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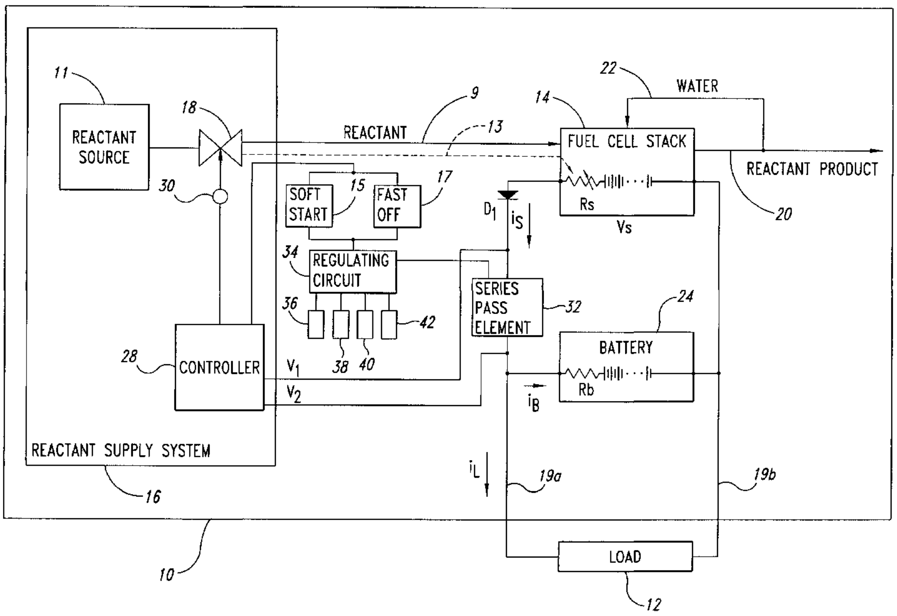

(57) Abstract: A fuel cell system having a battery employs a first stage that regulates current through a series pass element in response to a greater of a battery charging current error, a battery voltage error and a stack current error. The fuel cell system employs a second stage that controls a partial pressure of a reactant flow to the fuel cell stack based on a deviation of voltage across the series pass element, or based on a battery condition. The fuel cell system may employ either, or both, of the stages. Individual fuel cell systems can be combined in series and/or parallel to produce a combined fuel cell system having a desired output voltage and current.

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FUEL CELL SYSTEM

BACKGROUND OF THE INVENTION

Field of the Invention

This invention is generally related to fuel cell systems, and more particularly to controlling an output voltage of the fuel cell system.

Description of the Related Art

Electrochemical fuel cells convert fuel and oxidant to electricity. Solid polymer electrochemical fuel cells generally employ a membrane electrode assembly ("MEA") which includes an ion exchange membrane or solid polymer electrolyte disposed between two electrodes typically comprising a layer of porous, electrically conductive sheet material, such as carbon fiber paper or carbon cloth. The MEA contains a layer of catalyst, typically in the form of finely comminuted platinum, at each membrane electrode interface to induce the desired electrochemical reaction. In operation, the electrodes are electrically coupled for conducting electrons between the electrodes through an external circuit. Typically, a number of MEAs are electrically coupled in series to form a fuel cell stack having a desired power output.

In typical fuel cells, the MEA is disposed between two electrically conductive fluid flow field plates or separator plates. Fluid flow field plates have flow passages to direct fuel and oxidant to the electrodes, namely the anode and the cathode, respectively. The fluid flow field plates act as current collectors, provide support for the electrodes, provide access channels for the fuel and oxidant, and provide channels for the removal of reaction products, such as water formed during fuel cell operation. The fuel cell system may use the reaction products in maintaining the reaction. For example, reaction water may be used for hydrating the ion exchange membrane and/or maintaining the temperature of the fuel cell stack.

Stack current is a direct function of the reactant flow, the stack current increasing with increasing reactant flow. The stack voltage varies inversely with respect to the stack current in a non-linear mathematical relationship. The relationship between stack voltage and stack current at a given flow of reactant is typically represented as a polarization curve for the fuel cell stack. A set or family of polarization curves can represent the stack voltage-current relationship at a variety of reactant flow rates.

In most applications, it is desirable to maintain an approximately constant voltage output from the fuel cell stack. One approach is to employ a battery in the fuel cell system to provide additional current when the demand of the load exceeds the output of the fuel cell stack. This approach often requires a separate battery charging supply to maintain the charge on the battery, introducing undesirable cost and complexity into the system. Attempts to place the battery in parallel with the fuel cell stack to eliminate the need for a separate battery charging supply raises additional problems. These problems may include, for example, preventing damage to the battery from overcharging, increasing efficiency, as well as the need for voltage, current, or power conversion or matching components between the fuel cell stack, battery and/or load. A less costly, less complex and/or more efficient approach is desirable.

BRIEF SUMMARY OF THE INVENTION

In one aspect, a fuel cell system includes a fuel cell stack, a battery, a series pass element electrically coupled between at least a portion of the fuel cell stack and a portion of the battery, and a regulating circuit for regulating current through the series pass element in response to a greater of a battery charging current error, a battery voltage error, and a stack current error.

In another aspect, the fuel cell system includes a reactant delivery system for delivering reactant to the fuel cells, the reactant delivery system having at least a first control element adjustable to control a partial pressure in a flow of a reactant to at least some of the fuel cells, and a control circuit coupled to control the first control element. The control circuit may control the first control element based on a determined deviation of a voltage across the series pass element from some desired value, for example, a value corresponding to between approximately 75 percent and 95 percent of a saturation level for the series pass element. Alternatively or additionally, the control circuit may control the first control element based on a determined operational condition of the battery, such as a current flow into, and out of, the battery over time, a battery voltage, or a charge state of the battery.

In a further aspect, the fuel cell system may include the series pass element and regulating circuit as a first stage, and the reactant delivery system and control circuit as a second stage. The first and second stages operate together, even simultaneously, in cooperation with the parallel coupled battery to achieve efficient and continuous output voltage control while protecting the battery from damage. The first stage is a relatively fast reacting stage, while the second stage is a slower reacting stage relative to the first stage. The first stage ensures that the battery is properly charged and discharged in an efficient manner without damage. The second stage controls the efficiency of the fuel cell stack operation (*i.e.*, represented as the particular polarization curve on which the fuel cell is operating). Thus, the second stage limits the amount of heat dissipated by the series pass element by causing more energy to be dissipated via the fuel cell stack (*i.e.*, via less efficient operation).

In yet still a further aspect, a combined fuel cell system includes two or more individual fuel cell systems electrically coupled in series and/or parallel combinations to produce a desired current at a desired voltage.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

In the drawings, identical reference numbers identify similar elements or acts. The sizes and relative positions of elements in the drawings are not necessarily drawn to scale. For example, the shapes of various elements and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility. Further, the particular shapes of the elements as drawn, are not intended to convey any information regarding the actual shape of the particular elements, and have been solely selected for ease of recognition in the drawings.

Figure 1 is a schematic diagram of a fuel cell system powering a load, the fuel cell system having a fuel cell stack, a battery, a series pass element, a first stage including a regulating circuit for regulating current flow through the series pass element and a second stage including a controller employing a voltage difference across the series pass element to reduce the energy dissipated by the series pass element by controlling a reactant partial pressure in accordance with an illustrated general embodiment in the invention.

Figure 2 is a schematic diagram of the first stage of the fuel cell system of Figure 1 including the regulating circuit, for use with, or without the second stage.

Figure 3 is an alternative embodiment of the first stage of the fuel cell system, employing a microprocessor as the regulating circuit, for use with, or without the second stage.

Figure 4 is a flow diagram of an exemplary method of operating the first stage of the fuel cell system of Figures 2 and 3.

Figure 5A is an electrical schematic diagram of the second stage of the fuel cell system of Figure 1 including the control circuit to control reactant partial pressure based on a variation of voltage across the series pass element with respect to a desired value, for use with, or without the first stage.

Figure 5B is an electrical schematic diagram of the second stage of the fuel cell system illustrating an alternative control circuit to control reactant partial pressure based on battery charging current, for use with, or without, the first stage.

Figure 5C is an electrical schematic diagram of the second stage of the fuel cell system illustrating an alternative control circuit to control reactant partial pressure based on battery voltage, for use with, or without, the first stage.

Figure 6A is a flow diagram of an exemplary method of operating the second stage of the fuel cell system of Figure 5A.

Figure 6B is a flow diagram of an exemplary method of operating the second stage of the fuel cell system of Figure 5B.

Figure 6C is a flow diagram of an exemplary method of operating the second stage of the fuel cell system of Figure 5C.

Figure 7 is a graphical representation of the polarization curves for an exemplary fuel cell stack, for five exemplary partial pressures.

Figure 8 is a schematic diagram of an alternative embodiment of the fuel cell system of Figure 1, in which portions of the fuel cell stack are interconnected with portions of the battery.

Figures 9A-9F are a series of graphs relating stack, battery and load currents, battery and bus voltages and load resistances of the fuel cell system, where the fuel cell stack is sufficiently powering the load without draining or recharging the battery.

Figures 10A-10C are a series of graphs relating stack, battery and load current over time for the fuel cell systems, where the battery supplies current to the load to cover a shortfall from the fuel cell stack and the fuel cell stack later recharges the battery.

Figure 11 is a schematic diagram of a power supply system powering a load, the power supply system including a number of individual fuel cells systems forming a one-dimensional array of fuel cell systems electrically couplable in series to provide a desired power at a desired voltage and a desired current to the load.

Figure 12 is a schematic diagram of a power supply system including a number of fuel cell systems forming a two-dimensional array of fuel cell systems electrically couplable in a variety of series and parallel combinations.

Figure 13 is a schematic diagram illustrating a number of the fuel cell systems of Figure 12 electrically coupled in a series combination to provide a desired output power at a first output voltage and a first output current.

Figure 14 is a schematic diagram illustrating a number of the fuel cell systems of Figure 12 electrically coupled in a parallel combination to provide the desired output power at a second output voltage and a second output current.

Figure 15 is a schematic diagram illustrating a number of the fuel cell systems of Figure 12 electrically coupled in a series and parallel combination to provide the desired output power at a third output voltage and a third output current.

Figure 16 is a flow diagram of a method of operating the power supply system of Figures 11 and 12 according to one exemplary embodiment which includes replacing a faulty fuel cell system with a redundant fuel cell system.

Figure 17 is a flow diagram of an optional step for inclusion in the method of Figure 16.

Figure 18 is a flow diagram of an optional step for inclusion with the method of Figure 16.

Figure 19 is a flow diagram showing a method of operating the power supply system of Figures 11 and 12 according to an additional or alternative exemplary embodiment including electrically coupling a number of fuel cell systems in a determined series and/or parallel combination to produce at least one of a desired power, voltage and current output.

DETAILED DESCRIPTION OF THE INVENTION

In the following description, certain specific details are set forth in order to provide a thorough understanding of the various embodiments of the invention. However, one skilled in the art will understand that the invention may be practiced without these details. In other instances, well-known structures associated with fuel cells, fuel cell stacks, batteries and fuel cell systems have not been shown or described in detail to avoid unnecessarily obscuring descriptions of the embodiments of the invention.

Unless the context requires otherwise, throughout the specification and claims which follow, the word "comprise" and variations thereof, such as, "comprises" and "comprising" are to be construed in an open, inclusive sense, that is as "including, but not limited to."

Fuel Cell System Overview

Figure 1 shows a fuel cell system 10 providing power to a load 12 according to an illustrated embodiment of the invention. The load 12 typically constitutes the device to be powered by the fuel cell system 10, such as a vehicle, appliance, computer and/or associated peripherals. While the fuel cell system 10 is not typically considered part of the load 12, portions of the fuel cell system 10 such as the control electronics may constitute a portion or all of the load 12 in some possible embodiments.

The fuel cell system 10 includes a fuel cell stack 14 composed of a number of individual fuel cells electrically coupled in series. The fuel cell stack 14 receives reactants, represented by arrow 9, such as hydrogen and air via a reactant supply system 16. The reactant supply system 16 may include one or more reactant supply reservoirs or sources 11, a reformer (not shown), and/or one or more control elements such as one or more compressors, pumps and/or valves 18 or other reactant regulating elements. Operation of the fuel cell stack 14 produces reactant product, represented by arrow 20, typically including water. The fuel cell system 10 may reuse some or all of the reactant products 20. For example, as represented by arrow 22, some or all of the water may be returned to the fuel cell stack 14 to humidify the hydrogen and air at the correct temperature and/or to hydrate the ion exchange membranes (not shown) or to control the temperature of the fuel cell stack 14.

The fuel cell stack 14 can be modeled as an ideal battery having a voltage equivalent to an open circuit voltage and a series resistance R_S. The value of the series resistance R_S is principally a function of stack current I_S, the availability of reactants, and time. The series resistance R_S varies in accordance with the polarization curves for the particular fuel cell stack 14. The series resistance R_S can be adjusted by controlling the availability of reactants 9 to drop a desired voltage for any given current, thus allowing an approximately uniform stack voltage V_S across a range of stack currents I_S. The relationship between the reactant flow and the series resistance R_S is illustrated in Figure 1 by the broken line arrow 13. However, simply decreasing the overall reactant and reaction pressures within the fuel cell system 10 may interfere with the overall system operation, for example interfering with the hydration of the ion exchange membrane and/or temperature control of the fuel cell stack. To avoid these undesirable results, the fuel cell system 10 may adjust the reactant partial pressure, as explained in more detail below.

The fuel cell stack 14 produces a stack voltage V_S across a high voltage bus formed by the positive and negative voltage rails 19a, 19b. The stack current I_S flows to the load 12 from the fuel cell stack 14 via the high voltage bus. As used herein, "high voltage" refers to the voltage produced by conventional fuel cell stacks 14 to power loads 12, and is used to distinguish between other voltages employed by fuel cell system 10 for control and/or communications (*e.g.*, 5V). Thus, high voltage and is not necessarily "high" with respect to other electrical systems.

The fuel cell system 10 includes a battery 24 electrically coupled in parallel with the fuel cell stack 14 across the rails 19a, 19b of the high voltage bus to power the load 12. The open circuit voltage of the battery 24 is selected to be similar to the full load voltage of the fuel cell stack 14. An internal resistance R_B of the battery 24 is selected to be much lower than the internal resistance of the fuel cell stack 14. Thus, the battery 24 acts as a buffer, absorbing excess current when the fuel cell stack 14 produces more current than the load 12 requires, and providing current to the load 12 when the fuel cell stack 14 produces less current than the load 12 requires. The voltage across the high voltage bus 19a, 19b will be the open circuit voltage of the battery 24 minus the battery discharging current multiplied by the value of the internal resistance R_B of the battery 24. The smaller the internal resistance R_B of the battery 24, the smaller the variations in bus voltage.

An optional reverse current blocking diode D1 can be electrically coupled between the fuel cell stack 14 and the battery 24 to prevent current from flowing from the battery 24 to the fuel cell stack 14. A drawback of the reverse current blocking diode D1 is the associated diode voltage drop. The fuel cell system 10 may also include other diodes, as well as fuses or other surge protection elements to prevent shorting and/or surges.

Stages

As illustrated in Figure 1, the fuel cell system 10 includes two control stages; a first stage employing a series pass element 32 and a regulating circuit 34 for controlling current flow through the series pass element 32, and a second stage employing a controller 28 for adjusting reactant partial pressures to control the series resistance R_S of the fuel cell stack 14. The first and second stages operate together, even simultaneously, in cooperation with the parallel coupled battery 24 to achieve efficient and continuous output voltage control while protecting the battery 24 from damage. In some embodiments, the fuel cell system 10 may include only the first stage, or only the second stage, providing a simply, less costly alternative.

The first stage is a relatively fast reacting stage, while the second stage is a slower reacting stage relative to the first stage. As discussed above, the battery 24 provides a very fast response to changes in load requirements, providing current to the load 12 when demand is greater than the output of the fuel cell stack 14 and sinking excess current when the output of the fuel cell stack 14 exceeds the demand of the load 12. By controlling the flow of current through the series pass element 32, the first stage ensures that the battery 24 is properly charged and discharged in an efficient manner without damage. By controlling the reactant partial pressures, and hence the series resistance R_S, the second stage controls the efficiency of the fuel cell stack 14 operation (*i.e.*, represented as the particular polarization curve on which the fuel cell is operating). Thus, the second stage limits the amount of heat dissipated by the series pass element 32 by causing more energy to be dissipated via the fuel cell stack 14 (*i.e.*, via less efficient operation).

Where the fuel cell stack 14 dissipates energy as heat, this energy is recoverable in various portions of the fuel cell system, and thus can be reused in other portions of the fuel cell system (*i.e.*, cogeneration). For example, the energy dissipated as heat may be recycled to the fuel cell stack 14 via an airflow, stack coolant, or via the reactants. Additionally, or alternatively, the energy dissipated as heat may be recycled to a reformer (not shown), other portion of the fuel cell system 10, or to some external system. Additionally, limiting the amount of energy that the series pass element 32 must dissipate, can reduce the size and associated cost of the series pass element 32 and any associated heat sinks.

The details of the first and second stages are discussed in detail below.

First Stage Overview, Series Pass Element Regulator

With continuing reference to Figure 1, the first stage of the fuel cell system 10 includes the series pass element 32 electrically coupled between the fuel cell stack 14 and the battery 24 for controlling a flow of current I_S from the fuel cell stack 14 to the battery 24 and the load 12. The first stage of the fuel cell system 10 also includes the regulating circuit 34 coupled to regulate the series pass element 32 based on various operating parameters of the fuel cell system 10. The series pass element 32 can take the form of a field effect transistor ("FET"), having a drain and source electrically coupled between the fuel cell stack 14 and the battery 24 and having a gate electrically coupled to an output of the regulating circuit 34.

The first stage of the fuel cell system 10 includes a number of sensors for determining the various operating parameters of the fuel cell system 10. For example, the fuel cell system 10 includes a battery charge current sensor 36 coupled to determine a battery current I_B. Also for example, the fuel cell system 10 includes a fuel cell stack current sensor 38 coupled to determine the stack current I_S. Further for example, the fuel cell system 10 includes a battery voltage sensor 40 for determining a voltage V_B across the battery 24. Additionally, the fuel cell system 10 may include a battery temperature sensor 42 positioned to determine the temperature of the battery 24 or ambient air proximate the battery 24. While the sensors 36-42 are illustrated as being discrete from the regulating circuit 34, in some embodiments one or more of the sensors 36-42 may be integrally formed as part of the regulating circuit 34.

The first stage of the fuel cell system 10 may include a soft start circuit 15 for slowly pulling up the voltage during startup of the fuel cell system 10. The fuel cell system 10 may also include a fast off circuit 17 for quickly shutting down to prevent damage to the battery 24, for example when there is no load or the load 12 is drawing no power.

Second Stage Overview, Reactant Partial Pressure Controller

The second stage of the fuel cell system 10 includes the controller 28, an actuator 30 and the reactant flow regulator such as the valve 18. The controller 28 receives a value of a first voltage V_1 from an input side of the series pass element 32 and a value of a second voltage V_2 from an output side of the series pass element 32. The controller 28 provides a control signal to the actuator 30 based on the difference between the first and second voltages V_1, V_2 to adjust the flow of reactant to the fuel cell stack 14 via the valve 18 or other reactant flow regulating element.

Since the battery 24 covers any short-term mismatch between the available reactants and the consumed reactants, the speed at which the fuel cell reactant supply system 16 needs to react can be much slower than the speed of the electrical load changes. The speed at which the fuel cell reactant supply system 16 needs to react mainly effects the depth of the charge/discharge cycles of the battery 24 and the dissipation of energy via the series pass element 32.

First Stage Description, Series Pass Element Regulation

Figure 2 shows a one embodiment of the regulating circuit 34, including components for determining a battery charging current error, stack current error and battery voltage error, and for producing an output to the series pass element 32 corresponding to the greater of the determined errors.

The regulating circuit 34 includes a battery charging current error integrating circuit 44 and a battery charging current limit circuit 46 for determining the battery charging current error. The battery charging current limit circuit 46 provides a battery charging current limit value to the inverting terminal of the battery charging current error integrating circuit 44, while the battery charging current sensor 36 provides a battery charging current value to the non-inverting terminal. A capacitor C9 is coupled between the inverting terminal and an output terminal of the battery charging current error integrating circuit 44. The battery charging current limit error integrating circuit 44 integrates the difference between the battery charging current value and the battery charging current limit value.

