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(71) Applicant: **ELECTRIC HYDROGEN CO.** [US/US]; 33 Jackson Road, Devens, Massachusetts 01434 (US).

(72) Inventors: **LIU, Yang**; 835 E. San Carlos Ave., San Carlos, California 94070 (US). **GARABEDIAN, Raffi**; 835 E. San Carlos Ave., San Carlos, California 94070 (US).

(74) Agent: **BROADDUS, Daniel**; Lempia Summerfield Katz LLC, 20 S. Clark Street, Suite 600, Chicago, Illinois 60603 (US).

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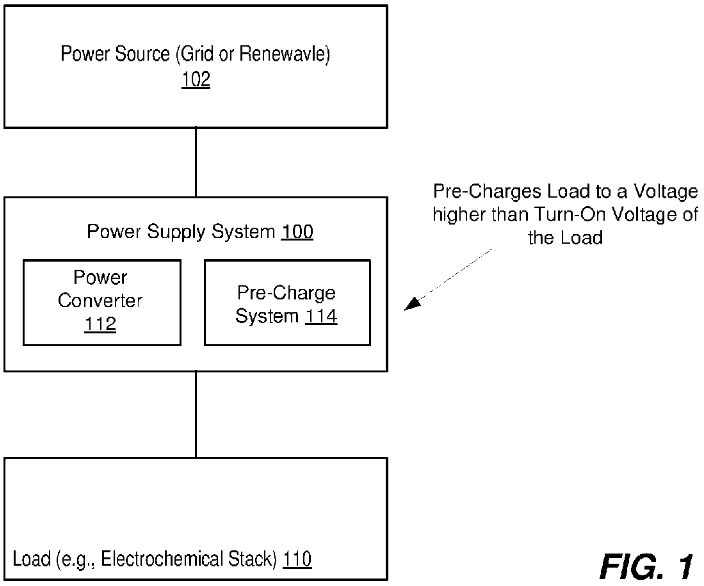

FIG. 1

(57) **Abstract:** A system includes an output port configured to be coupled to a load, the load having a turn-on voltage. The system also includes a power converter configured to convert power from a power source to provide power to the load. The system additionally includes a pre-charge system configured to pre-charge the load to a voltage that is higher than the turn-on voltage of the load prior to turning on the power converter such that the power converter is turned on during an operating mode of the load.

POWER CONVERTER OPTIMIZATION

PRIORITY

[0001] The is application claims the benefit of U.S. Provisional Patent Application No. 63/532,284, filed August 11, 2023, and titled Power Converter Optimization, which is incorporated by reference herein in its entirety.

BACKGROUND

a. Technical Field

[0002] The disclosure relates generally to optimization of a power converter for an electrochemical stack.

b. Brief Description of Related Technology

[0003] Electrolyzer systems use electrical energy to drive a chemical reaction. For example, water is split to form hydrogen and oxygen. The products may be used as energy sources for later use. In recent years, improvements in operational efficiency have made electrolyzer systems competitive market solutions for energy storage, generation, and/or transport. For example, the cost of generation may be below $10 per kilogram of hydrogen in some cases. Increases in efficiency and/or improvements in operation will continue to drive installation of electrolyzer systems.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Fig. 1 is a block diagram of an example power supply system 100, according to various implementations.

[0005] Fig. 2 is a flow chart showing example power supply logic (PSL), according to various implementations.

[0006] Fig. 3 shows an example power supply system for an electrolysis system, according to various implementations.

[0007] Fig. 4 shows another example power supply system for an electrolysis system, according to various implementations.

DETAILED DESCRIPTION

[0008] The discussed architectures and techniques may support large-scale (and/or other scale) electrolysis systems directly or virtually connected to a renewable generation energy source, and/or electrolysis systems providing grid services. Everything described here can also be applied to electrochemical processes other than electrolysis, for example electrochemical reduction of oxide ores, chloralkali processes and the like, so long as they are powered directly by resources utilizing controllable power converter.

[0009] The discussed architectures and techniques disclosed herein may also be configured to operate electrochemical cells within an electrochemical stack with 200 mV or less of pure resistive loss when operating at a high current density (e.g., at least 3 Amps/cm^2, at least 4 Amps/cm^2, at least 5 Amps/cm^2, at least 6 Amps/cm^2, at least 7 Amps/cm^2, at least 8 Amps/cm^2, at least 9 Amps/cm^2, or at least 10 Amps/cm^2). Further, the discussed architectures and techniques disclosed herein may be applied in the formation or operation of a large-scale electrochemical plant that may be configured to generate at least 1 megawatt (MW) of power, at least 5 MW, at least 10 MW, at least 25 MW, at least 50 MW, at least 75 MW, at least 100 MW, in a range of 1-100 MW, in a range of 10-100 MW, in a range of 25-100 MW, or in a range of 50-100 MW of power.

