US Patent & Trademark Office
Patent Public Search | Text View

FUEL CELL SYSTEM ARCHITECTURE FOR ARTIFICIAL INTELLIGENCE MODEL TRAINING

Abstract

The present disclosure is directed to a system that employs fuel cell-based power generation for decentralized data centers that perform large, processing intensive tasks, such as training processes for large artificial intelligence models. The system utilizes various modules, such as energy storage systems, load banks, and other types of loads, to supplement power output by the fuel cells, as well as store any excess power generated by the fuel cell systems. As a result, swings in the power output by the fuel cell systems are minimized and the life of the fuel cell systems may be extended.

Inventors: PMSVVSV; Prasad (San Jose, CA), GURUNATHAN; Ranganathan (Bengaluru, IN), PANATI; Razvan (San Jose, CA), COTTULI; Carlton (San Jose, CA), PRASHER; Ravi (San Jose, CA), SRIDHAR; KR (San Jose, CA)

Applicant: Bloom Energy Corporation (San Jose, CA)

Family ID: 94605487

Assignee: Bloom Energy Corporation (San Jose, CA)

Appl. No.: 19/046306

Filed: February 05, 2025

Related U.S. Application Data

Publication Classification

H02J3/06 (20060101); **H02J3/28** (20060101)

U.S. Cl.:

CPC   **H02J3/38** (20130101); **H01M8/04067** (20130101); **H01M8/04604** (20130101); **H01M8/04992** (20130101); **H01M8/2425** (20130101); **H02J3/06** (20130101); **H02J3/28** (20130101); H01M2008/1293 (20130101); H02J2300/30 (20200101)

Background/Summary

BACKGROUND

Technical Field

[0001] The present disclosure is directed to system architectures and power control methods for fuel cell systems.

Description of the Related Art

[0002] Fuel cells, such as solid oxide fuel cells (SOFC), are energy conversion devices that can produce electricity and heat directly from hydrogen and hydrocarbon gases combined with oxidants. Fuel cell systems are capable of generating power continuously without interruption. Fuel cell systems are highly efficient compared to conventional power generation devices. For instance, in a diesel generator, diesel fuel and compressed air are ignited, converting the chemical energy of the fuel to thermal energy; thermal energy is then transformed to mechanical energy (e.g., using heat to drive a turbine); and mechanical energy is finally converted to electrical energy. In contrast, fuel cell systems bypass the conversion of mechanical energy into electrical energy. Instead, fuel cells generate electricity and heat via an electrochemical reaction, contributing to clean baseload power and serving as a backup solution.

[0003] Due to these advantages, fuel cell systems are desirable as a primary power source for various applications seeking reliable, sustainable, clean energy. Fuel cell systems can be used to power decentralized data centers that perform large, processing intensive tasks, such as training processes for artificial intelligence (AI) models.

BRIEF SUMMARY

[0004] The present disclosure is directed to a system that employs fuel cell-based power generation for decentralized data centers performing large, intermittent processing intensive tasks.

[0005] The system utilizes various supporting modules and technologies that cater to the power load demand on the fuel cell power modules. In cases where the fuel cell power modules are unable to ramp up or increase at the same rate as the power load demands, additional energy is provided by one or more of an energy storage system, a load bank, and/or a secondary load (e.g., a utility power grid or another connected microgrid). Conversely, in cases where the fuel cell power modules generate excess power, the excess power is provided to one or more of the energy storage system, the load bank, and the secondary load.

[0006] As a result, swings in the power output by the fuel cell power modules may be selectively minimized and the life of the fuel cell power modules may be extended.

Description

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0007] In the drawings, identical reference numbers identify similar features or elements. The size and relative positions of features in the drawings are not necessarily drawn to scale.

[0008] FIG. **1** shows a power signal that indicates power consumption during training and checkpoints for a model training process according to an embodiment disclosed herein.

[0009] FIG. **2** shows a power signal that indicates power consumption during a software crash and recovery, and a stand-by state for a model training process according to an embodiment disclosed herein.

[0010] FIG. **3** shows a system according to an embodiment disclosed herein.

[0011] FIG. **4** shows a fuel cell power system according to an embodiment disclosed herein.

[0012] FIG. **5** shows power signals for a primary load, a fuel cell power system, and an energy storage system in a case where the fuel cell power system follows an entire load cycle of the primary load according to an embodiment disclosed herein.

[0013] FIG. **6** shows power signals for a primary load, a fuel cell power system, and an energy storage system in a case where the fuel cell power system follows a portion of a load cycle of the primary load according to an embodiment disclosed herein.

[0014] FIG. **7** shows power signals for a primary load, a fuel cell power system, and an energy storage system in a case where the fuel cell power system follows a portion of a load cycle of the primary load according to another embodiment disclosed herein.

[0015] FIG. **8** shows power signals for a primary load, a fuel cell power system, and an energy storage system in a case where the fuel cell power system remains at a constant power level according to an embodiment disclosed herein.

[0016] FIGS. **9**, **9**A, and **9**B show a method of managing the power balance of a system according to an embodiment disclosed herein.

DETAILED DESCRIPTION

[0017] In the following description, certain specific details are set forth to provide a thorough understanding of various aspects of the disclosed subject matter. However, the disclosed subject matter may be practiced without these specific details. In some instances, well-known structures, functions, and methods of manufacturing of electronic devices, electronic components, and power systems have not been described in detail to avoid obscuring the descriptions of other aspects of the present disclosure.