The regulating circuit 34 includes a stack current error integrating circuit 50 and a stack current limit circuit 52 for determining the stack current error. The stack current limit circuit 52 provides a stack current limit value to the inverting terminal of the stack current error integrating circuit 50, while stack current sensor 38 provides a stack current value to the non-inverting terminal. A capacitor C8 is coupled between the inverting terminal and an output terminal of the stack current error integrating circuit 50. The stack current error integrating circuit 50 integrates the difference between the stack current value and the stack current limit value. The limiting effect of the second stage on the stack current limit is represented by broken line arrow 53.

The regulating circuit 34 includes a battery voltage error integrating circuit 56 and a battery voltage set point circuit 58. The battery voltage set point circuit 58 provides a battery voltage limit value to the inverting terminal of the battery voltage error integrating circuit 56, while the battery voltage sensor 40 provides a battery voltage value to the non-inverting terminal. A capacitor C7 is electrically coupled between the inverting terminal and the output terminal of the battery voltage error integrating circuit 56. The battery voltage error integrating circuit 56 integrates the difference between the battery voltage value and the battery voltage set point value.

The regulating circuit 34 may also include a temperature compensation circuit 62 that employs the battery temperature measurement from the battery temperature detector 42 to produce a compensation value. The battery voltage set point circuit 58 employs the compensation value in determining the battery voltage set point value.

The regulating circuit 34 also includes an OR circuit 64 for selecting the greater of the output values of the error integrators 44, 50, 56. The OR circuit 64 can take the form of three diodes (not shown) having commonly coupled cathodes. The anode of each of the diodes are electrically coupled to respective ones of the error integration circuits 44, 50, 56.

The regulating circuit 34 also includes a charge pump 66 for providing a voltage to a control terminal (*e.g.*, gate) of the series pass element 32 by way of a level shifter, such as an inverting level shifter 68. The inverting level shifter 68 provides a linear output value that is inverted from the input value.

Figure 3 shows an alternative embodiment of the first stage of the fuel cell system 10, employing a microprocessor 70 as the regulating circuit.

This alternative embodiment and those other alternatives and alternative embodiments described herein are substantially similar to the previously described embodiments, and common acts and structures are identified by the same reference numbers. Only significant differences in operation and structure are described below.

The microprocessor 70 can be programmed or configured to perform the functions of the regulating circuit 34 (Figure 1). For example, the microprocessor 70 may perform the error integration for some or all of the battery charging current, stack current and battery voltage values. The microprocessor 70 may store some or all of the battery charging current limit, stack current limit and/or battery voltage limit values. The microprocessor 70 may also determine the temperature compensation based on the battery temperature value supplied by the battery temperature detector 42. Further, the microprocessor 70 may select the greater of the error values, providing an appropriate signal to the control terminal of the series pass element 32.

Figure 4 shows an exemplary method 100 of operating the first stage of fuel cell system 10 of Figures 1, 2 and 3. The method 100 repeats during operation to continually adjust the operating parameters of the fuel cell system 10.

In step 102, the battery charging current sensor 36 (Figures 1-3) determines the value of the battery charging current I_B. In step 104, the battery charging current error integrating circuit 44 (Figure 2) or microprocessor 70 (Figure 3) determines the value of the battery charging current error.

In step 106, the stack current sensor 38 (Figures 1-3) determines the value of the stack current. In step 108, the stack current error integrating circuit 50 (Figure 2) or microprocessor 70 (Figure 3) determines the value of the stack current error.

In step 110, the battery voltage sensor 40 (Figures 1-3) determines the value of the voltage V_B across the battery 24. In optional step 112, the battery temperature sensor 42 determines the temperature of the battery 24 or the ambient space proximate the battery 24. In optional step 114, the temperature compensation circuit 62 (Figure 2) or microprocessor 70 (Figure 3) determines the value of the battery voltage limit based on determined battery temperature. In step 116, the battery voltage error integrating circuit 56 (Figure 2) or microprocessor 70 (Figure 3) determines the value of the battery voltage error.

The fuel cell system 10 may perform the steps 102, 106 and 110 in a different order than described above, for example performing step 106 before step 102, or performing step 110 before step 102 and/or step 106. The sensors 36, 38, 40, 42 may perform the steps 102, 106, 110, 112 at the same time or approximately at the same time so as to appear be operating in parallel. Thus, the enumeration of the above acts does not identify any specific sequence or order.

In step 118, the OR circuit 64 (Figure 2) or an OR circuit configured in the microprocessor 70 (Figure 3) determines the greater of the determined errors values. The OR circuit may be hardwired in the microprocessor 70, or may take the form of executable instructions. In step 120, the charge pump 66 (Figure 2) produces charge. While not illustrated, the embodiment of Figure 3 may also include a charge pump, or the microprocessor 70 can produce an appropriate signal value. In step 122, the level shifter 68 (Figure 2) or microprocessor 70 (Figure 3) applies the charge as an input voltage to the control terminal of the series pass element 32 (Figures 1-3) in proportion to determined greater of errors values.

The first stage of the fuel cell system 10 thus operates in essentially three modes: battery voltage limiting mode, stack current limiting mode, and battery charging current limiting mode. For example, when the battery 24 is drained, the fuel cell system 10 will enter the battery charging current mode to limit the battery charging current in order to prevent damage to the battery 24. As the battery 24 recharges, the fuel cell system 10 enters the battery voltage limiting mode, providing a trickle charge to the battery 24 in order to maintain a battery float voltage (*e.g.*, approximately 75%-95% of full charge) without sulfating the battery 24. As the load 12 pulls more current than the fuel cell stack 14 can provide, the fuel cell system 10 enters the stack current limiting mode. Additionally, there can be a fourth "saturation" mode where, as the load 12 pulls even more current, the stack voltage V_S drops below the battery voltage V_B. The battery 24 will discharge in this "saturation" mode, eventually entering the battery charging current limiting mode when the battery 24 is sufficiently drained, as discussed above.

Second Stage Description, Reactant Partial Pressure Control

Figure 5A illustrates one embodiment of the second stage of the fuel cell system 10 in further detail, which employs a voltage difference across the series pass element 32 as the operating condition.

In particular, the controller 28 includes a first comparator 90A that receives the value of the first voltage V_1 from the input side of the series pass element 32 and the value of the second voltage V_2 from the output side of the series pass element 32. The first comparator 90A produces a process variable ΔV corresponding to a difference between the first and second voltages V_1, V_2.

The controller 28 also includes a second comparator 92 that receives the process variable ΔV from the first comparator 90A and a set point. The comparator 92 compares the process variable ΔV to the set point and produces a first control voltage CV1. The set point reflects the desired maximum operating level of the series pass element 32, and may typically be between approximately 75% and approximately 95% of the saturation value for the series pass element 32. A set point of 80% of the saturation value is particularly suitable, providing some resolution in the circuitry even when the fuel cell stack 14 is operating under a partial load.

The comparator 92 supplies the resulting control variable CV1 to the actuator 30 which adjusts the compressor or valve 18 accordingly. The valve 18 adjusts the reactant partial pressure to the fuel cell stack 14, which serves as a second control variable CV2 for the fuel cell system 10. As noted above, controlling the reactant partial pressure adjusts the internal resistance of R_S of the fuel cell stack 14, as well as adjusting the power output of the fuel cell stack 14. The first and second comparators 90A, 92 may be discrete components or may be implemented in a microprocessor, microcontroller or other integrated circuit.

The controller 28 may also include logic 94 for controlling various switches, such as a first switch 96 that electrically couples the battery 24 in parallel with the fuel cell 14, and second switch 98 that electrically couples the load 12 in parallel with the fuel cell stack 14 and the battery 24.

Figure 6A illustrates an exemplary method 200 of operating the second stage of the fuel cell system 10, of Figures 1 and 5A. In step 102, the battery 24 is electrically coupled in parallel with the fuel cell stack 14. In step 204, the load 12 is electrically coupled to the battery 24 and fuel cell stack 14. In step 206, at least one of the fuel cell stack 14 and battery 24 supplies current to the load 12. The fuel cell stack 12 supplies the current to the load 12 where the fuel cell stack 14 is producing sufficient current to meet the demand of the load 12. Excess current from the fuel cell stack 14 recharges the battery 24. The battery 24 may supply a portion or even all of the power to the load 12 where the fuel cell stack 14 is not producing sufficient power to meet the demand.

In step 208, the second stage of the fuel cell system 10 determines the first voltage V_1 on the input side of the series pass element 32. In step 210, the second stage of the fuel cell system 10 determines the second voltage V_2 on the output side of the series pass element 32. The order of steps 208 and 210 are not important, and can occur in any order or even at a same time.

In step 212, the first comparator 90A determines the difference between the first and the second voltages V_1, V_2. In step 214, the second comparator 92 compares the determined difference ΔV to the set point. In step

216, the second stage of the fuel cell system 10 adjusts a partial pressure of at least one reactant flow to the fuel cell stack 14 via the actuator 30 and valve 18 based on the determined amount of deviation. For example, fuel cell system 10 may adjust the partial pressure of the hydrogen, the partial pressure of the oxidant (*e.g.*, air), or the partial pressure of both the hydrogen and the oxidant. As discussed above, by varying the partial pressure of fuel and/or oxidant, the value of the internal series resistance R_S inherent in the fuel cell stack 14 can be varied to control the voltage that is dropped at any given stack output current. By varying the partial pressure in such a way, the maximum voltage dropped across the series pass element 32 can be reduced.

Figure 5B illustrates another embodiment of the second stage of the fuel cell system 10 in further detail, which employs battery current as the operating condition. This specific embodiment and those other specific embodiments described herein are substantially similar to previously described embodiments, and common acts and structures are identified by the same reference numbers. Only significant differences in operation and structure are described below. The embodiment illustrated in Figure 5B may implemented in the fuel cell system10 along with the regulating circuit (Figures 1-4), forming a second stage, or may be used independently without the first stage regulating circuit.

In the embodiment of Figure 5B, a battery condition sensor takes the form of a current sensor 26b coupled to sense the flow of current to and from the battery 24. The controller 28 includes a battery charging current integrator 90. The integrator 90 may be a discrete component or may be implemented in a microprocessor or microcontroller. The integrator 90 integrates the battery charging current to determine the approximate overall charge of the battery 24. The integrator 90 should be supplied with the correct initial battery charge at the start of operation, and should be rationalized from time to time. The resulting process variable ("PV") is supplied to a comparator 92.

The comparator 92 may be a discrete component or may be implemented in a microprocessor or microcontroller. The comparator 92 compares the PV to a set point and produces a first control voltage ("CV1"). The set point reflects the desired nominal battery charge at the start of operation, and may typically be between approximately 75% and approximately 95% of the full charge of the battery. The comparator 92 supplies the resulting CV1 to the actuator 30 which adjusts the compressor or valve 18 accordingly. The valve 18 adjusts the reactant partial pressure to the fuel cell stack 14, which serves as a second control variable ("CV2") for the fuel cell system 10. As noted above, controlling the reactant partial pressure adjusts the internal resistance of R_S of the fuel cell stack 14 as well as adjusting the power output of the fuel cell stack 14.

The controller 28 may also include logic 94 for controlling various switches, such as a first switch 96 that electrically couples the battery 24 in parallel with the fuel cell 14, and second switch 98 that electrically couples the load 12 in parallel with the fuel cell stack 14 and the battery 24.

Figure 6B shows a method 300 of operating the fuel cell system 10 of Figure 5B. In step 302, the correct initial battery charge is supplied to the integrator 90. In step 304, the sensor 26b determines the current flow to and from the battery 24. In step 306, the integrator 90b integrates the battery current flow to determine the total charge of the battery 24.

In step 308, the comparator 92 compares the integrated battery current flow to a set point. The set point is selected to apply a trickle charge to the battery in order to maintain the battery 24 at a suitable float voltage, thereby preventing damage to the battery 24, for example from sulfating. A suitable range for may be between approximately 75% to 95% of the desire nominal battery charge, with approximately 80% of the desire nominal battery charge being particularly suitable.

In step 310, the fuel cell system 10 adjusts the partial pressure of fuel flow to the fuel cell stack 14 to maintain the desired battery charge. For example, the actuator 30 may adjust the partial pressure of hydrogen flow via one or more valves 18. Alternatively, the actuator 30 may adjust the speed of one or more compressors (not shown). In step 312, the fuel cell system 10 adjusts the partial pressure of oxidant flow (*e.g.*, air) to the fuel cell stack to maintain the desired battery charge. Again, the fuel cell system 10 may employ one or more values 18 and/or one or more compressors (not shown) to adjust the oxidant partial pressure. The controller 28 may attempt to maintain the appropriate stoichiometric relationship between the fuel and oxidant.

Figure 5C illustrates a further embodiment of the second stage of the fuel cell system 10 in further detail, employing the voltage V_B across the battery 24 as the operating condition. The embodiment illustrated in Figure 5C may implemented in the fuel cell system10 along with the regulating circuit (Figures 1-4), forming a second stage, or may be used independently without the first stage regulating circuit.

In the embodiment of Figure 5C, the battery condition sensor takes the form of a voltage sensor 26c for detecting voltage V_B across the battery 24. The controller 28 takes a form similar to a field controller 90c. Field controllers are commonly found in the alternators of automotive systems, as well as other electrical systems. The field controller 90c supplies an output CV1 to the actuator 30 to control the reactant partial pressure to the fuel cell stack 14.

Figure 6C shows a method 400 of operating the fuel cell system 10 of Figure 5C. In step 402, the voltage sensor 26c determines the voltage V_B across the battery 24. In step 404, the field controller 90c determines an amount of deviation of battery voltage V_B from the desired battery voltage. In step 406, the controller 28 adjusts the partial pressure of the fuel flow to the fuel cell stack 14 to maintain the desired battery voltage. In step 408, the controller 28 adjusts the partial pressure of oxidant to the fuel cell stack to maintain the desired battery voltage. As noted above, the fuel cell system 10 may employ one or more valves, compressors, pumps and/or other regulating means to adjust the partial pressure of the fuel and/or oxidant.

Figure 7 illustrates exemplary polarization curves for the fuel cell stack 14, corresponding to five different reactant partial pressures. Stack voltage V_S is represented along the vertical axis, and stack current I_S represented along the horizontal axis. A first curve 59 represents the polarization at a low reactant partial pressure. Curves 61, 62, 63 and 65 represent the polarization at successively increasing reactant partial pressures. A broken line 69 illustrates a constant nominal output voltage of 24 volts. Vertical broken lines 71, 723, 75, 77, 79 illustrate the stack current corresponding to the 24 volt output for the respective partial pressure curves 59, 61, 63, 65, 67.

Battery Portions/Fuel Cell Portions Interconnected Embodiment of Fuel Cell System

Figure 8 shows a further embodiment of the fuel cell system 10 where the where portions of the battery 24 are interconnected with portions of the fuel cell stack 14.

In particular, the fuel cell stack 14 can include a number of groups or portions 14a, 14b, . . . 14n which are interconnected with respective groups or portions of the battery 24a, 24b, . . . 24n. While illustrated as one battery cell 24a, 24b, . . . 24n to each set of fuel cells 14a, 14b, . . . 14n, the fuel cell system 10 can employ other ratios of battery cells to fuel cells.

The fuel cell system 10 can include a capacitor, such as a super-capacitor 140, electrically coupled in parallel across the load 12. The fuel cell system 10 of Figure 8 may be operated in accordance with the methods 100 and 200 of Figures 4 and 6A.

While not illustrated in Figure 8, separate control elements such as valve 18, controller 28, and/or actuator 30 can be associated with respective ones the sets of fuel cells 14a, 14b. . .14n.

Currents, Voltages, and Resistance of Fuel Cell System and Load

Figures 9A-9F show a series of graphs illustrating the relationship between various currents, voltages, and resistance in the fuel cell system 10 in single phase AC operation where the fuel cell stack is sufficiently powering the load without draining or recharging the battery. The various graphs of Figure 9A-9F share a common, horizontal time axis.

Figure 9A is a graph 150 illustrating the actual stack current I_S and the average stack current $I_{S\text{-}AVG}$ as a function of time. Figure 9B is a graph 152 illustrating the actual battery current I_B as a function of time. Figure 9C is a graph 154 illustrating the actual battery voltage V_B and the average battery voltage $V_{B\text{-}AVG}$ as a function of time. Figure 9D is a graph 156 illustrating the actual current through the load I_L and the average load current $I_{L\text{-}AVG}$ as a function of time. Figure 9E is a graph 158 illustrating the actual load resistance R_L as a function of time. Figure 9F is a graph 160 illustrating an AC voltage V_{ac} across the load 12 as a function of time.

Figures 10A-10C show a series of graphs illustrating the relationship between various currents, voltages, and resistance in the fuel cell system 10 in single phase AC operation where the battery supplies current to the load to cover a shortfall from the fuel cell stack and the fuel cell stack later recharges the battery. The various graphs of Figures 10A-10C share a common, horizontal time axis.

Figure 10A is a graph 162 illustrating the stack current I_S as a function of time. Figure 10B is a graph 164 illustrates the battery current I_B as a function of time. Figure 10C is a graph 166 illustrating the load current I_L as a function of time. As can be seen from Figures 10A-10C, as the load 12 increases demand, the battery 24 supplies current to make up for the shortfall from the fuel cell stack 14. As the load 12 decreases demand, the fuel cell stack 14 recharges the battery 24 until the battery 24 returns to the float voltage.

Fuel Cell Systems As Component Blocks Of Combined Fuel Cell System

Figure 11 shows a number of fuel cell systems 10a-10f, electrically coupled to form a combined fuel cell system 10g, for powering the load 12 at a desired voltage and current. The fuel cell systems 10a-10f can take the form of any of the fuel cell systems 10 discussed above, for example the fuel cell systems 10 illustrated in Figures 1 and 2.

The combined fuel cell system 10g takes advantage of a matching of polarization curves between the fuel cell stacks 14 and the respective batteries 24. One approach to achieving the polarization curve matching includes the first stage regulating scheme generally discussed above. Another approach includes controlling a partial pressure of one or more reactant flows based on a deviation of a voltage across the battery 24 from a desired voltage across the battery 24. A further approach includes controlling a partial pressure of one or more reactant flows based on a deviation of a battery charge from a desired battery charge. The battery charge can be determined by integrating the flow of charge to and from the battery 24. Other approaches may include phase or pulse switching regulating or control schemes.

As an example, each of the fuel cell systems 10a-10f may be capable of providing a current of 50A at 24V. Electrically coupling a first pair of the fuel cell systems 10a, 10b in series provides 50A at 48V. Similarly electrically coupling a second pair of the fuel cells systems 10c, 10d in series provides 50A at 48V. Electrically coupling these two pairs of fuel cell systems 10a, 10b and 10c, 10d in parallel provides 100A at 48V. Electrically coupling a third pair of fuel cells systems 10e, 10f in series provides an 50A at 48V. Electrically coupling the third pair of fuel cell systems 10e, 10f in parallel with the first pair of series coupled fuel cell systems 10a:10b and the second pair of series coupled fuel cell systems 10c:10d, provides 150A at 48V.

Figure 11 shows only one possible arrangement. One skilled in the art will recognize that other arrangements for achieving a desired voltage and current are possible. A combined fuel cell system 10g may include a lesser or greater number of individual fuel cell systems 10a-10f than illustrated in Figure 11. Other combinations of electrically coupling numbers of individual fuel cell systems 10 can be used to provide power at other desired voltages and currents. For example, one or more additional fuel cell systems (not shown) can be electrically coupled in parallel with one or more of the fuel cell systems 10a-10b. Additionally, or alternatively, one or more additional fuel cell systems (not shown) can be electrically coupled in series with any of the illustrated pairs of fuel cell systems 10a:10b, 10c:10d, 10e:10f. Further, the fuel cell systems 10a-10f may have different voltage and/or current ratings. The individual fuel cell systems 10a-10f can be combined to produce an "n+1" array, providing a desired amount of redundancy and high reliability.