[0010] Power converters that supply power to high power electrochemical stacks may be based on boost topologies. These power converters have intrinsic limits in output voltage control range based on their finite input current ratings. As boost converters, their minimum output voltage is proportional to their input voltage, and the lower the input voltage, the higher the input current for a given converter output current rating. These constraints may result in high power converter costs.

[0011] Typical boost power converters for electrochemical stacks are controlled from 0% to 100% of full current required for the electrochemical stack. Thus, for example, a typical boost converter is configured to have a boost ratio that steps up an input voltage to an output voltage in the range from a turn-on voltage corresponding to zero, or almost zero, current to a maximum voltage corresponding to 100% of full current required for the electrochemical stack.

Due to the wide control range and high boost ratio of the traditional boost power converter, the power converter suffers from efficiency loss, particularly towards the higher end of the control range of the power converter.

[0012] In many electrolyzer stack applications, however, control range that is used during operation of the electrolyzer stack typically does not start at zero current. For example, the lower 10% of the control range may be not used during operation of the electrolyzer stack. Thus, the lower end of the control range of the power converter may not necessarily be needed during operation. Nonetheless, the power converter may be designed to safely traverse this lower range to achieve stable control at the higher range. For example, a range that starts at a voltage that is 10% above the turn-on voltage of the electrolyzer may be used. Thus, in typical power converters for electrolyzer applications, a certain percentage (e.g., 10% or 15%) of the power converter's voltage range is consumed (e.g., in some cases, exclusively)during turn on transients, adding power system cost roughly proportionally, without adding value during operation.

[0013] Embodiments described herein provide a power supply system for an electrolyzer stack configured to pre-charge the electrolyzer stack to a voltage that is above a turn-on voltage that corresponds to zero, and/or nearly zero, current drawn by the electrolyzer stack, prior to turning on a power converter (e.g., rectifier) to provide power to the electrolyzer stack. For example, the power supply system may be configured to pre-charge the electrolyzer stack to a voltage that corresponds to a certain percentage (e.g., 10%, 15%, etc.) of full current for the electrolyzer stack. Pre-charging may be performed by a switched inrush current limiter configured to allow the electrolyzer stack to traverse the voltage range up to the certain percentage (e.g., up to 10% above the turn-on voltage, up to 15% above the turn-on voltage, and/or other proportional value) before the power converter is turned on. By pre-charging the electrolyzer stack to a voltage that is above a turn-on voltage that corresponds to zero, and/or nearly zero, current drawn by the electrolyzer stack, prior to turning on a power converter, the power supply system reduces the control range used by the power converter and increases efficiency of the power converter. For example, by pre-charging the electrolyzer stack to a voltage that is 10% higher than the turn-on voltage of the electrolyzer stack, such as that done by at least some embodiments of the power supply system described herein, eliminate the lower 10% or 15% of control range required for the power converter. Accordingly, embodiments of the power supply system allow for a smaller power converter and/or fewer power converter blocks for a given electrolyzer stack as compared, for example, to power supply systems that pre-charge the electrolyzer stack to the turn-on voltage and control a power converter in the range from the turn-on voltage to 100% voltage of the electrolyzer stack.

[0014] Fig. 1 shows a block diagram of an example power supply system 100, according to various implementations. The power supply system 100 includes an input port for coupling the power supply system to a power source, such as the grid or a renewable energy (e.g., solar, wind, and/or other renewable source) power source and an output port for coupling the power supply system to a load 110. The load 110 may be an electrochemical (e.g., electrolyzer) stack, for example. The power system 100 also includes a power converter 112 and a pre-charge system 114. The power converter 112 may include a rectifier configured to convert AC power of the power source to DC power and a boost converter configured to step-up the power to generated required DC power at the output port. The pre-charge system 114 may include circuitry configured to operate at start-up of the load 110 to pre-charge the load 110 to a volage that is higher than a turn-on voltage of the load. For example, the pre-charge system 114 is configured to pre-charge the load to a voltage that corresponds to a certain percentage (e.g., 10%, 15%, etc.) of maximum current used by the load. When the load is pre-charged to the voltage that is, for example, 10% that corresponds to a certain percentage (e.g., 10%, 15%, etc.) of maximum current used by the load, the power supply system 100 turns on the power converter 112 and switch the output port from the pre-charge system 114 to the power converter 112. Thus, the power converter 112 is turned on passed the turn-on of the load 110 and during an operating mode of the load 110. Therefrom, the remainder of the voltage/current range of the load may be provided by the power converter 112. Thus, the power converter 112 may have a reduced control range as compared to systems in which a power converter covers the entire voltage/current range of the load. For example, the power converter 112 may have a control range that only covers 10% to 100% of the voltage/current range required by the load. Due to the reduced control range of the power converter 112, efficiency of the power converter 112 may be improved, in at least some embodiments. As a result, the power converter 112 may be smaller (e.g., include smaller components, include fewer power converter blocks, etc.) and cheaper as compared to systems in which power converters configured to cover the entire voltage/current range of the load, in at least some embodiments.

