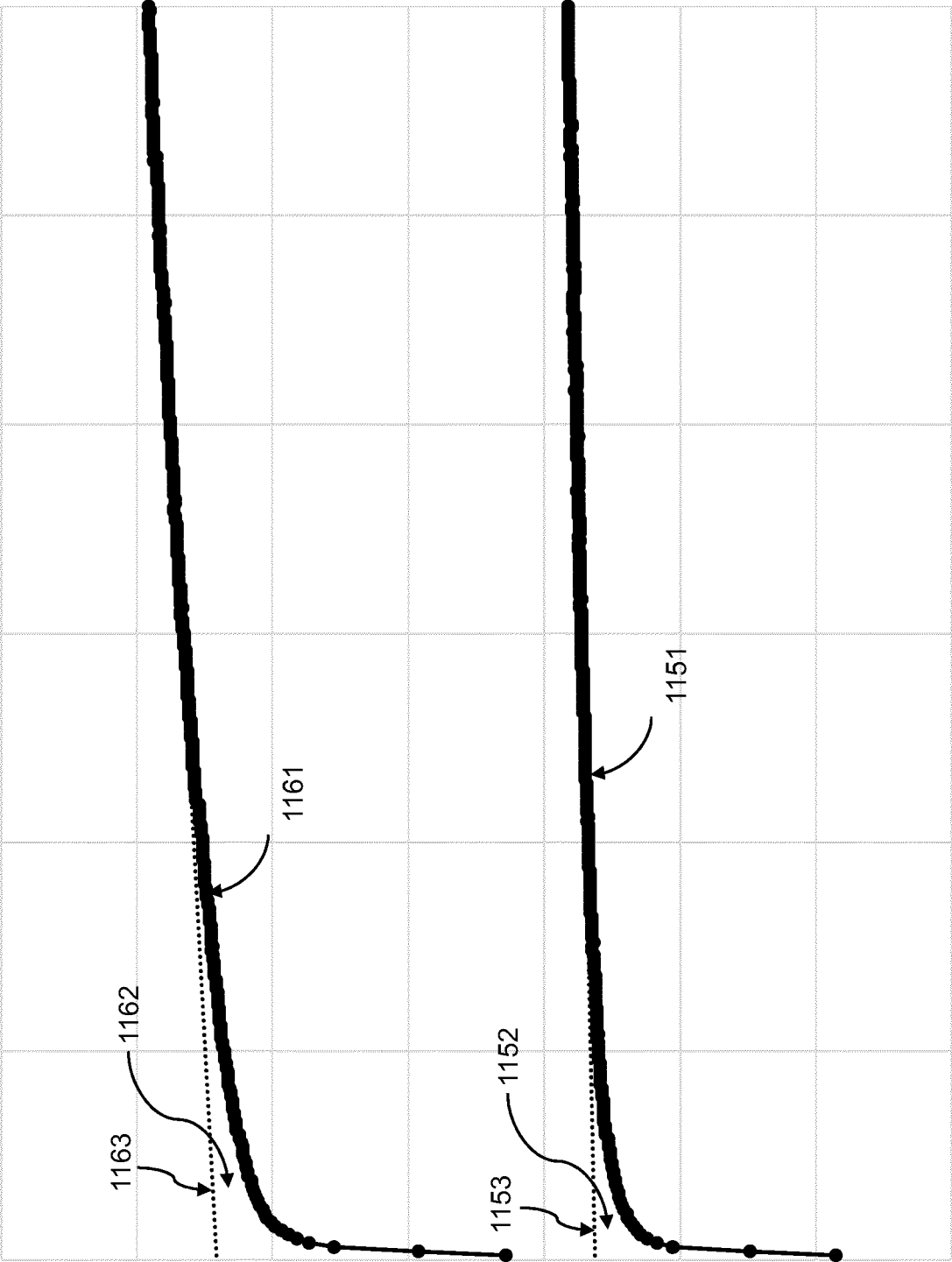


FIGURE 9