Power Supply System

Figure 11 shows one embodiment of a power supply system 550 including a one-dimensional array 552 of a fuel cells systems, collectively referenced as 10, that are electrically couplable in series to positive and negative voltage rails 556a, 556b, respectively, that form a power bus 556 for supplying power to the load 12. A respective diode, collectively referenced as 558, is electrically coupled between the positive and negative outputs of each of the fuel cell systems 10. The illustrated power supply system 550 includes a number M+1 fuel cell systems, which are individually referenced as 10(1)-10(M+1), the number in the parenthesis referring to the position of the fuel cell system 10 in the array. The ellipses in Figure 11 illustrate that the power supply system 550 may include additional fuel cell systems (not explicitly shown) between the third fuel cell system 10(3) and the M^{th} fuel cell system 10(M). One or more of the fuel cell systems (*e.g.*, 10(M+1)) may serve as a "redundant" fuel cell system, being electrically coupled in series on the power bus 556 as needed, for example, when one of the other fuel cell systems 10(1)-10(M) is faulty or when the load 12 requires additional power or voltage.

The power supply system 550 may employ one or more fault switches such as a contactor or transistor 560, that can automatically disconnect a respective fuel cell system 10 in the event of a fault or failure. For example, the fault transistor 560 may open upon a fault or failure in the fuel cell system's 10 own operating condition or upon a fault or failure in the operating condition of the power supply system 550.

The power supply system 550 may employ one or more redundancy switches, such as a contractor or transistor 562, that can manually or automatically electrically couple a respective fuel cell system 10(M+1) to the power bus 556 based on a condition other than the fuel cell system's 10(M+1) own operating condition. For example, where another fuel cell system 10 is faulty, the redundancy transistor 562 may close to electrically couple the redundant fuel cell system 10(M+1) to the power bus 556 to maintain the power, voltage and current to the load 12. Also for example, where a higher output power is desired, the redundancy transistor 562 may close to electrically couple the redundant fuel cell system 10(M+1) to the power bus 556 to adjust the power, voltage and current to the load 12.

While manual operation may be possible, the power supply system 550 may include control logic 564 for automatically controlling the operation of the redundancy switch (*e.g.*, transistor 562).

The control logic 564 may receive an input from one or more of the other fuel cell systems 10(1)-10(M), the input relating to an operating condition of the respective fuel cell system 10(1)-10(M) (*i.e.*, "connect on failure of Unit 1 through M"). For example, the control logic 564 may receive voltage, current and/or power measurements related to the fuel cell stack 14 and/or electrical storage 24 of the fuel cell system 10. Such measurements may include, but are not limited to, stack current I_S, stack voltage V_S, battery current I_B, and battery voltage V_B, and/or temperature. Also for example, the control logic 564 may receive logical values relating to the operating condition of various systems of the fuel cell system 10, including, but not limited to, an ambient hydrogen level, an ambient oxygen level, and a reactant flow. In this respect, reference is made to commonly assigned U.S. application Serial No. 09/916,240, filed July 25, 2001 and entitled "FUEL CELL SYSTEM METHOD, APPARATUS AND SCHEDULING" (Atty. Docket No. 130109.409).

Additionally, or alternatively, the control logic 564 may receive an input from other components of the power supply system 550, such as voltage and current sensors coupled to determine a voltage or current at various points on the power bus 556. For example, the control logic 564 may receive a voltage reading corresponding to the voltage across the power bus measured at a "top" of the one-dimensional array 552, allowing the control logic 564 to indirectly detect a fault in one or more of the fuel cell systems 10 by detecting a measurement below an expected threshold value (*i.e.*, "connect if $V_X <$ Mx24V"). The threshold for detecting a fault condition may be predefined in the control logic 564 or may be set by a user or operator via a user interface 566 such as analog or digital controls, or a graphical user interface on a special purpose or general purpose computer.

Additionally or alternatively, the control logic 564 may receive an input from the user or operator via the user interface 566 which may include a set of user controls to set operating parameters such as power, voltage, and or current thresholds, to set desired parameters such as desired power, desired voltage or desired current nominal values, to provide electrical configuration information, to provide switching signals, and/or to signals to override the automatic operating aspects of the control logic 564. The user interface 566 may be remote from the remainder of the power supply system 550. The control logic 564 can be embodied in one or more of hardwired circuitry, firmware, micro-controller, application specific processor, programmed general purpose processor, and/or instructions on computer-readable media.

Where the output voltage of the fuel cell systems 10 can be tightly controlled, such as under the first and/or second stage operation discussed above, the series coupling of the fuel cell systems 10 is possible. Thus any desired number of fuel cell systems 10 may be electrically coupled in series to realize any integer multiple of voltage output of the individual fuel cell system 10. For example, where each fuel cell system 10 produces 24 volts across the rails 19a, 19b, three fuel cell systems 10(1)-10(3) are electrically couplable to produce 72 volts across the power bus 556. More generally stated, a number M of fuel cell systems 10 can be electrically coupled in series to produce M times the nominal fuel cell system voltage across the power bus 556. Additionally, the series coupling renders the position of the redundant fuel cell system 10(M+1) in the one-dimensional array 552 unimportant.

Figure 12 shows a two-dimensional array 568 of fuel cell systems 10, arranged in a number M of rows and a number N of columns for powering the load 12 via the power bus 556. The fuel cell systems 10 are individually referenced 10(1,1)-10(M,N), where the first number in the parenthesis refers to a row position and the second number in the parenthesis refers to a column position of the fuel cell system 10 in the two-dimensional array 568. The ellipses in Figure 12 illustrate that the various rows and columns of the two-dimensional array 568 may include additional fuel cell systems (not explicitly shown). The diodes 558, fault and redundancy switches 560, 562, respectively, control logic 564, and user interface 566 have been omitted from Figure 12 for clarity of illustration.

Each of the fuel cell systems 10(1,1)-10(M,N) is individually couplable to the power bus 556 to provide a variety of desired output power, voltage or current. The fuel cell systems 10(1-M,1), 10(1-M,2), 10(1-M,3)-10(1-M,N) in each column 1-M are electrically couplable in series to one another. The fuel cell systems 10(1,1-N), 10(2,1-N), 10(3,1-N)-10(M,1-N) in each row 1-N are electrically couplable in parallel to one another. From Figure 12 and this description, one skilled in the art will recognize that the two-dimensional array 568 permits the series coupling of fuel cell systems 10 to adjust an output power of the power supply system 550 by adjusting an output voltage. One skilled in the art will also recognize that the two-dimensional array 568 permits the parallel coupling of fuel cell systems 10 to adjust the output power of the power supply system 550 by adjusting an output current. One skilled in the art will further recognize that the two-dimensional array 568 permits the series and parallel coupling of fuel cell systems 10 to adjust the output power of the power supply system 550 by adjusting both the output current and the output voltage. Thus, for the illustrated embodiment where each fuel cell system produces, for example, 1 kW at 24 volts and 40 amps, a maximum output power of N×M kW is possible. One skilled in the art will further recognize that the one- and two-dimensional array structures discussed herein refer to electrically couplable positions relative to one another, and do not necessary require that the fuel cell systems 10 be physically arranged in rows and/or columns.

<u>Example</u>

Figures 13-15 illustrate three different electrical configurations of the fuel cell systems 10 of the two-dimensional array 568 of Figure 12, to produce a desired output power, for example 4kW where each fuel cell system 10 is capable of providing 1kW at 24 volts and 40 amps. In particular, Figure 13 shows one illustrated example employing four of the fuel cell systems 10(1,1)-10(4,1) from the first column of the two-dimensional array 568 electrically coupled in series to provide 4 kW of power at 96 volts and 40 amps. Figure 14 shows an illustrated embodiment of four of the fuel cell systems 10(1,1)-10(1,4) of a first row of the two-dimensional array 568 electrically coupled in parallel to provide 4 kW of power at 24 volts and 160 amps. Figure 15 shows an illustrated example employing four fuel cell systems 10(1,1), 10(1,2), 10(2,1), 10(2,2) of the two-dimensional array 568, where two pairs of series coupled fuel cell systems 10(1,1), 10(2,1) and 10(1,2), 10(2,2) are electrically coupled in parallel to produce 4 kW of power at 48 volts and 80 amps. One skilled in the art will recognize from these teachings that other combinations and permutations of electrical couplings of the fuel cell systems 10 of the two-dimensional array 568 are possible.

Power Supply System Operation

Figure 16 shows a method 600 of operating the power supply system 550 according to one exemplary illustrated embodiment, which is discussed with reference to Figure 11. The method 600 may be embodied in the control logic 564, discussed above.

In step 602, the control logic 564 electrically couples a number M of fuel cell systems 10(1)-10(M) in series on the power bus 556 by selectively operating appropriate ones of the switches 560, 562. In step 604, the control logic 564 determines if there is a fault. For example, the control logic 564 may determine whether any of the parameters of one of the fuel cell systems 10(1)-10(M) is outside of an acceptable range, or exceeds, or falls below, an acceptable threshold. As discussed above the control logic 564 may receive voltage, current and/or power measurements related to the fuel cell stack 14 and/or electrical storage 24 of the fuel cell system 10. Additionally, or alternatively, the control logic 564 may receive logical values relating to the operating condition of various systems of the fuel cell system 10. Additionally, or alternatively, the control logic 564 may receive an input from other components of the power supply system 550, such as voltage and current sensors coupled to determine a voltage or current at various points on the power bus 556. The control logic 564 can include comparison circuitry such as a comparator, or instructions for comparing the received values to defined range and/or threshold values, for example, ensuring that the total voltage across the power bus 556 is above a defined threshold or within a defined range. Alternatively, or additionally, the control logic 564 can rely on a set of logical values returned by the individual fuel cell systems 10(1)-10(M), such as a “1” or “0” corresponding to one or more operating conditions of the respective fuel cell system 10(1)-10(M).

If there is no fault, the method 600 returns to step 604, performing a monitoring loop. If there is a fault, the control logic 564 electrically couples the redundant fuel cell system 10(M+1) in series on the power bus 556 in step

606, for example, by sending an appropriate signal to the corresponding redundant switch such as by applying a signal to a gate of the redundant transistor 562. The fuel cell systems 10(1)-10(M+1) are "hot swappable" so the power supply system 550 does not have to be shutdown.

In optional step 608, the control logic 564 electrically decouples the faulty fuel cell system, for example 10(3), from the power bus 556, for example, by sending an appropriate signal to the corresponding fault switch such as by applying a signal to a gate of the fault transistor 560. In optional step 610, a user or service technician replaces the faulty fuel cell system 10(3) in the array 552 of the power supply system 550. The replacement fuel cell system 10 may serve as a redundant fuel cell system for a possible eventual failure of another fuel cell system 10.

Figure 17 shows an optional step 612 for inclusion in the method 600. In step 612, an additional fuel cell system 10 is electrically coupled in series on the power bus 550 with one or more of the fuel cell systems 10(1)-10(M). For example, where the faulty fuel cell system 10(3) has been replaced, the replacement fuel cell system may be electrically coupled in series to increase the power output of the power supply system 550.

Figure 18 shows an optional step 614 for inclusion in the method 600. In step 614, an additional fuel cell system 10 is electrically coupled in parallel on the power bus 552 with one or more of the fuel cell systems 10(1)-10(M). From this description, one skilled in the art will recognize that the method 600 may employ any variety of series and/or parallel combinations of fuel cell systems 10.

Figure 19 shows a method 630 of operating the power supply system 550 according to an additional, or alternative, illustrated embodiment, which is discussed with reference to the two-dimensional array 568 of Figure 12. Thus, the power supply system 550 may employ the method 630 in addition to, or alternatively from, the method 600.

In step 632, the control logic 564 determines at least one of a desired power, voltage and current output from the power supply system 550. The desired values may be defined in the control logic 564 or the control logic 564 may receive the desired value(s) from the user or operator by way of the user interface 566. In step 634, the control logic 564 determines an electrical configuration of series and/or parallel combinations of a number of fuel cell systems 10(1,1)-10(M,N) to provide the desired power, voltage and/or current. In step 636, the control logic 564 operates a number of the redundant switches such as a transistor 560 (Figure 11, only one shown) to electrically couple respective ones of fuel cell systems 10(1,1)-10(M,N) into the determined electrical configuration.

Conclusion

The description shows that any number of fuel cell systems 50 are electrically couplable in series and/or parallel combinations to form a combined power supply system 550 for powering the load 12 at a desired voltage and current.

The fuel cell systems 10 can take the form of any of the fuel cell systems discussed above, for example, the fuel cell system 10 illustrated in Figure 1. As discussed above, the power supply system 550 takes advantage of a matching of polarization curves between the fuel cell stacks 14 and the respective electrical storage 24 to allow series coupling of fuel cell systems. One approach to achieving the polarization curve matching includes the first stage regulating scheme generally discussed above. Another approach includes controlling a partial pressure of one or more reactant flows based on a deviation of a voltage across the electrical storage device such as battery 24 from a desired voltage across the electrical storage device 24. A further approach includes controlling a partial pressure of one or more reactant flows based on a deviation of an electrical storage charge from a desired electrical storage charge. The electrical storage charge can be determined by integrating the flow of charge to and from the electrical storage device 24. Other approaches may include phase or pulse switching regulating or control schemes. Reasons for employing a series configuration include the cost advantage, and the configuration having the highest efficiency at the full output power point if the stack voltage equals the battery float voltage at that point, *e.g.*, efficiency can exceed 97% in a 24V system with no R.F. noise problem. While the fuel cell systems 10 are illustrated having two stages, in some embodiments the power supply system 550 may incorporate one or more fuel cell systems 10 having only one of the stages, either the first or the second stage.

The disclosed embodiments provide a "building block" or "component" approach to the manufacture of power supply systems, allowing a manufacturer to produce a large variety of power supply systems 550 from a few, or even only one, basic type of fuel cell system 10. This approach may lower design, manufacturer and inventory costs, as well as providing redundancy to extend the mean time between failures for the resulting end user product (*i.e.*, the power supply system). This approach may also simplify and reduce the cost of maintenance or repair.

Although specific embodiments of and examples for the fuel cell system and method are described herein for illustrative purposes, various equivalent modifications can be made without departing from the spirit and scope of the invention, as will be recognized by those skilled in the relevant art. For example, the teachings provided herein can be applied to fuel cell systems including other types of fuel cell stacks or fuel cell assemblies, not necessarily the polymer exchange membrane fuel cell assembly generally described above. Additionally or alternatively, the fuel cell system 10 can interconnect portions of the fuel cell stack 14 with portions of the battery B1, B2. The fuel cell system can employ various other approaches and elements for adjusting reactant partial pressures. The various embodiments described above can be combined to provide further embodiments.

U.S. patent application Serial No. 10/017470, filed December 14, 2001, entitled "METHOD AND APPARATUS FOR CONTROLLING VOLTAGE FROM A FUEL CELL SYSTEM" (Attorney Docket No. 130109.436); and U.S. patent application serial No. 10/017462, filed December 14, 2001, entitled "METHOD AND APPARATUS FOR MULTIPLE MODE CONTROL OF VOLTAGE FROM A FUEL CELL SYSTEM" (Attorney Docket No. 130109.442); U.S. patent application serial No. 10/017461, filed December 14, 2001, entitled "FUEL CELL SYSTEM MULTIPLE STAGE VOLTAGE CONTROL METHOD AND APPARATUS" (Attorney Docket No. 130109.446); and U.S. Application No. _________, entitled "ADJUSTABLE ARRAY OF FUEL CELL SYSTEMS IN POWER SUPPLY" (Express Mail No. EV064990705US, Attorney Docket No. 130109.449), are incorporated herein by reference in their entirety. Aspects of the invention can be modified, if necessary, to employ systems, circuits and concepts of the various patents, applications and publications to provide yet further embodiments of the invention. For example, the fuel cell system 10 can additionally, or alternatively control the reactant partial pressure as a function of the either the battery voltage V_B, current flow to and from the battery 24 or battery charge, as taught in U.S. patent application Serial No. 10/017470.

These and other changes can be made to the invention in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the invention to the specific embodiments disclosed in the specification and claims, but should be construed to include all fuel cell systems that operate in accordance with the claims. Accordingly, the invention is not limited by the disclosure, but instead its scope is to be determined entirely by the following claims.

CLAIMS

We/I claim:

1. A fuel cell system, comprising:

a fuel cell stack having a number of fuel cells;

a battery having a number of battery cells electrically coupleable in parallel across the fuel cell stack;

a series pass element electrically coupled between at least a portion of the fuel cell stack and a portion of the battery;

a regulating circuit for regulating current through the series pass element in response to a greater of a battery charging current error, a battery voltage error and a stack current error;

a reactant delivery system for delivering reactant to the fuel cells, the reactant delivery system including at least a first control element adjustable to control a partial pressure in a flow of a reactant to at least some of the fuel cells; and

a control circuit coupled to control the at least first control element based on at least one of a determined operational condition of the battery and a determined deviation of a voltage across the series pass element.

2. The fuel cell system of claim 1 wherein the regulating circuit comprises:

a battery charging current error integrator having a first input coupled to receive a battery charging current signal and a second input coupled to receive a battery charging current limit signal;

a battery voltage error integrator having a first input coupled to receive a battery voltage signal and a second input coupled to receive a battery voltage limit signal; and a stack current error integrator having a first input coupled to receive a stack current signal and a second input coupled to receive a stack current limit signal.

3. The fuel cell system of claim 1 wherein the regulating circuit comprises:

a charge pump; and

a level shifter coupled between the charge pump and the series pass element.

4. The fuel cell system according to claims 1, 2, or 3 wherein the regulating circuit comprises:

an OR circuit having an input side and an output side, the input side coupled to the battery charging current error integrator, the battery voltage error integrator, and the stack current error integrator.

5. The fuel cell system of claim 1 wherein the series pass element comprises a field effect transistor, further comprising:

a blocking diode electrically coupled between the fuel cell stack and the series pass element.

6. The fuel cell system of claim 1 wherein at least a portion of the battery is electrically coupled in parallel with at least a portion of the fuel cell stack.

7. The fuel cell system of claim 1 wherein the regulating circuit comprises a microprocessor programmed to regulate the current through the series pass element by:

integrating a difference between a battery current and a battery current limit;

integrating a difference between a battery voltage and a battery voltage limit;

integrating a difference between a stack current and a stack current limit;

selecting a greater of the integrated differences; and

applying a control signal to the series pass element proportional to the greater of the integrated differences.

8. The fuel cell system of claims 2, 3, or 4 wherein the regulating circuit comprises:

a battery charging current sensor to provide a battery charging current signal proportional to a battery charging current;

a battery voltage sensor to provide a battery voltage signal proportional to a battery voltage; and

a stack current sensor to provide a stack current signal proportional to a stack current.

9. The circuit of claim 1 wherein the regulating circuit comprises either a number of discrete integrators or a microprocessor.

10. The fuel cell system of claim 1 wherein the control circuit comprises a voltage sensor to determine a voltage across the series pass element and a comparator coupled to compare the determined voltage across the series pass element with a desired voltage.

11. The fuel cell system of claim 14 wherein the desired voltage corresponds to between approximately 75 percent and 95 percent of a saturation level for the series pass element.

12. The fuel cell system of claim 1 wherein the control circuit is coupled to control the at least first control element based only on the at least one of a determined operational condition of the battery.

13. The fuel cell system of claim 1 wherein the control circuit is coupled to control the at least first control element based only on the determined deviation of voltage across the series pass element.

14. A circuit for a fuel cell system having a fuel cell stack, a battery and a series pass element, comprising:

means for determining a greater of a difference between a battery charging current and a battery charging current limit, a difference between a battery voltage and a battery voltage limit, and a difference between a stack current and a stack current limit;

series pass regulating means for regulating a flow of stack current through a blocking diode in proportion to the determined greater difference; and

means for controlling a partial pressure of at least one reactant flow in proportion to at least one of a determined operational condition of the battery and a determined deviation of a voltage across the series pass element.

15. The circuit of claim 14, comprising:

integrating means for determining the difference between the battery charging current and the battery charging current limit;

integrating means for determining the difference between the battery voltage and the battery voltage limit; and

integrating means for determining the difference between the stack current and the stack current limit.

16. The circuit of claims 14 or 15, further comprising:

means for determining a deviation of a voltage across the series pass element.