[0015] In various embodiments, the pre-charge system 114 includes a switched inrush current limiter configured to allow the load to traverse the voltage range up to the certain percentage (e.g., up to 10% above the turn-on voltage, up to 15% above the turn-on voltage, etc.) before the power converter 112 is turned on. Because the pre-charge system 114 is configured to pre-charge the load beyond the start-up voltage of the load, the inrush current limiter is designed to handle a certain amount of current, such as current up to 10% or 15% of the full current required by the load 110.

[0016] In an example, the pre-charge system 114 includes a switched pre-charge element provided between the output of the power converter 112 and the load 110. The power supply system 100 may first pre-charge a capacitor at the output of the power converter 112 to the voltage that is higher than the turn-on voltage of the load. The pre-charge element may then be used to pre-charge the load to be approximately equal to the pre-charged output of the power converter 112, so that the output of the power supply 100 can be safely switched from the pre-charge circuitry 114 to the power converter 112. In an example, the switched pre-charge element may include a resistor provided between the output of the power converter 112 and the load 110. The resistor may be properly sized based on an equivalent resistance at the input of the load 110. For example, the resistor may be sized small enough so as to not cause a significant volage drop by a voltage divider created by the resistor and the equivalent resistance of the load. On the other hand, the resistor may be sized large enough such that the resistor can handle the current up to the certain percentage of the full current required by the load 110 (e.g., up to 10% or 15% of the full current required by the load 110) without generating too much heat. An example power supply system in which a switched resistor is provided to pre-charge a load to a voltage that is higher than a turn-on voltage of the load, according to an embodiment, is described in more detail below in connection with Fig. 3. In another example, switched pre-charge element may include an inductor provided between the output of the power converter 112 and the load 110. Current flowing through the inductor may be modulated so as to distribute heat generated as the current flows through the inductor over time. An example power supply system in which a switched inductor is provided to pre-charge a load to a voltage that is higher than a turn-on voltage of the load, according to an embodiment, is described in more detail below in connection with Fig. 4.

[0017] Fig. 2 is a flow chart showing example power supply logic (PSL) 200, which may be used with various power supply systems including the example power supply system 100, according to an embodiment. In some cases, the PSL 200 may be implemented on power supply circuitry. The PSL 200 may pre-charge, using a pre-charge system, a load to a voltage that is above a turn-on voltage of a load (202). When the load is pre-charged to the voltage that is higher than the turn-on voltage of the load, the PSL 200 may switch output of the power supply system from the pre-charge system to an output of a power converter (204). Then, during operation of the load, the power converter may be controlled (e.g., to provide a controlled voltage and/or current output) within a control range that begins at the voltage higher than the turn-on voltage of the load (206). The power converter may thus have a control range that covers voltage/current that begins at the voltage that is higher than the turn-on voltage of the load. Accordingly, the power converter may have a reduced control range and improved efficiency as compared to a power converter configured have a control range that covers the entire voltage/current range that begins from the turn-on voltage of the load.

Example Implementations

[0018] A typical electrolyzer may include multiple electrolyzer cells. For the case of a PEM water electrolyzer, the typical Vmax for each cell at end of life is 2.1V at 100% current. Typical V_{turnon} is 1.45V at nearly zero current. Typical $V_{10\%}$ is 1.55V at 10% current. A power converter must typically be specified to control current across this entire range of 0.65V. However, the bottom 0.10V are not useful in the application, though the converter must safely traverse this range to achieve stable control at $V_{10\%}$. In this scenario, 15% of the converter's voltage range is consumed only during turn on transients, adding power system cost roughly proportionally, without adding value during operation.

[0019] In various embodiments, a switched inrush current limiter is provided to allow the stack to traverse this 0-10% range up to $V_{10\%}$ before turning on the power converter.

[0020] Fig. 3 shows an illustrative example power supply system 300 for an electrolysis system, according to an embodiment. In the example power supply system 300, a pre-charge system 314 includes a switched series resistor 316 provided between an output of a rectifier 312 and a power supply input of an electrolyzer stack 310. A transformer 303 is provided to transform power from a power source, such as grid power, to a power usable by the power supply system 300. The power supply system 300 is configured to pre-charge a capacitor C_{in} at the output of the rectifier 304 using the transformed power, using an AC bus pre-charge system 305, prior to turning on the rectifier 312. In an embodiment, the power supply system 300 is configured to pre-charge a capacitor C_{in} to a voltage that is higher than the turn-on voltage of the electrolyzer stack 310. When the capacitor C_{in} is pre-charged to the voltage that is higher than the turn-on voltage of the electrolyzer stack 310, the power supply system 300 may use the charge of the capacitor C_{in} to pre-charge C_{out} at the input to the electrolyzer stack 310 to the voltage that is higher than the turn-on voltage of the electrolyzer stack 310. When C_{out} at the input to the electrolyzer stack 310 is thus pre-charged, power supply system 300 may turn on the rectifier 312 and switch the output of the power supply system 300 from the output of pre-charge system 314 to the output of the rectifier 312.