17. A method of operating a fuel cell system, comprising:

supplying current at a number of output terminals from at least one of a fuel cell stack and a battery electrically coupled in parallel with the fuel cell stack;

in a first stage, regulating a current through a series pass element in proportion to at least a greater of a difference between a battery charging current and a battery charging current limit, a difference between a battery voltage and a battery voltage limit, and a difference between the stack current and the stack current limit; and

in a second stage, adjusting a partial pressure of a reactant flow to at least a portion of the fuel cell stack to maintain at least one of a desired operational condition of the battery and a desired saturation level of a series pass element.

18. The method of claim 17 wherein the first stage and the second stage occur during a same time.

19. The method of claims 17 or 18, further comprising:

determining a first potential on an input side of the series pass element;

determining a second potential on an output side of the series pass element;

determining a voltage across the series pass element from the first and the second potentials; and

determining an amount of deviation of the voltage across the series pass element from a value corresponding to the desired saturation level, and wherein adjusting a partial pressure of a reactant flow to at least a portion of the fuel cell stack to maintain at least one of a desired operational condition of the battery and a desired saturation level of a series pass element includes adjusting the partial pressure of the reactant flow based on the determined amount of deviation.

20. The method of claims 17, 18, or 19, further comprising:

determining the difference between the battery charging current and the battery charging current limit by integrating a difference between a battery charging current and a battery charging current limit over time;

determining the difference between the battery voltage and the battery voltage limit by integrating a difference between a battery voltage and a battery voltage limit over time; and

determining the difference between the stack current and the stack current limit by integrating a difference between a stack current and a stack current limit over time.

21. The method of claims 17, 18, 19, or 20, further comprising:

selecting the greater of the difference between the battery charging current and the battery charging current limit, the difference between the battery voltage and the battery voltage limit and the difference between the stack current and the stack current limit;

level shifting the selected one of the differences; and

applying the level shifted selected one of the differences to a control terminal of the series pass element.

22. The method of claims 17, 18, or 19, further comprising:

determining a temperature proximate a battery;

determining a battery voltage limit based at least in part on the determined temperature; and

integrating a difference between a battery voltage and the determined battery voltage limit over time to determine the battery voltage error.

23. The method of claim 17, further comprising:

selectively coupling charge from a charge pump to a control terminal of the series pass element in response to the determined difference between the battery charging current and the battery charging current limit at a first time, the determined difference between the battery voltage and the battery voltage limit at a second time and the determined difference between the stack current and the stack current limit at a third time.

24. The method of claim 17 wherein the desired saturation level between approximately 75 percent and approximately 95 percent fully saturated.

25. The method of claim 17 wherein the desired operational condition of the battery is at least one of a current flow into, and out of, the battery over a period of time, a voltage across the battery, and a battery charge.

26. The method of claims 17 or 19 wherein adjusting a partial pressure of the reactant flow to at least a portion of the fuel cell stack includes adjusting a partial pressure of a flow of fuel to at least a portion of the fuel cell stack and adjusting a partial pressure of a flow of oxidant to at least the same portion of the fuel cell stack.

27. The method of claims 17, 19, or 26, further comprising:

holding a pressure of at least one reactant flow approximately constant while adjusting the partial pressure of the reactant flow.

28. A fuel cell system, comprising:

a fuel cell stack having a number of fuel cells;

a battery having a number of battery cells electrically coupleable in parallel across the fuel cell stack;

a series pass element electrically coupled between at least a portion of the fuel cell stack and a portion of the battery; and

a regulating circuit for regulating current through the series pass element in response to a greater of a battery charging current error, a battery voltage error and a stack current error;

29. The fuel cell system of claim 28 wherein the regulating circuit comprises:

a battery charging current error integrator having a first input coupled to receive a battery charging current signal and a second input coupled to receive a battery charging current limit signal;

a battery voltage error integrator having a first input coupled to receive a battery voltage signal and a second input coupled to receive a battery voltage limit signal; and

a stack current error integrator having a first input coupled to receive a stack current signal and a second input coupled to receive a stack current limit signal.

30. The fuel cell system of claims 28 or 29 wherein the regulating circuit comprises:

a charge pump;

a level shifter coupled between the charge pump and the series pass element; and

an OR circuit.

31. A circuit for a fuel cell system, comprising:

means for determining a greater of a difference between a battery charging current and a battery charging current limit, a difference between a battery voltage and a battery voltage limit, and a difference between a stack current and a stack current limit; and series pass regulating means for regulating a flow of stack current through a blocking diode in proportion to the determined greater difference.

32. A method of operating a fuel cell system, comprising:

supplying current at a number of output terminals from at least one of a fuel cell stack and a battery electrically coupled in parallel with the fuel cell stack; and

regulating a current through a series pass element in proportion to at least a greater of a difference between a battery charging current and a battery charging current limit, a difference between a battery voltage and a battery voltage limit, and a difference between the stack current and the stack current limit.

33. The method of claim 32, further comprising:

selecting the greater of the difference between the battery charging current and the battery charging current limit, the difference between the battery voltage and the battery voltage limit and the difference between the stack current and the stack current limit;

level shifting the selected one of the differences; and

applying the level shifted selected one of the differences to a control terminal of the series pass element.

34. A fuel cell system, comprising:

a fuel cell stack having a number of fuel cells;

a battery having a number of battery cells electrically coupleable in parallel across the fuel cell stack;

a reactant delivery system for delivering reactant to the fuel cells, the reactant delivery system including at least a first control element adjustable to control a partial pressure in a flow of a reactant to at least some of the fuel cells; and

a control circuit coupled to receive signals corresponding to a potential on an input side and an output side of the series pass element and configured to determine a deviation of a voltage across the series pass element from a desired operational voltage based on the received signals, the control circuit further coupled to control the at least first control element based on the determined deviation.

35. The fuel cell system of claim 34 wherein the control circuit comprises a voltage sensor to determine a voltage across the series pass element and a comparator coupled to compare the determined voltage across the series pass element with a desired voltage.

36. The fuel cell system of claims 34 or 35 wherein the control circuit comprises a comparator to compare a determined voltage across the series pass element with a desired voltage corresponding to between approximately 75 percent and 95 percent of a saturation level for the series pass element.

37. A circuit for a fuel cell system, comprising:

means for determining a difference between a voltage difference across the series pass regulating means and a desired a desired operational condition of the series pass regulating means; and

means for controlling a partial pressure of at least one reactant flow in proportion to the determined difference between the voltage across the series pass regulating means and the desired operational condition of the series pass regulating means.

38. A method of operating a fuel cell system having a series pass element, comprising:

supplying current at a number of output terminals from at least one of a fuel cell stack and a battery electrically coupled in parallel with the fuel cell stack; and

adjusting a partial pressure of a reactant flow to at least a portion of the fuel cell stack to maintain a series pass element at a desired saturation level.

39. The method of claim 38, further comprising:

determining a first potential on an input side of the series pass element;

determining a second potential on an output side of the series pass element;

determining a voltage across the series pass element from the first and the second potentials; and

determining an amount of deviation of the voltage across the series pass element with respect to a value corresponding to the desired saturation level, and wherein adjusting a partial pressure of a reactant flow to at least a portion of the fuel cell stack to maintain the series pass element at the desired saturation level includes adjusting the partial pressure of the reactant flow based on the determined amount of deviation.

40. The method of claim 38 wherein determining an amount of deviation of the determined voltage includes determining a difference between the determined voltage and a value corresponding to a percentage of a saturation level of the series pass element, where the percentage is between approximately 75 percent and approximately 95 percent.

41. A fuel cell system for providing power to a load, comprising:

a fuel cell stack having a number of fuel cells;

a battery having a number of battery cells electrically couplable in parallel across the fuel cell stack;

a reactant delivery system for delivering reactant to the fuel cells, the reactant delivery system including at least a first control element adjustable to control a partial pressure in a flow of a reactant to at least some of the fuel cells; and

a control circuit coupled to receive signals corresponding to an operating condition of the battery and configured to determine a deviation of the operating condition of the battery from a desired operational condition of the battery based on the received signals, the control circuit further coupled to control the at least first control element based on the determined deviation.

42. The fuel cell system of claim 41, further comprising:

a current sensor coupled to measure a flow of current into and out of the battery and to provide the measured flow of current to the control circuit as the signals corresponding to the operating condition of the battery.

43. The fuel cell system of claim 41, further comprising:

a voltage sensor coupled to measure a voltage across the battery and to provide the measured voltage to the control circuit as the signals corresponding to the operating condition of the battery.

44. A method of operating a fuel cell system to power a load, the method comprising:

supplying current to the load from at least one of a fuel cell stack and a battery electrically coupled in parallel with the fuel cell stack;

determining an operational condition of the battery;

determining an amount of deviation of the determined operational condition of the battery from a desired operational condition of the battery; and

for at least one reactant flow to at least a portion of the fuel cell stack, adjusting a partial pressure of the reactant flow based on the determined amount of deviation.

45. The method of claim 44 wherein determining an operational condition of the battery includes determining current flow into and out of the battery over a period of time.

46. The method of claims 44 or 45 wherein determining an amount of deviation of the determined operational condition of the battery from a desired

operational condition of the battery includes integrating a difference between a defined desired nominal charge and current flows into and out of the battery over a period of time.

47. The method of claims 44 or 45 wherein determining an amount of deviation of the determined operational condition of the battery from a desired operational condition of the battery includes integrating a difference between a defined desired nominal charge and current flows into and out of the battery over a period of time, where the desired nominal charge is between approximately 75 percent and approximately 85 percent of a full charge for the battery.

48. The method of claim 44 wherein determining an operational condition of the battery includes determining a voltage across the battery.

49. The method of claims 44 or 45 wherein determining an amount of deviation of the determined operational condition of the battery from a desired battery operational condition includes comparing a determined battery charge to a defined desired nominal battery charge.

50. A power supply system, comprising:

a power bus;

a first fuel cell system;

a second fuel cell system;

a first switch selectively operable to electrically couple the first fuel cell system in series in the power bus; and

a second switch selectively operable to electrically couple the second fuel cell system in series in the power bus.

51. The power supply system of claim 50 wherein the first fuel cell system comprises a first fuel cell stack and a first electrical storage device

electrically coupled in parallel with the first fuel cell stack, and wherein the second fuel cell system comprises a second fuel cell stack, a second electrical storage device electrically coupled in parallel with the second fuel cell stack.

52. The power supply system of claim 50 wherein the first fuel cell system and the second fuel cell system are according to claims 1, 14, 28, or 39.

53. The power supply system of claims 50 or 52 wherein the first switch is one of a contactor and a transistor.

54. The power supply system of claims 50 or 52, further comprising:

a third fuel cell system; and

a third switch selectively operable to electrically couple the third fuel cell system in series in the power bus.

55. The power supply system of claims 50 or 52, further comprising:

a third fuel cell system; and

a third switch selectively operable to electrically couple the third fuel cell system in the power bus in parallel with at least one of the first and the second fuel cell systems.

56. The power supply system of claims 50 or 52 wherein the first switch is selectively operable according to an operating condition of the first fuel cell system, and further comprising:

a first redundancy switch electrically coupled in series with the first switch and selectively operable therewith to electrically couple the first fuel cell system in series to the power bus, the first redundancy switch being selectively operable according to an operating condition of at least the second fuel cell system.

57. The power supply system of claims 50 or 52 wherein the first switch is selectively operable according to an operating condition of the first fuel cell system, and further comprising:

a first redundancy switch electrically coupled in series with the first switch and selectively operable therewith to electrically couple the first fuel cell system in series to the power bus, the first redundancy switch being selectively operable according to a voltage supplied by at least the second fuel cell system.

58. The power supply system of claims 50 or 52 wherein the first switch is selectively operable according to an operating condition of the first fuel cell system, and further comprising:

a first redundancy switch electrically coupled in series with the first switch and selectively operable therewith to electrically couple the first fuel cell system in series to the power bus, the first redundancy switch being selectively operable according to a voltage across the power bus.

59. The power supply system of claims 50 or 52 wherein the first switch is selectively operable according to an operating condition of the first fuel cell system, and further comprising:

a first redundancy switch electrically coupled in series with the first switch and selectively operable therewith to electrically couple the first fuel cell system in series to the power bus, the first redundancy switch being selectively operable according to a desired output of the power supply system.

60. The power supply system of claims 50 or 52 wherein the first switch is selectively operable according to an operating condition of the first fuel cell system, and further comprising:

a first redundancy switch electrically coupled in series with the first switch and selectively operable therewith to electrically couple the first fuel cell system in series to the power bus, the first redundancy switch being selectively operable according to at least one of a desired nominal power output of the power supply system, a desired nominal voltage output of the power supply system, and a desired nominal current output of the power supply system.

61. A power supply system, comprising:

a power bus;

a plurality of fuel cell systems electrically couplable in series to the power bus, each of the fuel cell systems having a fuel cell stack and an electrical storage device electrically coupled in parallel with the fuel cell stack;

a plurality of switches selectively operable to electrically decouple a respective one of the fuel cell systems from the power bus, each of the switches responsive to an operating condition of the respective one of the fuel cell systems; and

at least a first redundancy switch selectively operable to electrically couple a respective first one of the plurality of fuel cell systems to the power bus, the first redundancy switch responsive to an operating condition different from the operating condition of the respective first one of the plurality of fuel cells.

62. The power supply system of claim 60, further comprising:

an additional number of redundancy switches, each of the additional number of redundancy switches selectively operable to electrically couple a respective one of the fuel cell systems to the power bus in response to an operating condition different from the operating condition of the respective one of the fuel cells.

63. The power supply system of claim 60 wherein the operating condition that the first redundancy switch is responsive to is an operating condition of at least one of the fuel cell systems other than the respective first fuel cell system that the first redundancy switch is selectively operable to electrically couple to the power bus.

64. The power supply system of claim 60 wherein the operating condition that the first redundancy switch is responsive to is a voltage across an output of at least one of the fuel cell systems other than the respective first fuel cell system that the first redundancy switch is selectively operable to electrically couple to the power bus.

65. The power supply system of claim 60 wherein each of the fuel cell systems further comprise a number of sensors for determining a set of operating parameters of the respective fuel cell system and a processor configured to determine an operating condition of the respective fuel cell system based on the determined set of operating parameters, and wherein the operating condition that the first redundancy switch is responsive to is the operating condition determined by at least one of the processors.

66. The power supply system of claim 60 wherein the operating condition that the first redundancy switch is responsive to is at least one of a power output of the power bus, a voltage across the power bus, a current output of the power bus, a desired nominal power output of the power supply system, a desired nominal voltage output of the power supply system, and a desired nominal current output of the power supply system.

67. The power supply system of claim 60, further comprising:

a controller communicatingly coupled to receive a set of operating parameters from each of the plurality of fuel cell systems, the controller configured to determine an operating condition of the fuel cell systems based on the received sets of operating parameters, and wherein the operating condition that the first redundancy switch is responsive to is the operating condition determined by the controller.

68. A power supply system, comprising:

at least two fuel cell systems; and

means for selectively electrically coupling the at least two fuel cell systems in series.

69. The power supply system of claim 68 wherein the means for selectively electrically coupling the at least two fuel cell systems in series comprises a respective switch for each of the fuel cell systems, each of the switches responsive to an operating condition of at least one of the other fuel cell systems.

70. A method of operating a power supply system having at least a first and a second fuel cell system, the method comprising:

electrically coupling a first fuel cell system in series to a power bus at a first time;

determining an existence of a fault condition;

in response to the fault condition, at a second time automatically electrically coupling a second fuel cell system to the power bus in series; and

automatically electrically decoupling the first fuel cell system from the power bus.

71. The method of claim 70 wherein determining an existence of a fault condition includes monitoring at least one of an output power, output voltage, output current, a battery current, a battery voltage, a stack current, an ambient hydrogen level, an ambient oxygen level, and a reactant flow in the first fuel cell system.

72. A method of operating a power supply system including a plurality of fuel cell systems, a first number of the fuel cell systems electrically coupled in series to a power bus and a second number of the fuel cell systems electrically couplable in series to the power bus, comprising:

determining an existence of a fault condition in at least one of the first number of fuel cell systems; and

automatically electrically coupling at least one of the second number of fuel cell systems to the power bus in series at a second time in response to the determination of the existence of the fault condition to maintain an electrical output on the power bus of the power supply system.

73. The method of claim 72, further comprising:

replacing the at least one of the fuel cell systems having the fault condition with a replacement fuel cell system; and

electrically coupling the replacement fuel cell system in series to the power bus in response to the additional fault condition to maintain an electrical output on the power bus of the power supply system

74. The method of claims 72 or 73 wherein automatically electrically coupling at least one of the second number of fuel cell systems to the power bus in series at a second time in response to the determination of the existence of the fault condition to maintain an electrical output on the power bus of the power supply system includes activating a first transistor electrically coupled between the fuel cell and the power bus in proportion to a decrease associated with the fault condition in at least one of an output power, an output current, and an output voltage of the at least one of the first number of fuel cell systems.

75. A method of operating a power supply system having a plurality of fuel cell systems, at least a number of the fuel cell systems selectively couplable in series on a power bus, the method comprising:

determining at least one of a desired power, a desired current and a desired voltage for the power supply system based on a load;

automatically determining an electrical configuration for a number of the fuel cell systems that provide the at least one of the determined desired power, the determined desired current and the determined desired voltage when electrically coupled in at least one of a number of series combinations and parallel combinations to the power bus; and

automatically operating a number of switches to electrically couple the number of the fuel cell systems to the power bus in the determined electrical configuration.

76. The method of claim 75 wherein automatically operating a number of switches to electrically couple the number of the fuel cell systems to the power bus in the determined electrically configuration includes closing at least one of the switches to electrically couple at least two of the fuel cell systems in series.

77. The method of claim 75 wherein automatically operating a number of switches to electrically couple the number of the fuel cell systems to the power bus in the determined electrically configuration includes closing at least one of the switches to electrically couple at least two of the fuel cell systems in parallel.

78. The method of claim 75 wherein automatically operating a number of switches to electrically couple the number of the fuel cell systems to the power bus in the determined electrically configuration includes closing at least a first one of the switches to electrically couple at least two of the fuel cell systems in series and closing at least a second one of the switches to electrically couple at least one of the fuel cell systems in parallel with the at least two of the fuel cells electrically coupled in series.

79. The method of claim 75 wherein automatically operating a number of switches to electrically couple the number of the fuel cell systems to the power bus in the determined electrically configuration includes closing at least a first one of the switches to electrically couple at least two of the fuel cell systems in

parallel and closing at least a second one of the switches to electrically couple at least one fuel cell in series with the two of the fuel cell systems coupled in parallel.