[0021] In an embodiment, a secondary winding of the transformer 303 may be configured to provide the voltage that is higher than the turn-on voltage of the electrolyzer stack 310. In at least some examples, because a secondary winding of the transformer 303 is configured to provide the voltage that is higher than the turn-on voltage of the electrolyzer stack 310, less copper (and/or other raw material inputs) may be used and cost of the transformer 303 may be reduced as compared to a transformed used with power supply systems that pre-charge output of a rectifier to a turn-on voltage of an electrolyzer stack.

[0022] The resistor 316 may be sized to dissipate power and limit current up to 10% of the electrolyzer current during the startup transient. For example, the resistor 316 is sized such that the resistor is able to carry up to $I_{10\%}$ for the transient time, which is dominated by the time to charge the stack capacitance (in the range of 0.1 to 10 Farads) to $V_{10\%}$. As an example, in an embodiment in which the equivalent capacitance C_{out} of the electrolyzer stack 310 is 2F, $I_{10\%}$ is 2,000 A and the selected resistance of the resistor 316 is 100 mOhm, the initial voltage across the resistor 316 is 150mV (the differential voltage from V_{turnon} and $V_{10\%}$). In this example, the initial inrush current through the resistor is 1.5A and the initial power dissipation is only 0.2W. Continuing with this example, the electrolyzer stack capacitance RC time constant is then 0.2 sec. At the end of 1 sec, the stack capacitance may be largely charged, and the current through the resistor is then 2000A. In this case, the peak power dissipation in the resistor of 400kW. In an example, if the resistor is bypassed after about 1 sec., the energy dissipated by the resistor would be roughly 60 kWh. Thus, in this example, the power supply system 300 may be designed to handle dissipation of 60 kWh during start-up of the electrolyzer stack 310.

[0023] Fig. 4 shows an illustrative example power supply system 400 for an electrolysis system, according to an embodiment. The power supply system 400 is generally the same as the supply system 300 of Fig. 3, except that in the power supply system 400, instead of the resistor 316, a buck converter including a series inductor 416 is provided between the rectifier and the electrolyzer stack. The inductor is properly sized to impede inrush current allowing the stack capacitance to charge up to $V_{10\%}$. The example power supply system 400 includes the buck converter connects the capacitor C_{in} to the electrochemical stack 310. The buck converter may be configured to modulate current flowing through the inductor 416 to distribute heat dissipation due to current drawn by the load up to current that corresponds to the voltage that is above the turn-on voltage of the load over time. Due to the minimum back ratio of the buck converter, efficiency may be suitably high, and the cost may be low, in various embodiments.

[0024] In an embodiment, the resistor 316 in the power supply 300 of Fig. 3 is bypassed with a contactor or solid state switch during normal operation past startup. Similarly, the inductor 416 in the power supply 400 of Fig. 4 is bypassed with a contactor or solid state switch during normal operation past startup, in an embodiment. In various embodiments, a simple contactor is used for the bypass without risk of arcing because the voltage across the resistor 302 and the inductor 402 is small. In the case of the resistor 302, the bypass requirement may be necessary because the power dissipation from such a resistor would be untenable in steady state operation, and the power rating of the resistor sized to 100% current would drive excessive cost. In the case of the inductor 416, the intrinsic series resistance of the inductor 416 generally drives the conductor size of the inductor 416. Thus, cost of the power supply system 400 may be increased if the inductor 416 is designed to be left in-circuit.

[0025] In accordance with one aspect of the disclosure, a system includes an output port configured to be coupled to a load, the load having a turn-on voltage. The system also includes a power converter configured to convert power from a power source to provide power to the load. The system additionally includes a pre-charge system configured to pre-charge the load to a voltage that is higher than the turn-on voltage of the load prior to turning on the power converter such that the power converter is turned on during an operating mode of the load.

[0026] In accordance with another aspect of the disclosure, a method for providing power to a load by a power supply system includes pre-charging, by a pre-charge system, the load to a voltage that is higher than a start-up voltage of the load. The method also includes, when the load is pre-charged to the voltage that is higher than the turn-on voltage of the load, switching output of the power supply system from the pre-charge system to an output of a power converter. The method further includes, during operation of the load, controlling the power converter within a control range that begins at the voltage higher than the turn-on voltage of the load.