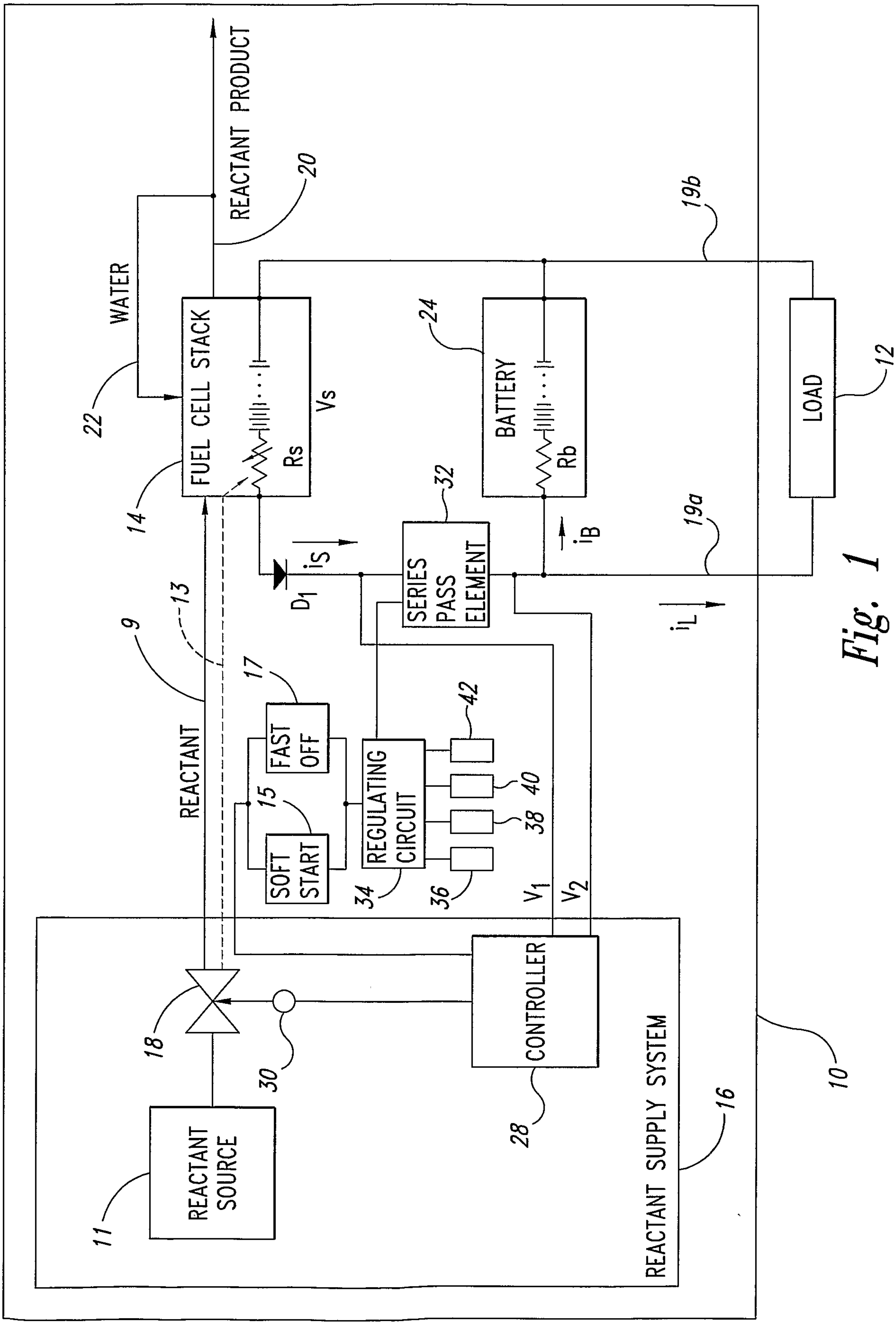

REACTANT PRODUCT
20
WATER
22
FUEL CELL STACK
14
Vs
Rs
24
BATTERY
Rb
19b
LOAD
12
32
SERIES PASS ELEMENT
i_S
i_B
i_L
D_1
19a
13
9
17
FAST OFF
42
40
38
REGULATING CIRCUIT
15
SOFT START
34
36
V_1
V_2
REACTANT
CONTROLLER
18
30
28
REACTANT SOURCE
11
REACTANT SUPPLY SYSTEM
16
10

Fig. 1

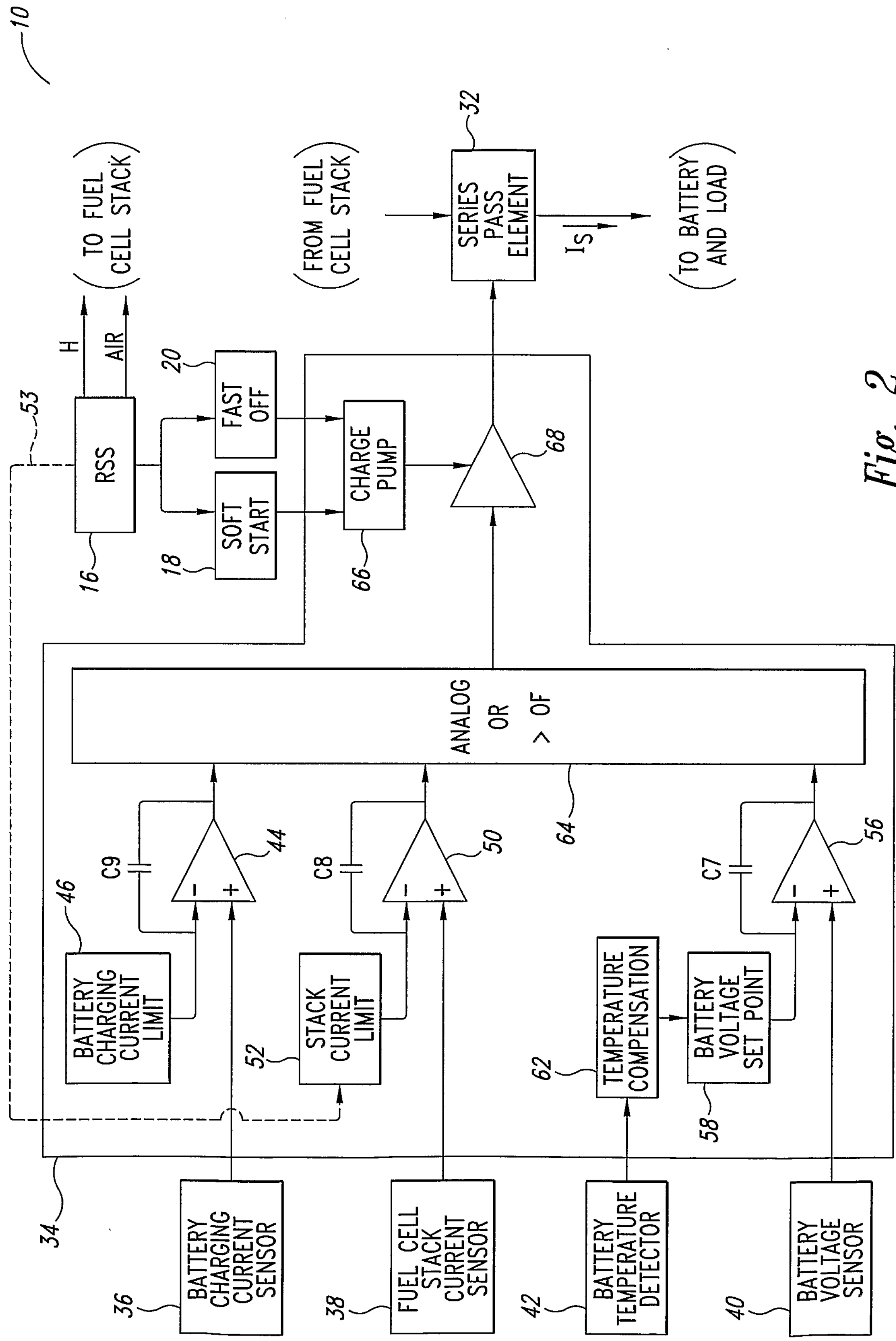

10
TO FUEL CELL STACK
H
AIR
53
RSS
16
SOFT START
18
FAST OFF
20
CHARGE PUMP
66
68
FROM FUEL CELL STACK
SERIES PASS ELEMENT
32
I_S
TO BATTERY AND LOAD
ANALOG OR > OF
64
C9
44
46
BATTERY CHARGING CURRENT LIMIT
C8
50
STACK CURRENT LIMIT
52
C7
56
TEMPERATURE COMPENSATION
62
BATTERY VOLTAGE SET POINT
58
34
BATTERY CHARGING CURRENT SENSOR
36
FUEL CELL STACK CURRENT SENSOR
38
BATTERY TEMPERATURE DETECTOR
42
BATTERY VOLTAGE SENSOR
40

Fig. 2

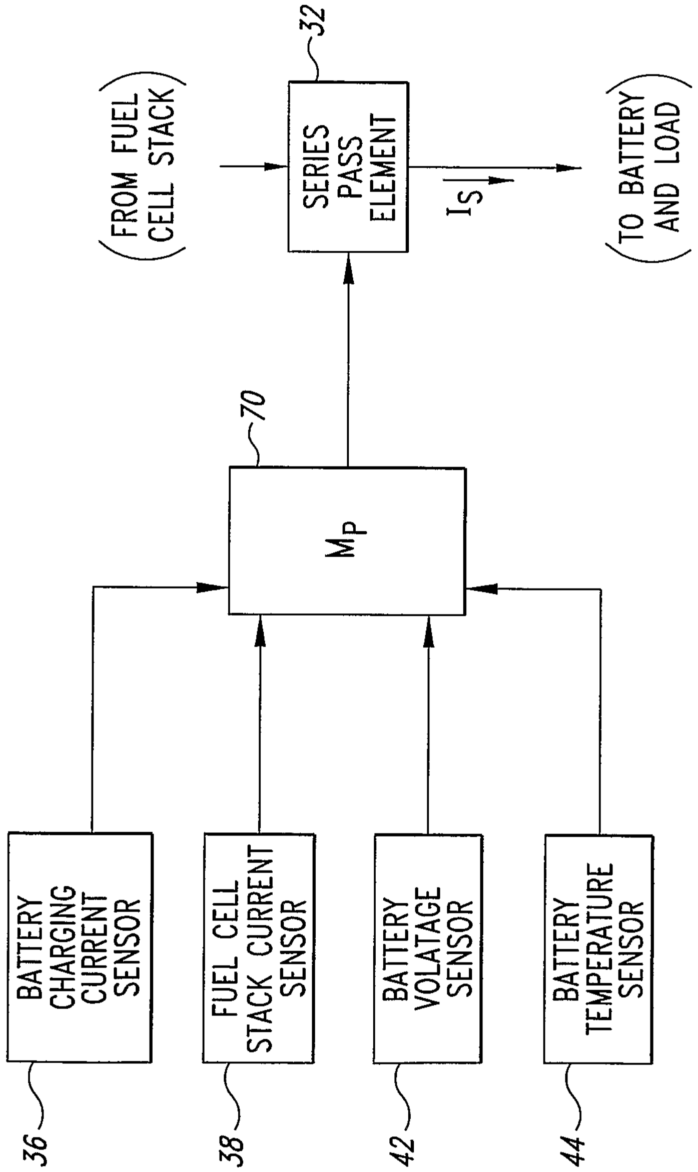

(FROM FUEL CELL STACK)
32
SERIES PASS ELEMENT
I_S
(TO BATTERY AND LOAD)
70
M_P
BATTERY CHARGING CURRENT SENSOR
FUEL CELL STACK CURRENT SENSOR
BATTERY VOLATAGE SENSOR
BATTERY TEMPERATURE SENSOR
36
38
42
44

Fig. 3

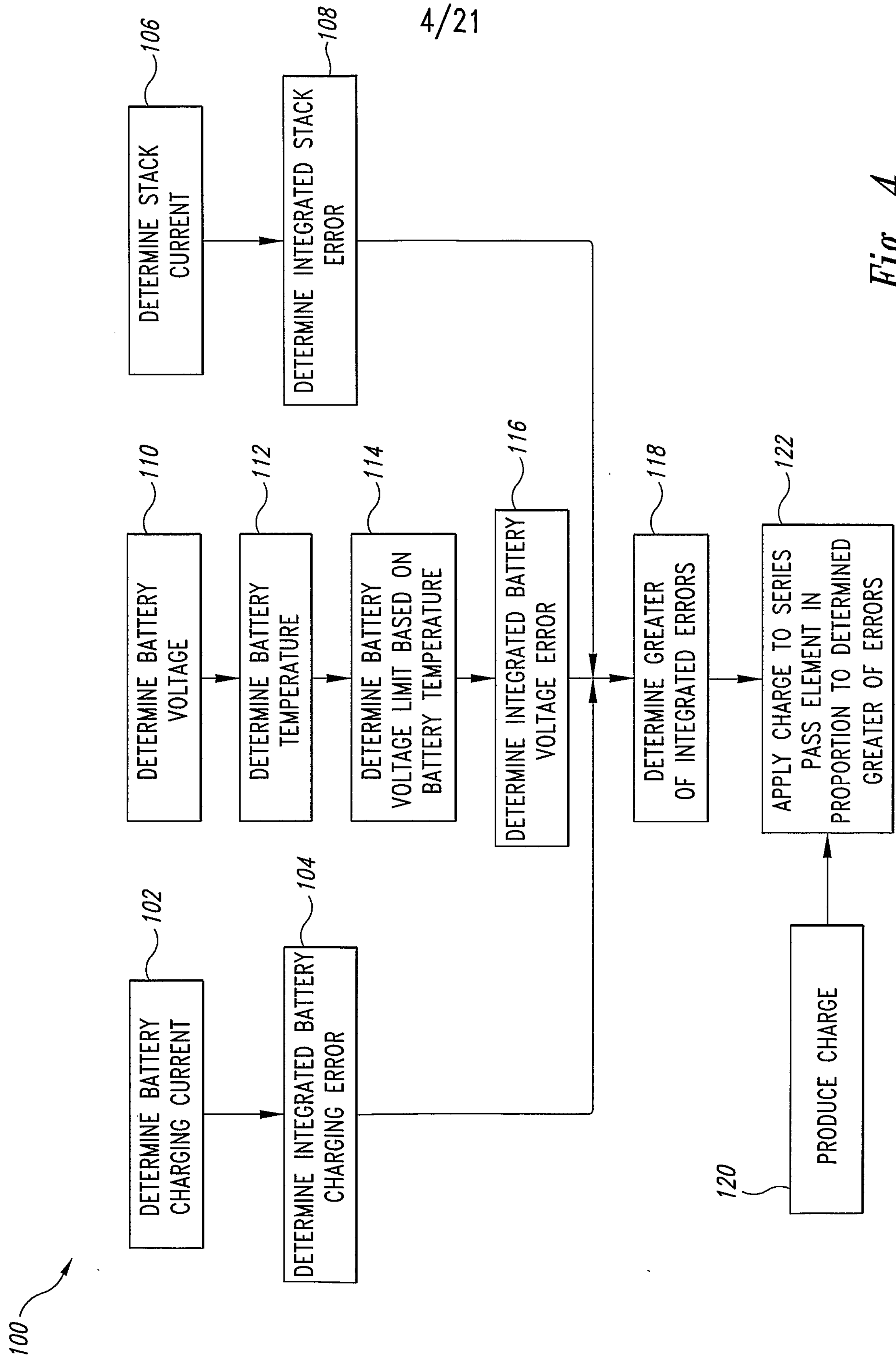

100
DETERMINE BATTERY CHARGING CURRENT
102
DETERMINE INTEGRATED BATTERY CHARGING ERROR
104
DETERMINE STACK CURRENT
106
DETERMINE INTEGRATED STACK ERROR
108
DETERMINE BATTERY VOLTAGE
110
DETERMINE BATTERY TEMPERATURE
112
DETERMINE BATTERY VOLTAGE LIMIT BASED ON BATTERY TEMPERATURE
114
DETERMINE INTEGRATED BATTERY VOLTAGE ERROR
116
DETERMINE GREATER OF INTEGRATED ERRORS
118
PRODUCE CHARGE
120
APPLY CHARGE TO SERIES PASS ELEMENT IN PROPORTION TO DETERMINED GREATER OF ERRORS
122

Fig. 4

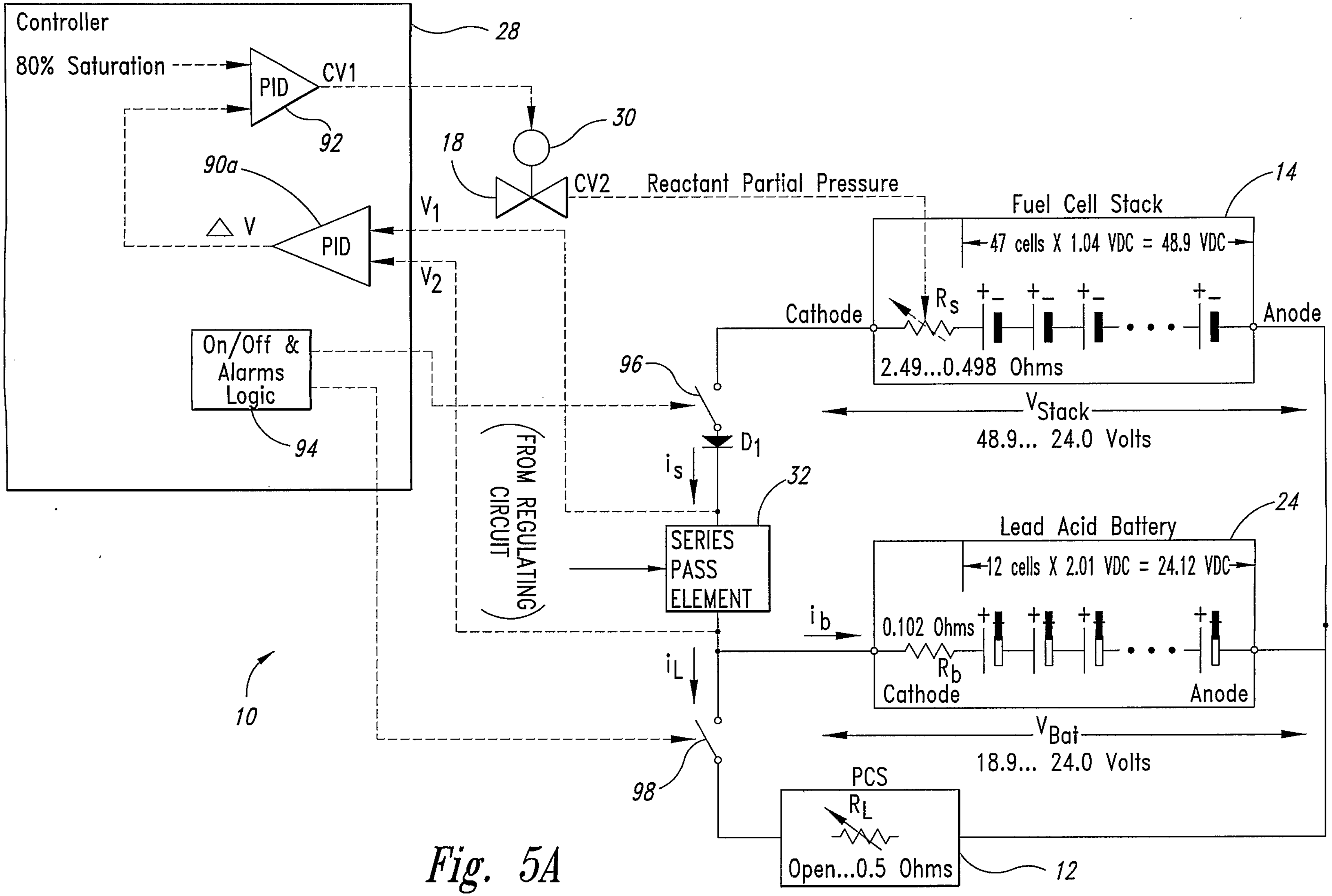

Controller
80% Saturation
PID
CV1
92
28
30
18
CV2
Reactant Partial Pressure
90a
△ V
PID
V1
V2
On/Off & Alarms Logic
94
14
Fuel Cell Stack
47 cells X 1.04 VDC = 48.9 VDC
Cathode
Rs
Anode
2.49...0.498 Ohms
96
VStack
48.9... 24.0 Volts
D1
is
32
(FROM REGULATING CIRCUIT)
SERIES PASS ELEMENT
24
Lead Acid Battery
12 cells X 2.01 VDC = 24.12 VDC
ib
0.102 Ohms
Rb
Cathode
Anode
iL
10
VBat
18.9... 24.0 Volts
98
PCS
RL
Open...0.5 Ohms
12

Fig. 5A

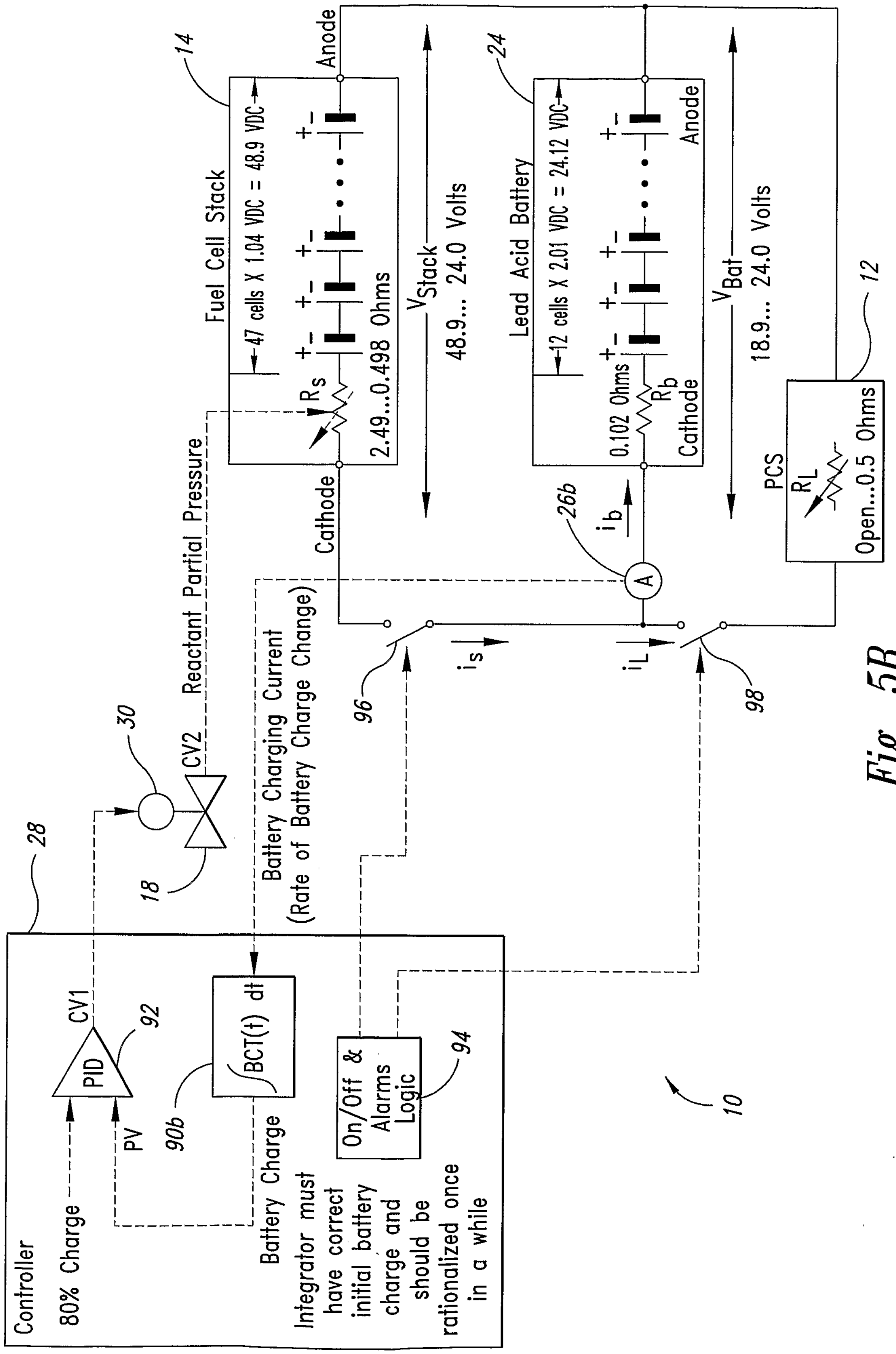
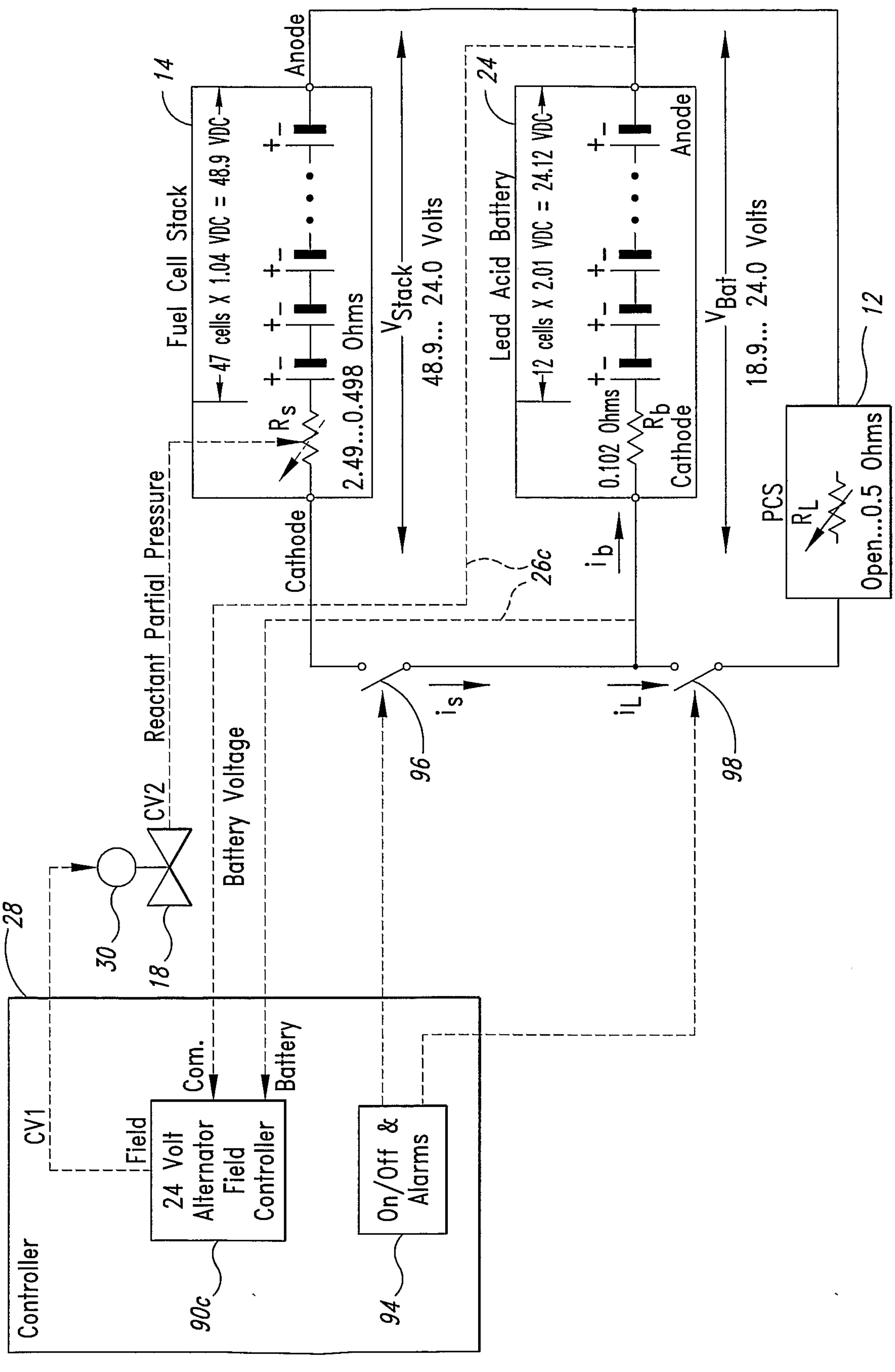

14
Fuel Cell Stack
47 cells X 1.04 VDC = 48.9 VDC
Anode
Cathode
Rs
2.49...0.498 Ohms
VStack
48.9... 24.0 Volts
24
Lead Acid Battery
12 cells X 2.01 VDC = 24.12 VDC
Anode
Cathode
Rb
0.102 Ohms
VBat
18.9... 24.0 Volts
12
PCS
RL
Open...0.5 Ohms
26b
ib
A
is
iL
96
98
Reactant Partial Pressure
Battery Charging Current
(Rate of Battery Charge Change)
30
CV2
18
28
Controller
80% Charge
PID
92
CV1
PV
∫BCT(t) dt
90b
Battery Charge
On/Off &
Alarms
Logic
94
Integrator must
have correct
initial battery
charge and
should be
rationalized once
in a while
10

Fig. 5B



Fuel Cell Stack
14
47 cells X 1.04 VDC = 48.9 VDC
Anode
Cathode
Rs
2.49...0.498 Ohms
VStack
48.9... 24.0 Volts
Lead Acid Battery
24
12 cells X 2.01 VDC = 24.12 VDC
Anode
Cathode
Rb
0.102 Ohms
VBat
18.9... 24.0 Volts
ib
26c
PCS
RL
Open...0.5 Ohms
Single Phase AC Conversion
12
is
iL
96
98
Reactant Partial Pressure
Battery Voltage
CV2
30
18
28
Controller
CV1
Field
Com.
Battery
24 Volt Alternator Field Controller
90c
On/Off & Alarms
94

Fig. 5C

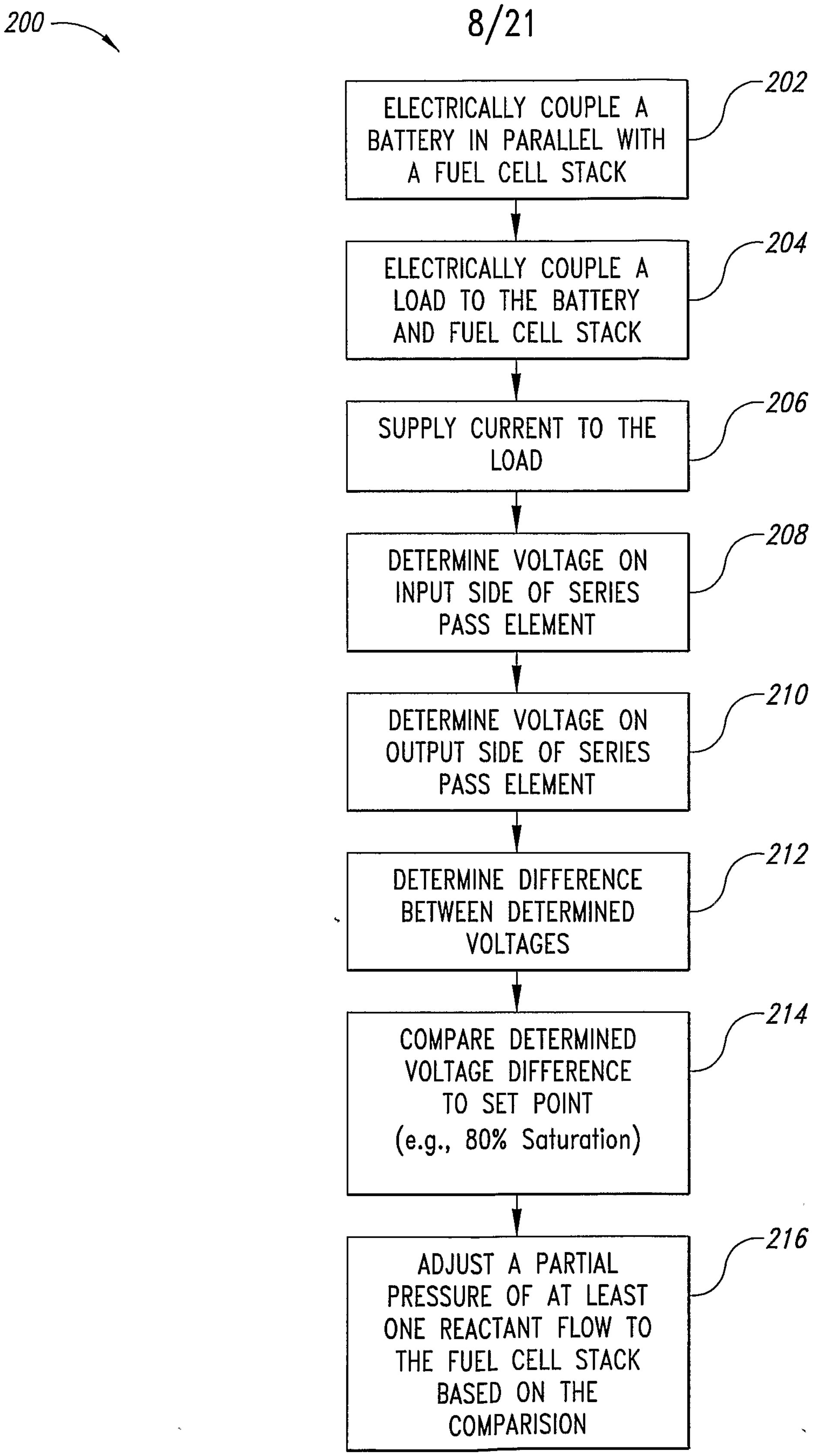

200
ELECTRICALLY COUPLE A BATTERY IN PARALLEL WITH A FUEL CELL STACK
202
ELECTRICALLY COUPLE A LOAD TO THE BATTERY AND FUEL CELL STACK
204
SUPPLY CURRENT TO THE LOAD
206
DETERMINE VOLTAGE ON INPUT SIDE OF SERIES PASS ELEMENT
208
DETERMINE VOLTAGE ON OUTPUT SIDE OF SERIES PASS ELEMENT
210
DETERMINE DIFFERENCE BETWEEN DETERMINED VOLTAGES
212
COMPARE DETERMINED VOLTAGE DIFFERENCE TO SET POINT (e.g., 80% Saturation)
214
ADJUST A PARTIAL PRESSURE OF AT LEAST ONE REACTANT FLOW TO THE FUEL CELL STACK BASED ON THE COMPARISION
216

Fig. 6A

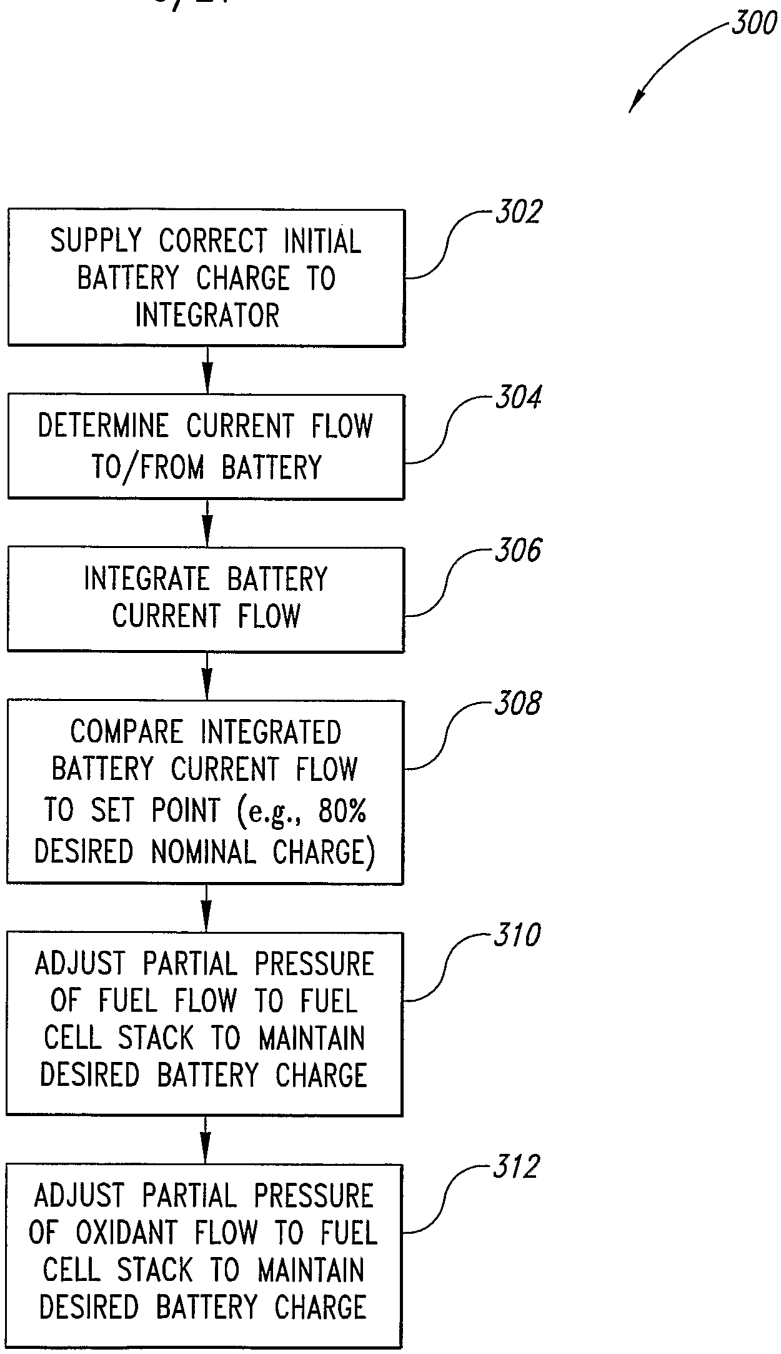

300
SUPPLY CORRECT INITIAL BATTERY CHARGE TO INTEGRATOR
302
DETERMINE CURRENT FLOW TO/FROM BATTERY
304
INTEGRATE BATTERY CURRENT FLOW
306
COMPARE INTEGRATED BATTERY CURRENT FLOW TO SET POINT (e.g., 80% DESIRED NOMINAL CHARGE)
308
ADJUST PARTIAL PRESSURE OF FUEL FLOW TO FUEL CELL STACK TO MAINTAIN DESIRED BATTERY CHARGE
310
ADJUST PARTIAL PRESSURE OF OXIDANT FLOW TO FUEL CELL STACK TO MAINTAIN DESIRED BATTERY CHARGE
312

Fig. 6B

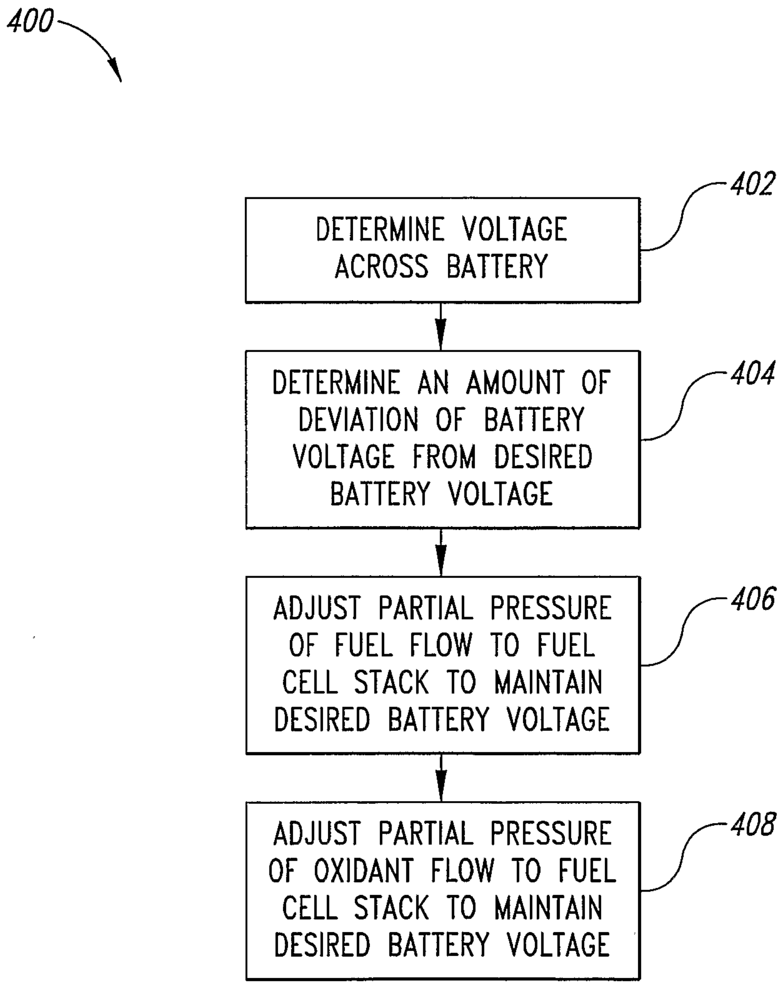

400
DETERMINE VOLTAGE ACROSS BATTERY
402
DETERMINE AN AMOUNT OF DEVIATION OF BATTERY VOLTAGE FROM DESIRED BATTERY VOLTAGE
404
ADJUST PARTIAL PRESSURE OF FUEL FLOW TO FUEL CELL STACK TO MAINTAIN DESIRED BATTERY VOLTAGE
406
ADJUST PARTIAL PRESSURE OF OXIDANT FLOW TO FUEL CELL STACK TO MAINTAIN DESIRED BATTERY VOLTAGE
408