[0027] In connection with any one of (or any combination of) the aforementioned the systems, devices and/or methods described herein may alternatively or additionally include or involve any combination of one or more of the following aspects or features. The power converter includes a boost power converter. The load includes an electrolyzer stack. The pre-charge system includes an inrush current limiter. The pre-charge system includes a switched resistor provided between an output of the power converter and the input of the load, wherein the resistor is sized such that i) the load is pre-charged to the voltage that is above the turn-on voltage of the load ii) the resistor is able to handle current drawn by the load up to current that corresponds to the voltage that is above the turn-on voltage of the load. The pre-charge system includes a buck converter including an inductor provided between an output of the power converter and the input of the load, wherein the buck converter is configured to modulate current flowing through the inductor to distribute heat dissipation due to current drawn by the load up to current that corresponds to the voltage that is above the turn-on voltage of the load over time. The power converter is controllable within a reduced control range from current corresponding to the voltage that is higher than the turn-on voltage of the load to a maximum current required for the load. The voltage that is higher than the turn-on voltage of the load corresponds to one of: 10% of the maximum current required for the load, 15% of the maximum current required for the load, 20% of the maximum current required for the load, 25% of the maximum current required for the load, and 30% of the maximum current required for the load.

[0028] Although specific implementations have been illustrated and described herein, it should be appreciated that any subsequent arrangement designed to achieve the same or similar purpose may be substituted for the specific implementations shown. This disclosure is intended to cover any and all subsequent adaptations or variations of various implementations. Combinations of the above implementations, and other implementations not specifically described herein, are apparent to those of skill in the art upon reviewing the description.

[0029] As used herein, the singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise.

[0030] As used herein, “for example,” “for instance,” “such as,” or “including” are meant to introduce examples that further clarify more general subject matter. Unless otherwise expressly indicated, such examples are provided only as an aid for understanding implementations illustrated in the present disclosure and are not meant to be limiting in any fashion. Nor do these phrases indicate any kind of preference for the disclosed implementations.

[0031] The Abstract of the Disclosure is provided to comply with 37 C.F.R. §1.72(b) and is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. In addition, in the foregoing Detailed Description, various features may be grouped together or described in a single implementation for the purpose of streamlining the disclosure. This disclosure is not to be interpreted as reflecting an intention that the claimed implementations require more features than are expressly recited in each claim. Rather, as the following claims reflect, subject matter may be directed to less than all of the features of any of the disclosed implementations. Thus, the following claims are incorporated into the Detailed Description, with each claim standing on its own as defining separately claimed subject matter.

[0032] It is intended that the foregoing detailed description be regarded as illustrative rather than limiting and that it is understood that the following claims including all equivalents are within the scope of the disclosure. The claims should not be read as limited to the described order or elements unless stated to that effect. Therefore, all implementations that come within the scope and spirit of the following claims and equivalents thereto are included within the disclosure.

What is claimed is:

1. A system comprising:

an output port configured to be coupled to a load, the load having a turn-on voltage;

a power converter configured to convert power from a power source to provide power to the load; and

a pre-charge system configured to pre-charge the load to a voltage that is higher than the turn-on voltage of the load prior to turning on the power converter such that the power converter is turned on during an operating mode of the load.

2. The system of claim 1, wherein the power converter comprises a boost power converter.

3. The system of claim 1, wherein the load comprises an electrolyzer stack.

4. The system of claim 1, wherein the pre-charge system comprises an inrush current limiter.

5. The system of claim 1, wherein the pre-charge system comprises a switched resistor provided between an output of the power converter and the input of the load.

6. The system of claim 5, wherein the resistor is sized such that the load is pre-charged to the voltage that is above the turn-on voltage of the load; and the resistor is rated to handle current drawn by the load up to current that corresponds to the voltage that is above the turn-on voltage of the load.

7. The system of claim 1, wherein the pre-charge system comprises a buck converter including an inductor provided between an output of the power converter and the input of the load.

8. The system of claim 7, wherein the buck converter is configured to modulate current flowing through the inductor to distribute heat dissipation due to current drawn by the load up to current that corresponds to the voltage that is above the turn-on voltage of the load over time.

9. The system of claim 1, wherein the power converter is configured to be controlled within a reduced control range from current corresponding to the voltage that is higher than the turn-on voltage of the load to a maximum current required for the load.

10. The system of claim 1, wherein a defined portion of voltage range of the power converter is utilized during a turn-on transient for the load.

11. A method for providing power to a load by a power supply system, the method comprising:

pre-charging, by a pre-charge system, the load to a voltage that is higher than a start-up voltage of the load;

at a time that the load is pre-charged to the voltage that is higher than the turn-on voltage of the load, switching output of the power supply system from the pre-charge system to an output of a power converter; and

during operation of the load, controlling the power converter within a control range that begins at the voltage higher than the turn-on voltage of the load.

12. The method of claim 11, wherein the power converter comprises a boost power converter.

13. The method of claim 11, wherein the load comprises an electrolyzer stack.

14. The method of claim 11, wherein the pre-charge system comprises an inrush current limiter.

15. The method of claim 11, wherein the pre-charge system comprises a switched resistor provided between an output of the power converter and the input of the load.

16. The method of claim 15, wherein the resistor is sized such that the load is pre-charged to the voltage that is above the turn-on voltage of the load; and the resistor is rated to handle current drawn by the load up to current that corresponds to the voltage that is above the turn-on voltage of the load.

17. The method of claim 11, wherein the pre-charge system comprises a buck converter including an inductor provided between an output of the power converter and the input of the load.

18. The method of claim 17, further including modulating, via the buck converter current flowing through the inductor to distribute heat dissipation due to current drawn by the load up to current that corresponds to the voltage that is above the turn-on voltage of the load over time.

19. The method of claim 11, further including controlling the power converter within a reduced control range from current corresponding to the voltage that is higher than the turn-on voltage of the load to a maximum current required for the load.

20. A device

circuitry configured to provide power to load by:

pre-charging, by a pre-charge system, the load to a voltage that is higher than a start-up voltage of the load;

at a time that the load is pre-charged to the voltage that is higher than the turn-on voltage of the load, switching output of the power supply system from the pre-charge system to an output of a power converter; and

during operation of the load, controlling the power converter within a control range that begins at the voltage higher than the turn-on voltage of the load.

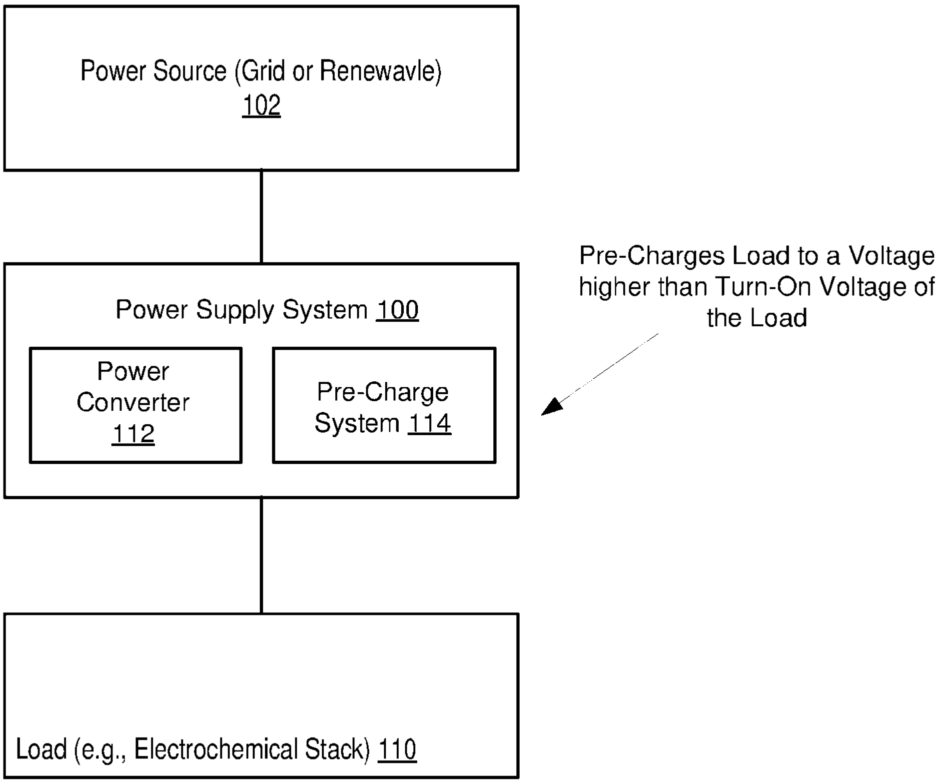
Power Source (Grid or Renewavle)
102
Power Supply System 100
Power Converter
112
Pre-Charge System 114
Pre-Charges Load to a Voltage higher than Turn-On Voltage of the Load
Load (e.g., Electrochemical Stack) 110