Fig. 6C

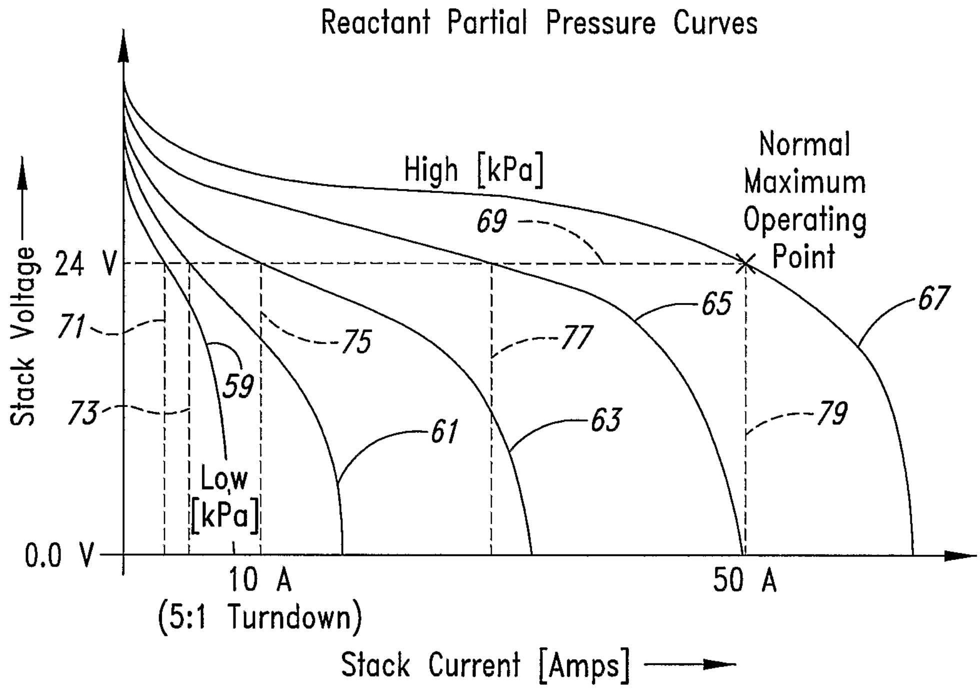

Reactant Partial Pressure Curves
High [kPa]
Normal
Maximum
Operating
Point
69
24 V
65
67
71
75
77
59
73
79
61
63
Low
[kPa]
0.0 V
10 A
(5:1 Turndown)
50 A
Stack Voltage
Stack Current [Amps]

Fig. 7

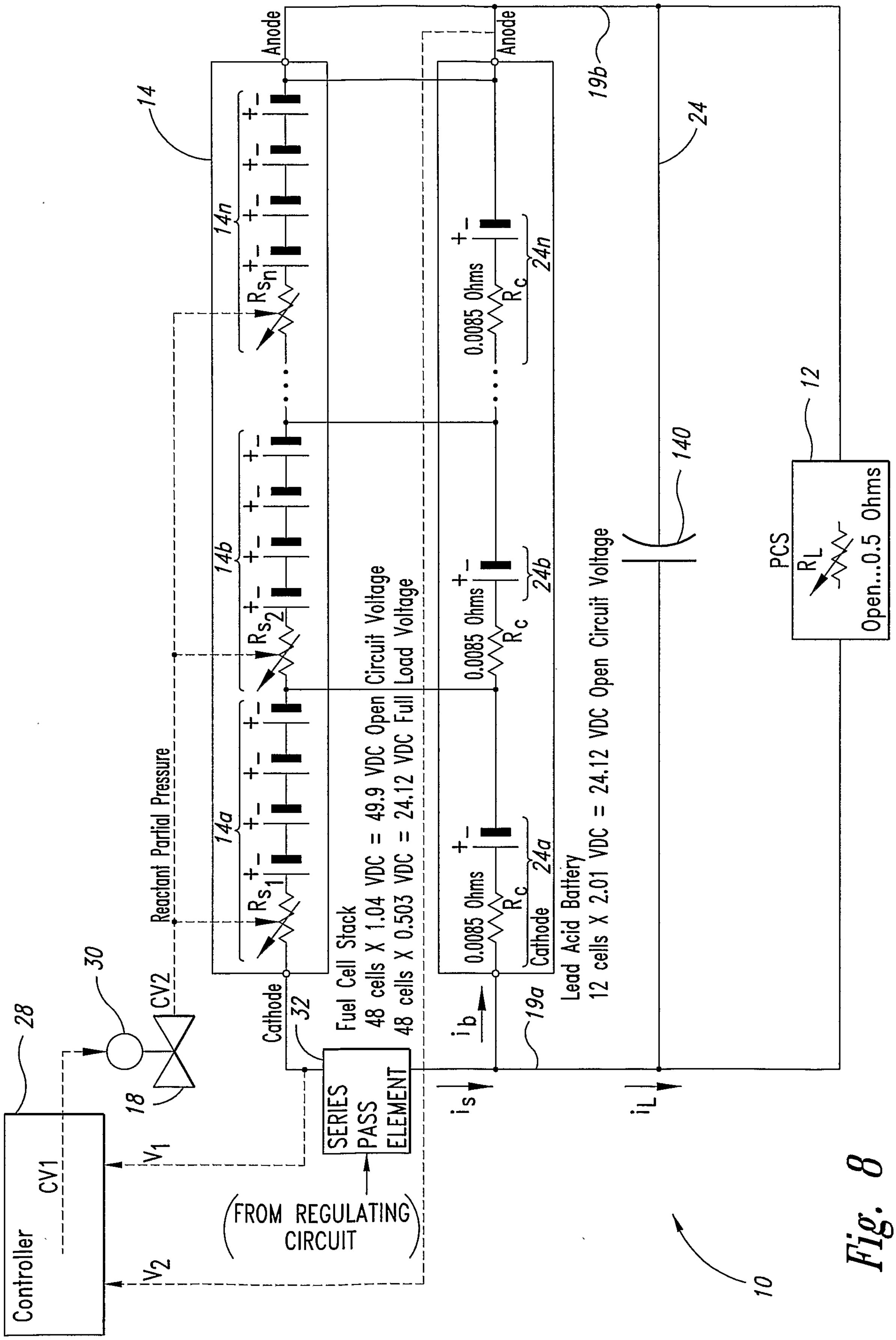

Controller
CV1
28
30
CV2
18
V1
V2
Reactant Partial Pressure
Cathode
Anode
32
SERIES PASS ELEMENT
(FROM REGULATING CIRCUIT)
14
14a
14b
14n
Rs1
Rs2
Rsn
Fuel Cell Stack
48 cells X 1.04 VDC = 49.9 VDC Open Circuit Voltage
48 cells X 0.503 VDC = 24.12 VDC Full Load Voltage
0.0085 Ohms
Rc
24a
24b
24n
Cathode
Anode
ib
is
iL
19a
19b
Lead Acid Battery
12 cells X 2.01 VDC = 24.12 VDC Open Circuit Voltage
24
140
12
PCS
RL
Open...0.5 Ohms
10

Fig. 8

Fig. 9A

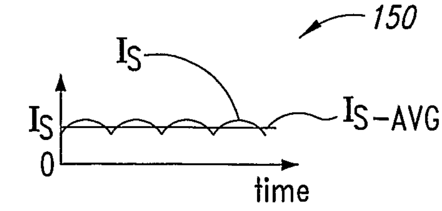


Fig. 9B

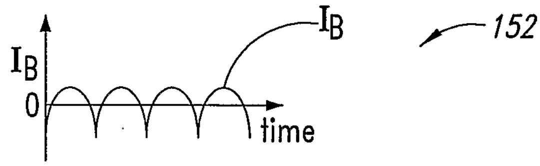


Fig. 9C

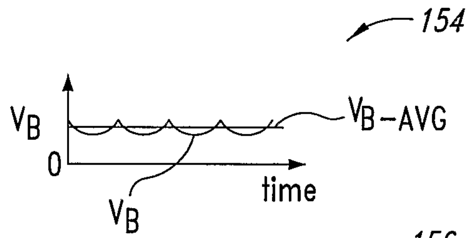


Fig. 9D

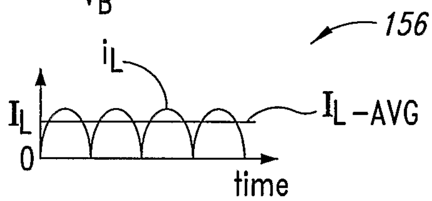


Fig. 9E

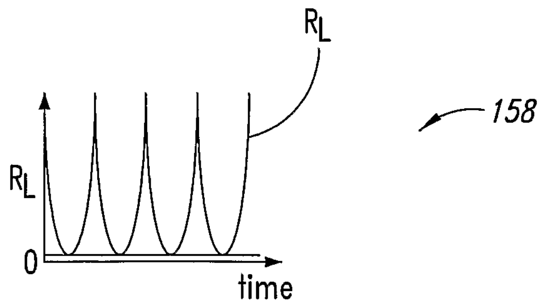
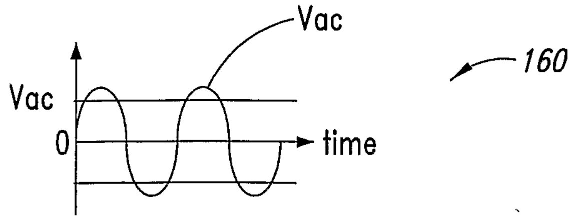


Fig. 9F



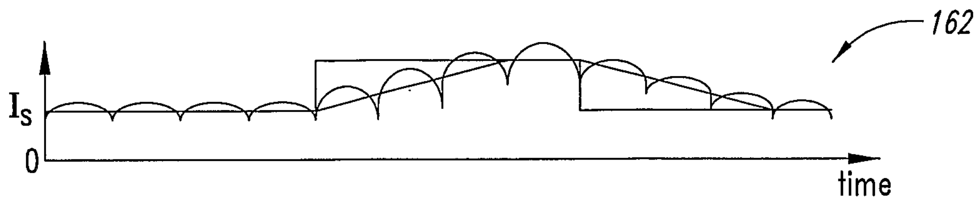


Fig. 10A

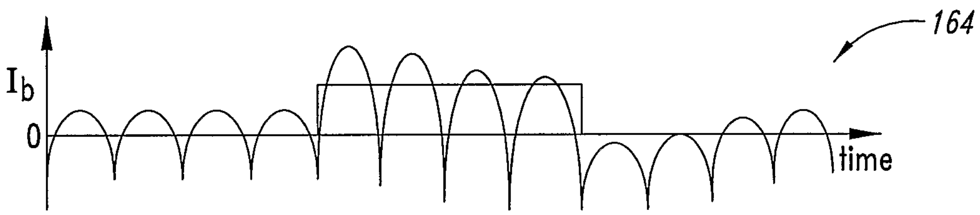


Fig. 10B

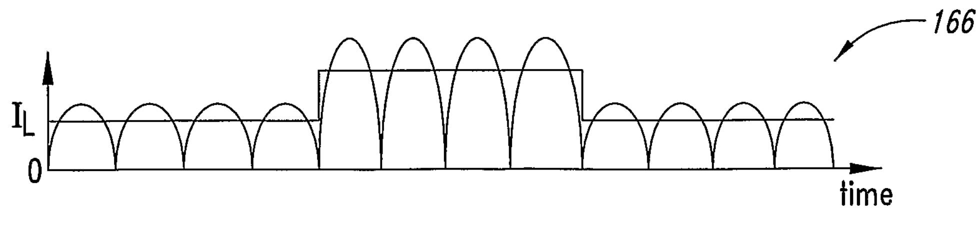


Fig. 10C

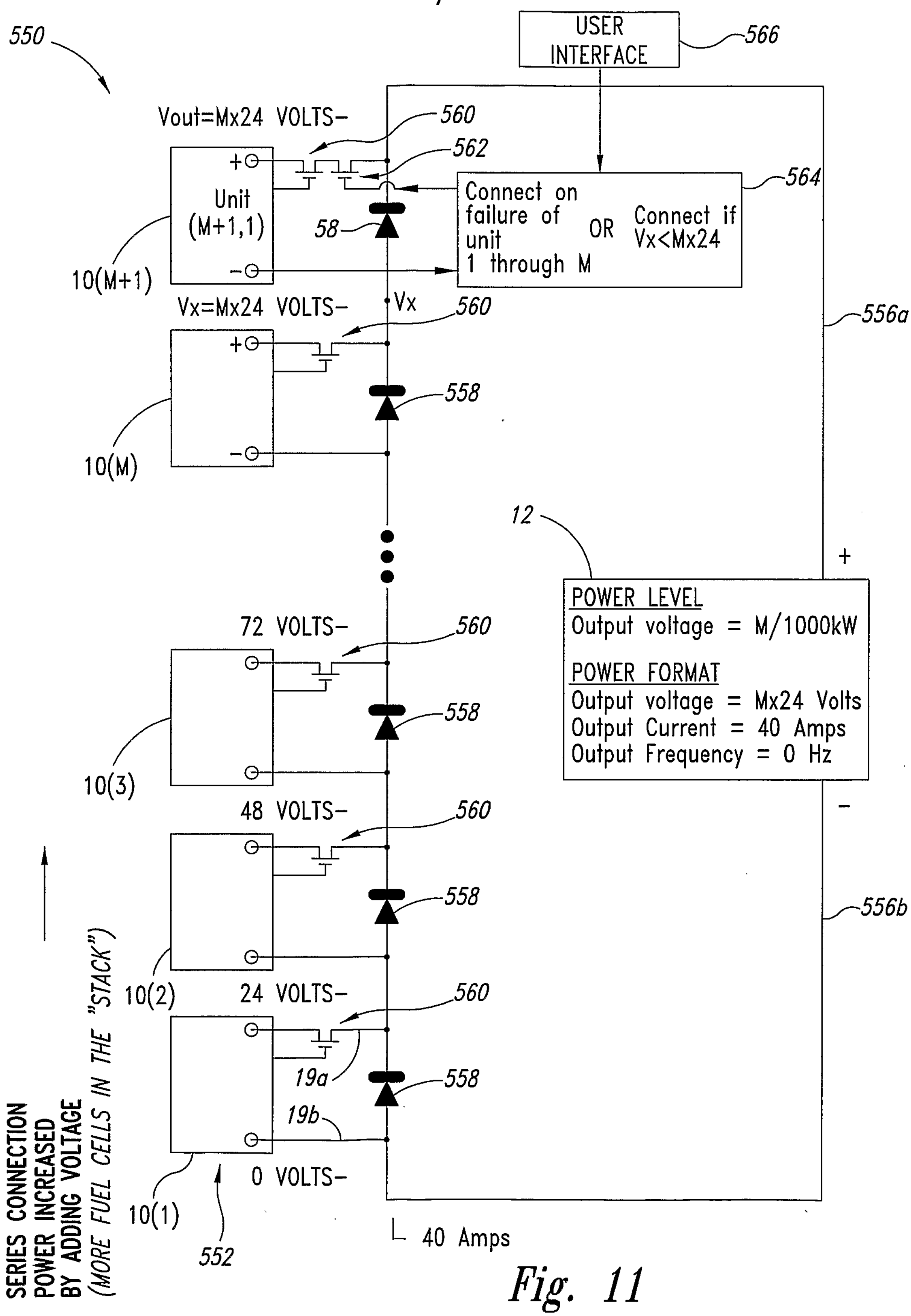

550
USER INTERFACE
566
Vout=Mx24 VOLTS
560
562
564
Unit (M+1,1)
58
Connect on failure of unit 1 through M
OR
Connect if Vx<Mx24
10(M+1)
Vx=Mx24 VOLTS
Vx
560
556a
558
10(M)
12
+
POWER LEVEL
Output voltage = M/1000kW
POWER FORMAT
Output voltage = Mx24 Volts
Output Current = 40 Amps
Output Frequency = 0 Hz
72 VOLTS
560
558
10(3)
48 VOLTS
560
-
558
556b
10(2)
24 VOLTS
560
19a
558
19b
0 VOLTS
10(1)
552
40 Amps
SERIES CONNECTION
POWER INCREASED
BY ADDING VOLTAGE
(MORE FUEL CELLS IN THE "STACK")

Fig. 11

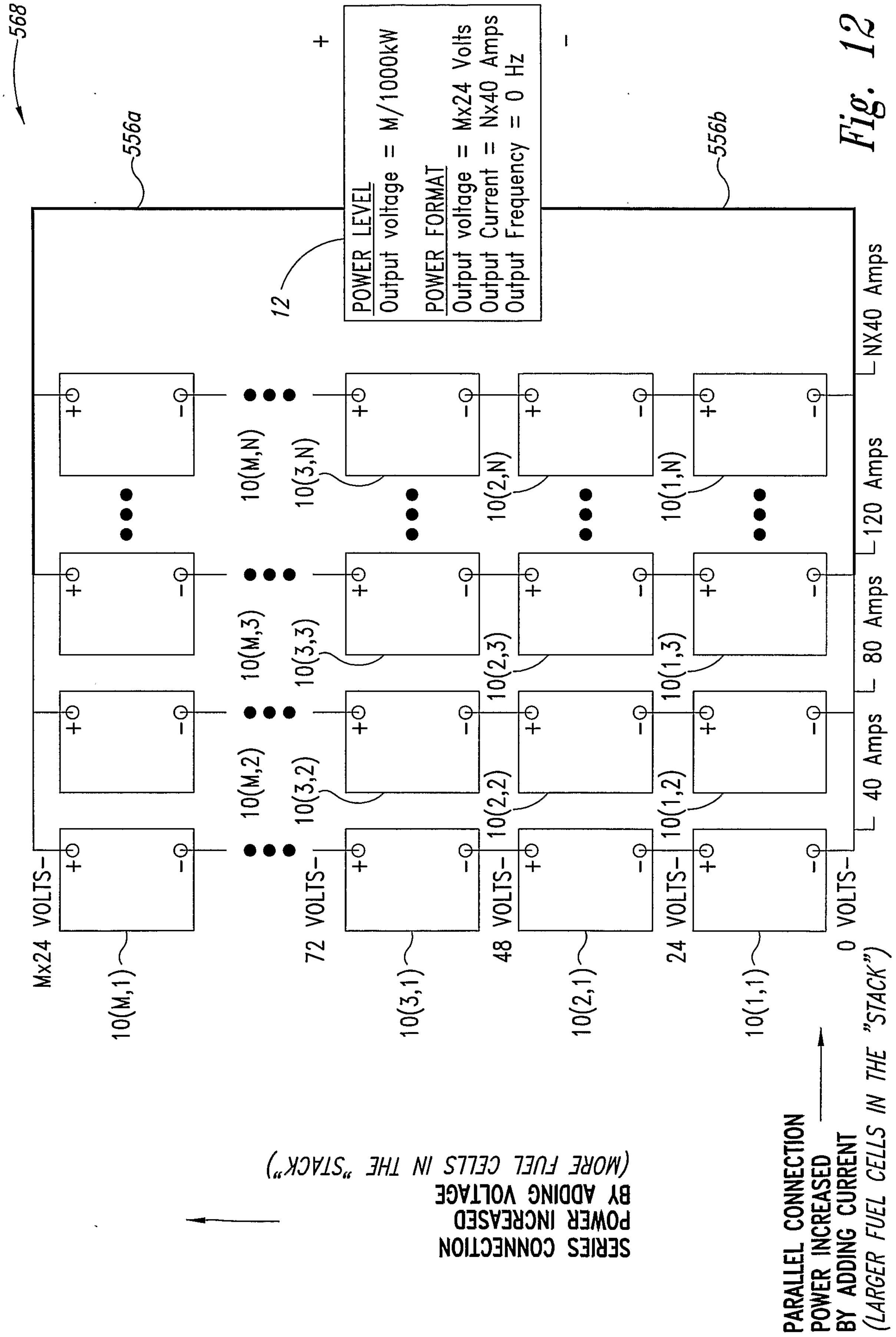

568
556a
556b
12
POWER LEVEL
Output voltage = M/1000kW
POWER FORMAT
Output voltage = Mx24 Volts
Output Current = Nx40 Amps
Output Frequency = 0 Hz
+
-
Mx24 VOLTS
72 VOLTS
48 VOLTS
24 VOLTS
0 VOLTS
40 Amps
80 Amps
120 Amps
NX40 Amps
10(M,1)
10(M,2)
10(M,3)
10(M,N)
10(3,1)
10(3,2)
10(3,3)
10(3,N)
10(2,1)
10(2,2)
10(2,3)
10(2,N)
10(1,1)
10(1,2)
10(1,3)
10(1,N)
PARALLEL CONNECTION
POWER INCREASED
BY ADDING CURRENT
(LARGER FUEL CELLS IN THE "STACK")
SERIES CONNECTION
POWER INCREASED
BY ADDING VOLTAGE
(MORE FUEL CELLS IN THE "STACK")