FIG. 1

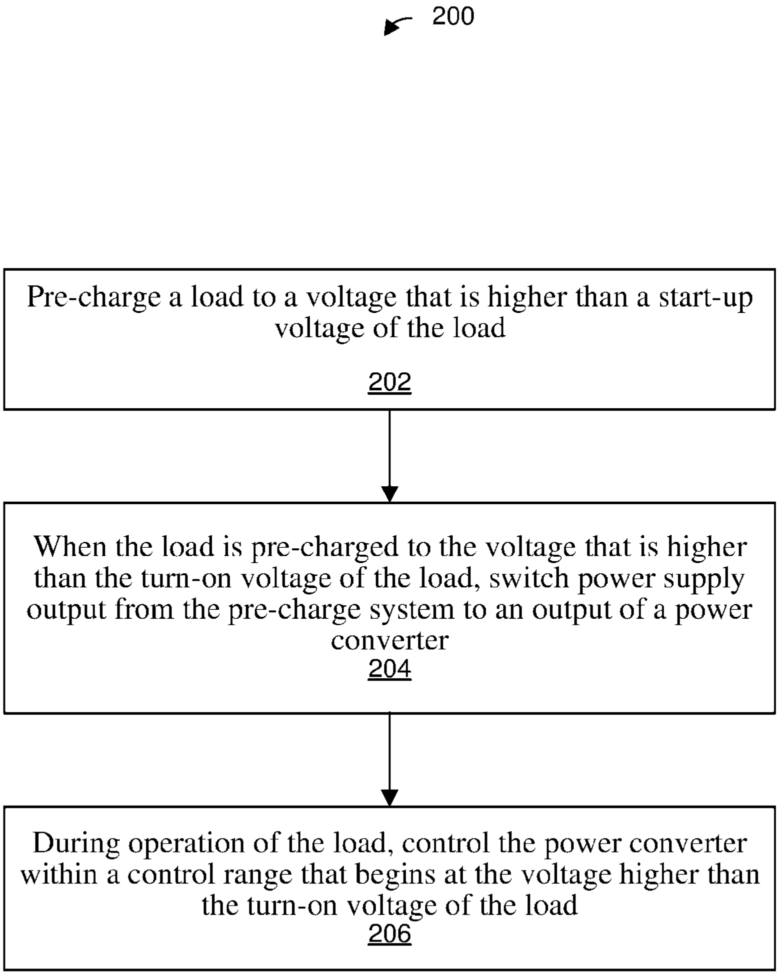
200
Pre-charge a load to a voltage that is higher than a start-up voltage of the load
202
When the load is pre-charged to the voltage that is higher than the turn-on voltage of the load, switch power supply output from the pre-charge system to an output of a power converter
204
During operation of the load, control the power converter within a control range that begins at the voltage higher than the turn-on voltage of the load
206

FIG. 2

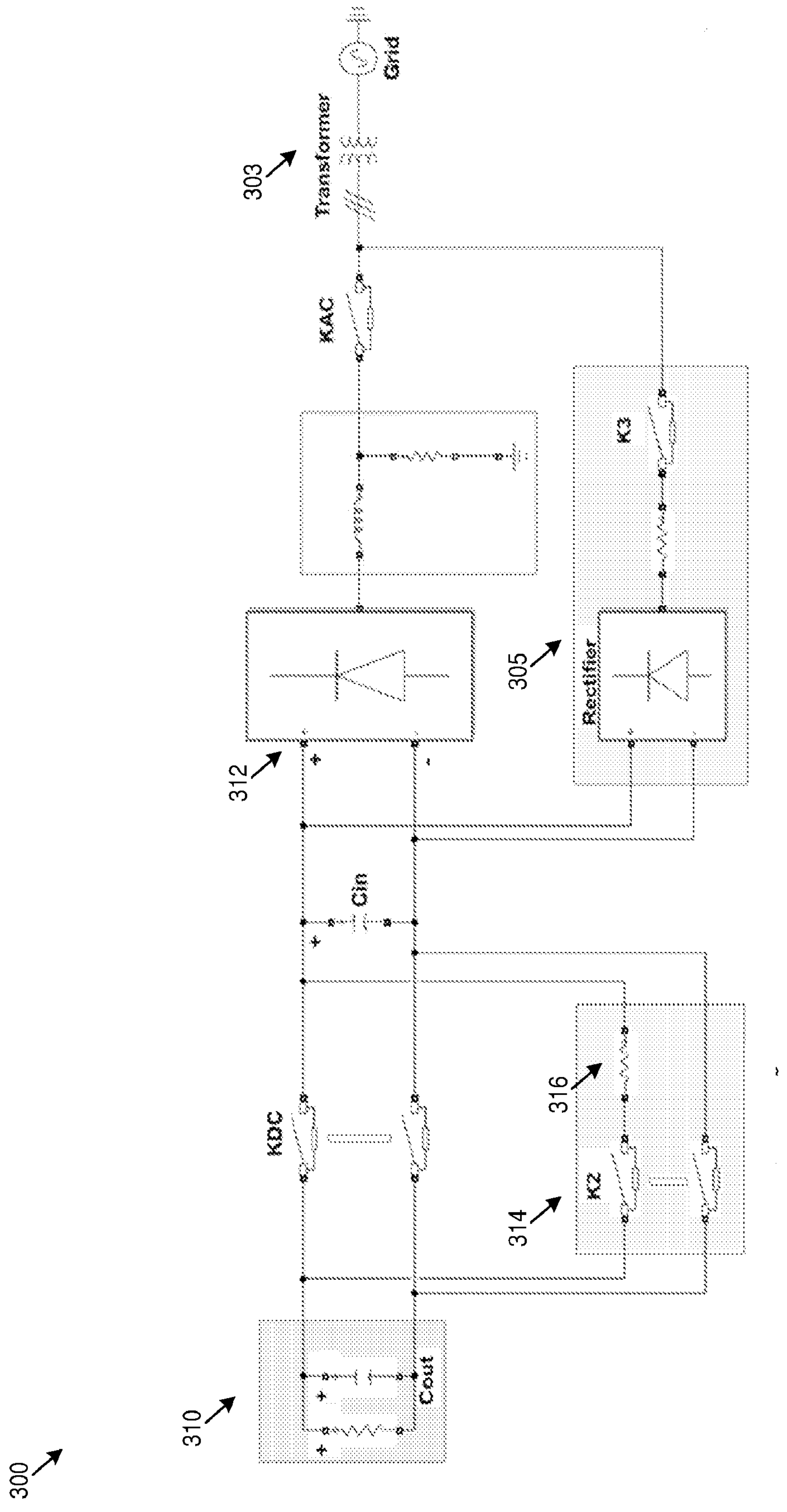
300
310
Cout
KDC
314
K2
316
Cin
312
305
Rectifier
K3
KAC
303
Transformer
Grid

FIG. 3

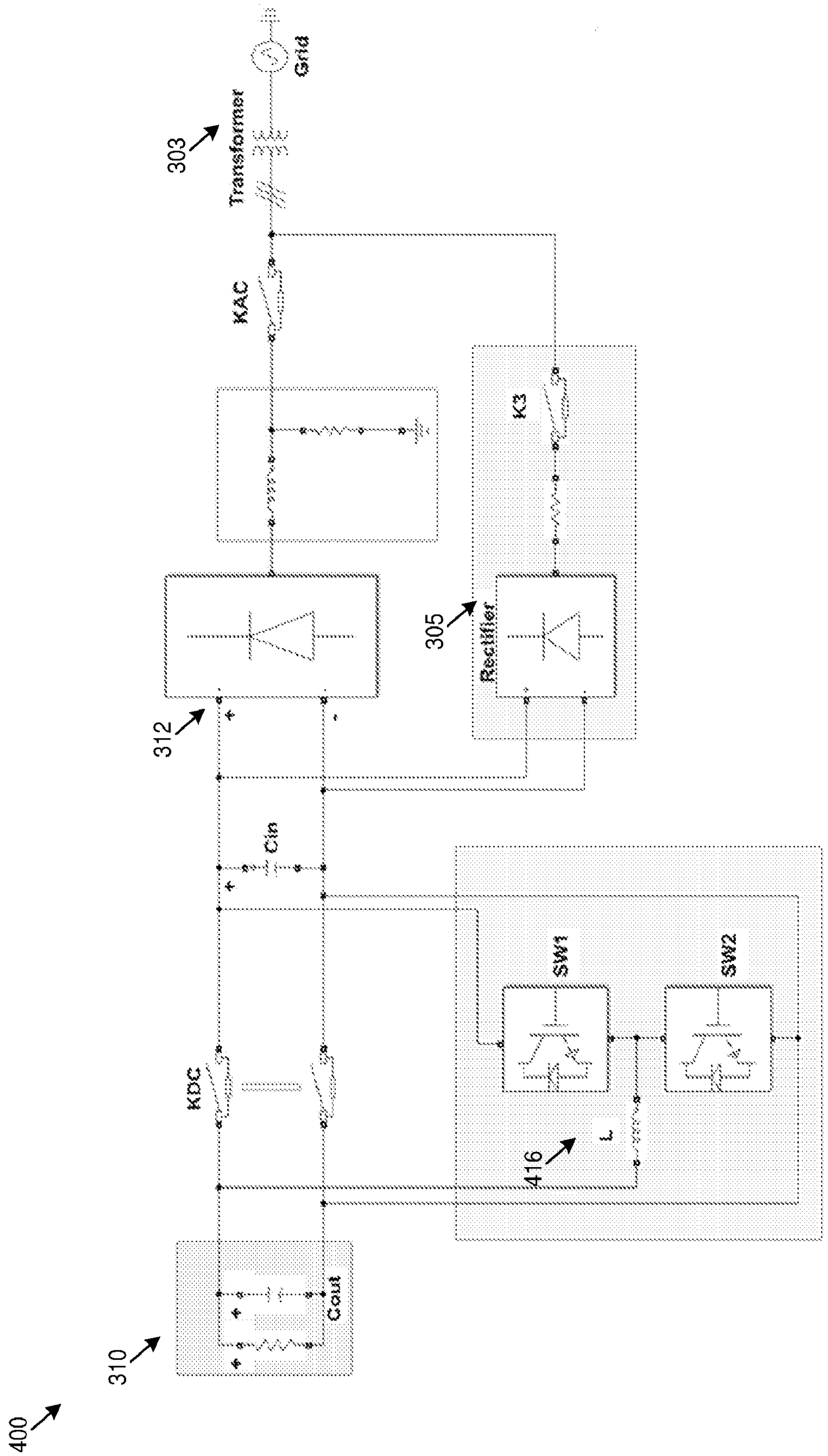
Grid
Transformer
303
KAC
K3
Rectifier
305
312
+
-
Cin
+
SW1
SW2
KDC
L
416
Cout
+
+
310
400

FIG. 4