Fig. 12

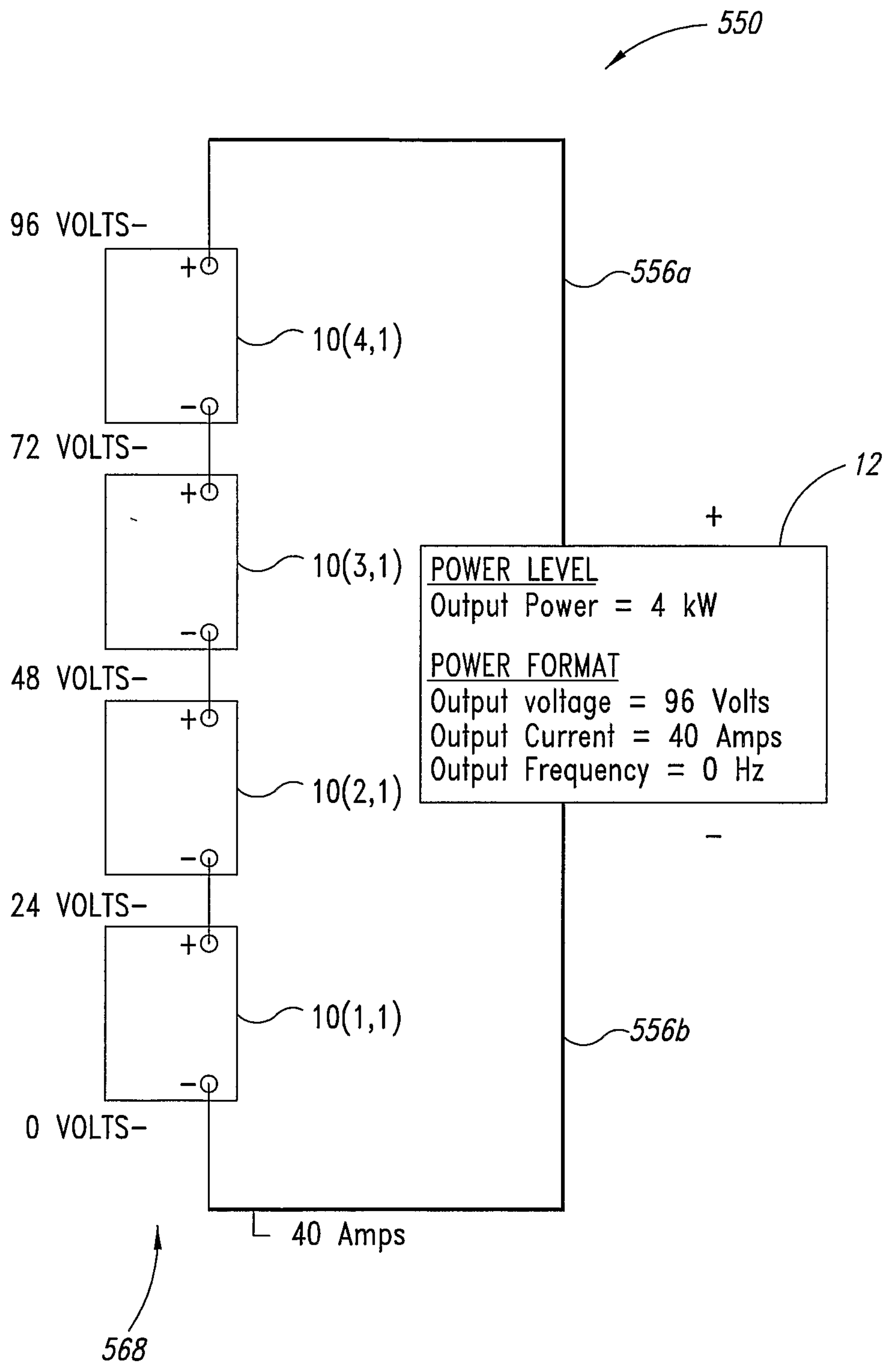

550
96 VOLTS-
72 VOLTS-
48 VOLTS-
24 VOLTS-
0 VOLTS-
10(4,1)
10(3,1)
10(2,1)
10(1,1)
556a
556b
12
POWER LEVEL
Output Power = 4 kW
POWER FORMAT
Output voltage = 96 Volts
Output Current = 40 Amps
Output Frequency = 0 Hz
40 Amps
568

Fig. 13

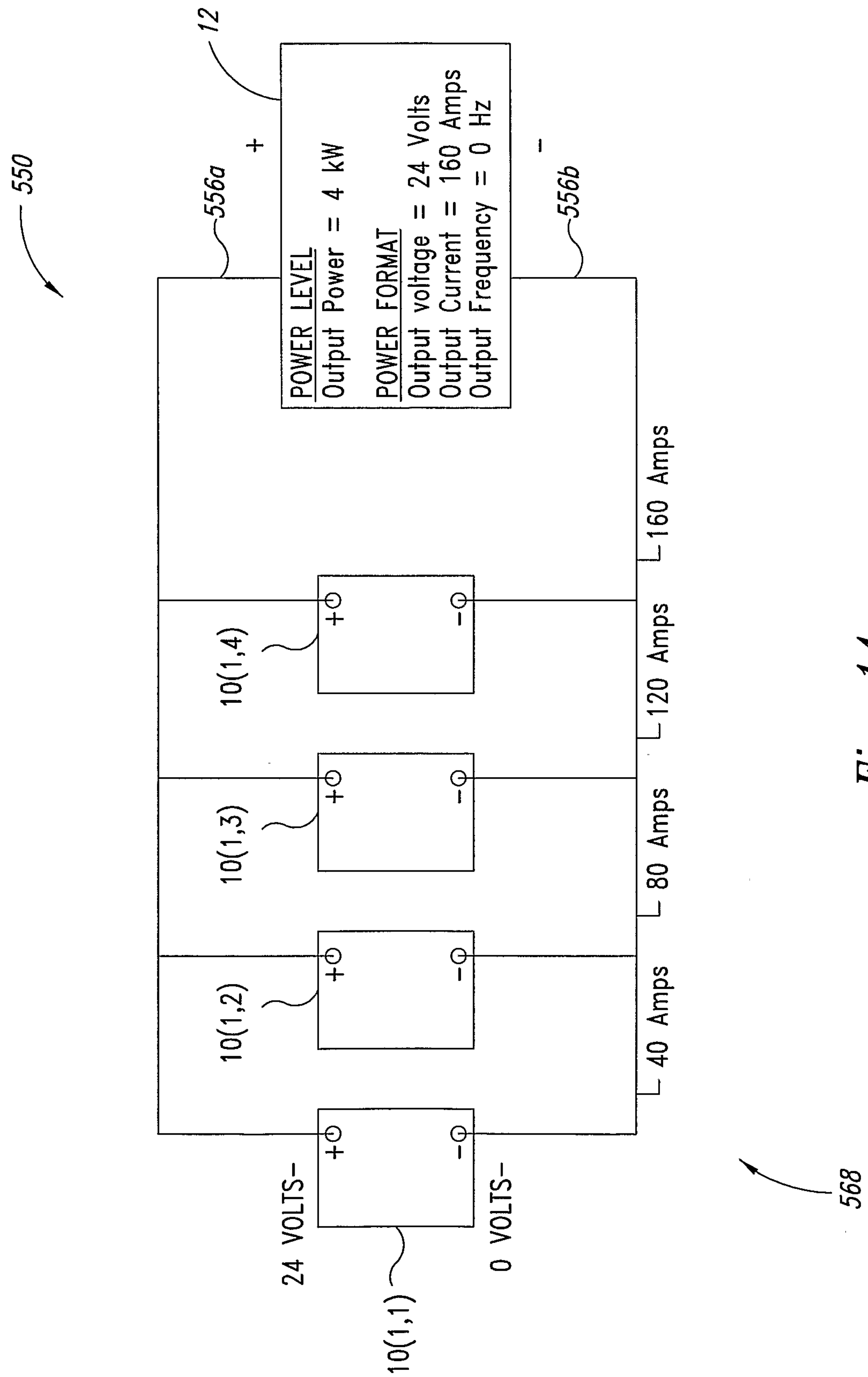

550
12
+
−
556a
556b
POWER LEVEL
Output Power = 4 kW
POWER FORMAT
Output voltage = 24 Volts
Output Current = 160 Amps
Output Frequency = 0 Hz
10(1,1)
10(1,2)
10(1,3)
10(1,4)
24 VOLTS
0 VOLTS
40 Amps
80 Amps
120 Amps
160 Amps
568

Fig. 14

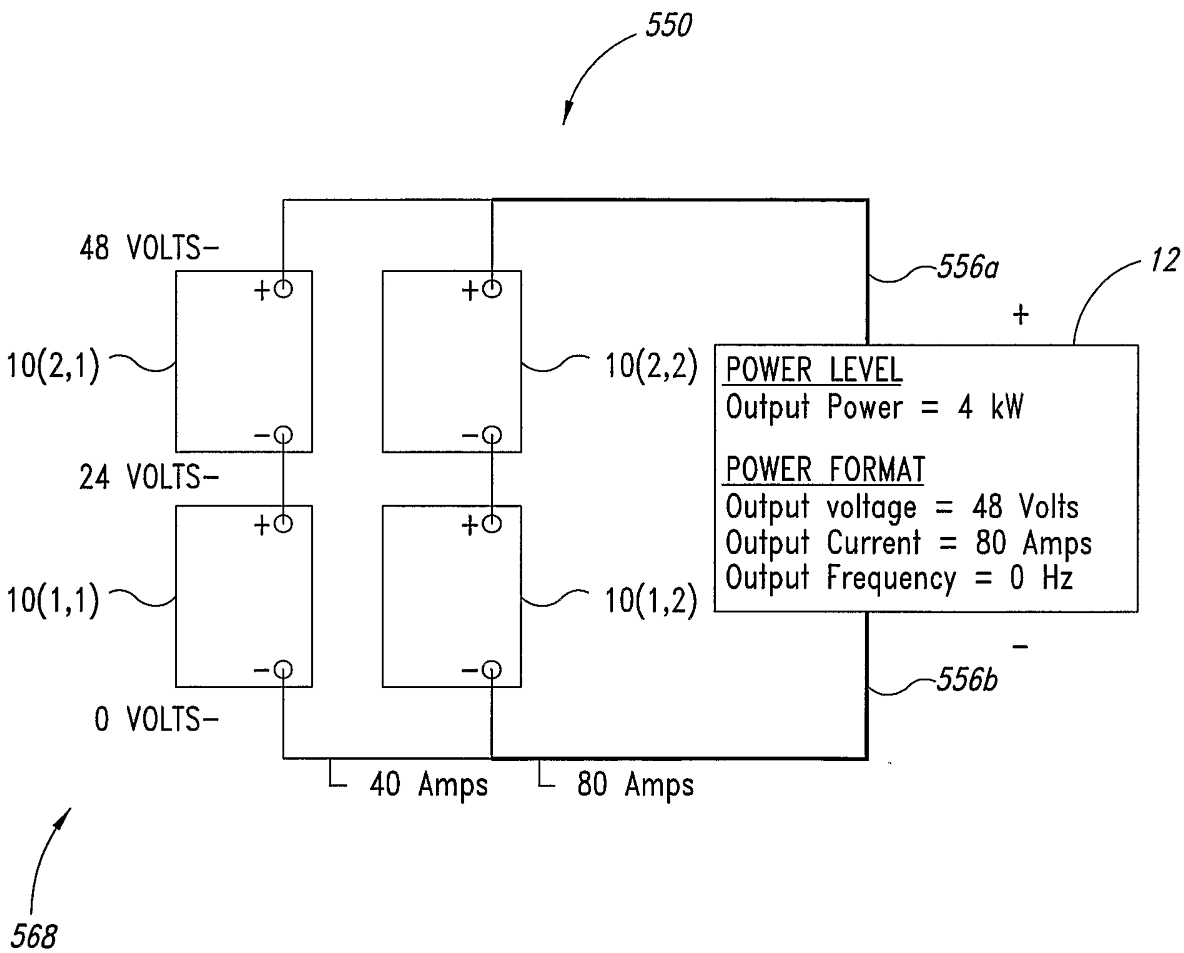

550
48 VOLTS
24 VOLTS
0 VOLTS
10(2,1)
10(1,1)
10(2,2)
10(1,2)
+
−
556a
556b
12
POWER LEVEL
Output Power = 4 kW
POWER FORMAT
Output voltage = 48 Volts
Output Current = 80 Amps
Output Frequency = 0 Hz
40 Amps
80 Amps
568

Fig. 15

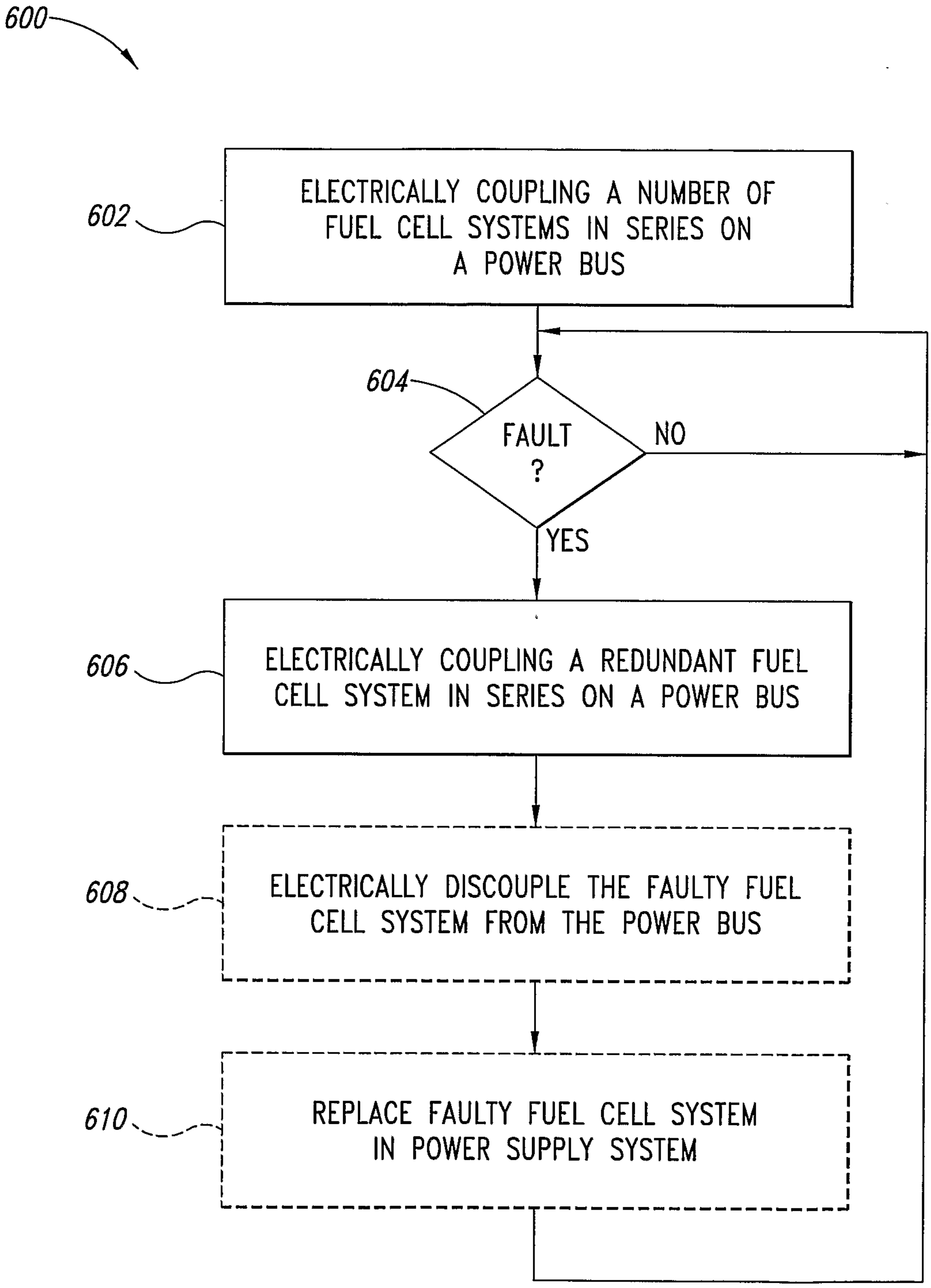

600
602
ELECTRICALLY COUPLING A NUMBER OF FUEL CELL SYSTEMS IN SERIES ON A POWER BUS
604
FAULT ?
NO
YES
606
ELECTRICALLY COUPLING A REDUNDANT FUEL CELL SYSTEM IN SERIES ON A POWER BUS
608
ELECTRICALLY DISCOUPLE THE FAULTY FUEL CELL SYSTEM FROM THE POWER BUS
610
REPLACE FAULTY FUEL CELL SYSTEM IN POWER SUPPLY SYSTEM

Fig. 16

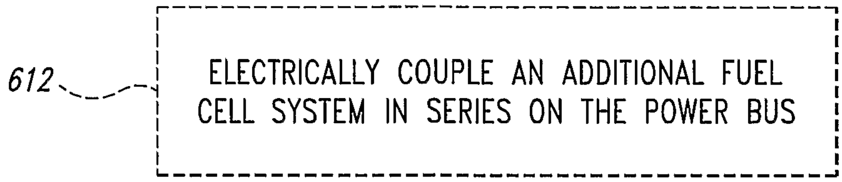


Fig. 17

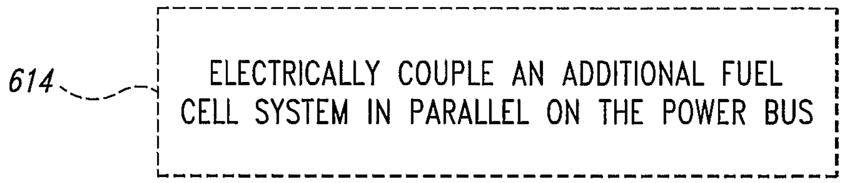


Fig. 18

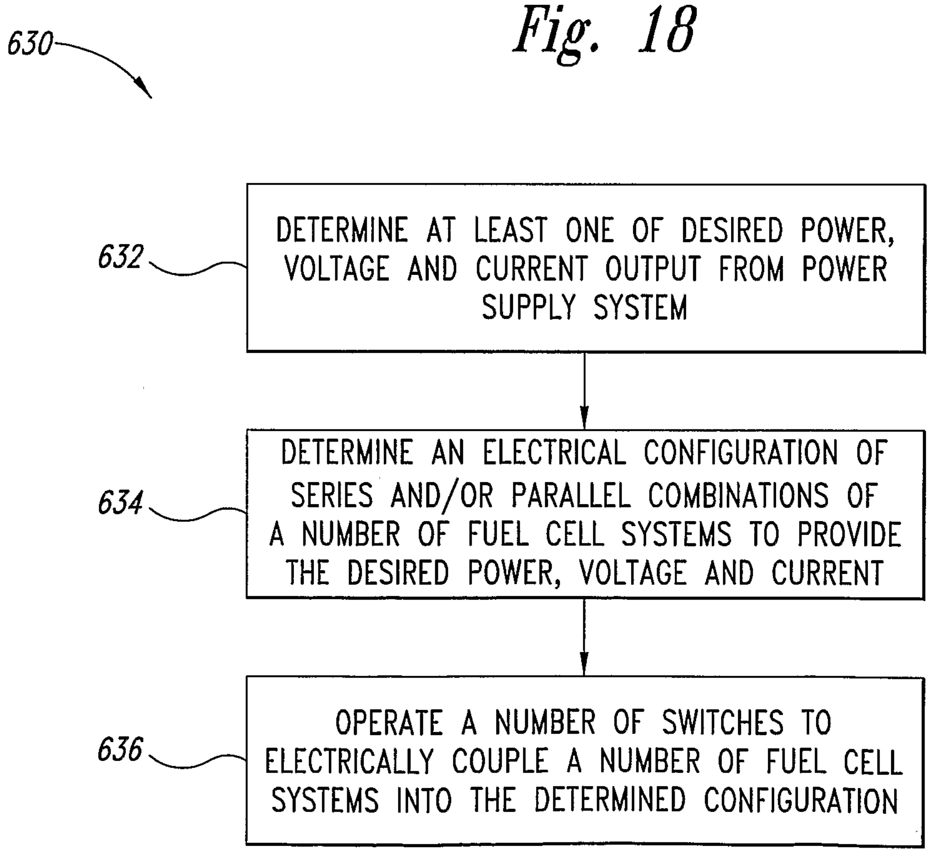


Fig. 19