[0018] Unless the context requires otherwise, throughout the specification and claims that 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."

[0019] Reference throughout the specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearance of the phrases "in one embodiment" or "in an embodiment" in various places throughout the specification are not necessarily all referring to the same aspect. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in one or more aspects of the present disclosure.

[0020] As discussed above, fuel cell systems can provide efficient, clean, and continuous power, and are a desirable choice for various applications. However, power consumption profiles of many applications can present challenges for fuel cell systems. Fuel cell systems, especially high-temperature technology-based ones (e.g., SOFC systems), easily handle base loads of applications, but can struggle with rapid changes in loads, such as frequent and fast changing loads, and extended multi-day stand-by times. For example, SOFC systems may not be able to adjust their power level to meet a change in load within a desired period of time. Further, frequent and fast changing loads can degrade and shorten the life of the fuel cell systems.

[0021] An AI model comprises both a set of selected algorithms and the data used to train those algorithms for the purpose of allowing the algorithms to make the most accurate predictions. The algorithms can be considered equations with undefined coefficients. The AI model comes into fruition when the algorithms digest data sets to determine the best fit coefficient values, thus creating a model for predictions. Thus, AI model training refers to the process of supplying the algorithms with data, examining the results, and modifying the model output to increase accuracy and efficiency. To be useful, AI model algorithms normally process massive amounts of data.

[0022] Power consumption profiles of training processes for AI models are particularly challenging for fuel cell systems due to their highly variable loads. Model training processes change between multiple different loads due to training processing, checkpoint processing, software crashes and recoveries, and stand-by states.

[0023] Examples of power consumption profiles during training processing, checkpoint processing, software crashes and recoveries, and stand-by states are explained with respect to FIGS. **1** and **2** below.

[0024] FIG. **1** shows a power signal **10** that indicates power consumption during training and checkpoints for a model training process according to an embodiment disclosed herein. The model training process changes between training processing and check point processing.

[0025] The vertical axis is an amplitude axis and the horizontal axis is a time axis. The amplitude axis indicates the power level of the power signal **10**. The amplitude axis may have any amplitude unit indicating power (e.g., watts, volts, amps, etc.). The time axis may have any time unit indicating time.

[0026] The power signal **10** changes between a load power high value L.sub.PH, and a load power low value LP.sub.L. The load power high value LP.sub.H is the power consumption during training processing and has a training duration of t.sub.T. The load power low value LP.sub.L is the power consumption during checkpoint processing and has a checkpoint duration of t.sub.CP.

[0027] The power levels of the load power high value LP.sub.H and the load power low value LP.sub.L depend on the type and size of the model being trained. The ratio of the load power high value LP.sub.H to the load power low value LP.sub.L may be, for example, between 15% and 25%. The power levels of the load power high value LP.sub.H and the load power low value LP.sub.L may change over time as well.

[0028] The training duration t.sub.T and the checkpoint duration t.sub.CP also depend on the type and size of the model being trained, as well as the amount of data to be stored during the checkpoint. The training duration t.sub.T may be between tens of seconds and tens of minutes. The checkpoint duration t.sub.CP may be between a few seconds and a few minutes. The training duration t.sub.T and the checkpoint duration t.sub.CP may change over time as well.

[0029] As can be seen in FIG. **1**, the power consumption during training processing and checkpoint processing varies significantly, switching between the load power high value LP.sub.H and the load power low value LP.sub.L with different durations. The power signal **10** increases to the load power high value LP.sub.H for training between two consecutive load power low values LP.sub.L for checkpoints.

[0030] FIG. **2** shows a power signal **12** that indicates power consumption during a software crash and recovery, and a stand-by state for a model training process according to an embodiment disclosed herein.

[0031] Similar to FIG. **1**, the vertical axis is an amplitude axis and the horizontal axis is a time axis. The amplitude axis indicates the power level of the power signal **12**.

[0032] In FIG. **2**, two training processes are performed: Training Job **1** and Training Job **2**. In each of Training Job **1** and Training Job **2**, the power signal **12** changes between a load power high value LP.sub.H having a training duration of t.sub.T and a load power low value LP.sub.L having a checkpoint duration of t.sub.CP, which are discussed above.

[0033] More specifically, in Training Job **1**, the power signal **12** changes between a load power high value LP.sub.H1 having a training duration of t.sub.T1 and a load power low value LP.sub.L1 having a checkpoint duration of t.sub.CP1. In Training Job **2**, the power signal **12** changes between a load power high value LP.sub.H2 having a training duration of t.sub.T2 and a load power low value LP.sub.L2 having a checkpoint duration of t.sub.CP2.

[0034] The power level values and durations of the power levels may differ between training processes. For example, in FIG. **2**, the load power low value LP.sub.L2 for Training Job **2** is higher than the load power low value LP.sub.L1 for Training Job **1**, the training duration of t.sub.T1 for

Training Job **1** is smaller than the training duration of t.sub.T2 for Training Job **2**, and the checkpoint duration of t.sub.CP1 for Training Job **1** is smaller than the checkpoint duration of t.sub.CP2 for Training Job **2**.

[0035] During Training Job **1**, the model training process experiences a software crash (e.g., the training process fails and is not performed properly) and performs processing to recover from the software crash (e.g., restarting Training Job **1**). When the software crash occurs at time T**1**, the power level of the power signal **12** drops to a load power software crash recovery value LP.sub.SCR, which is lower than the load power low value LP.sub.L1, for a software crash recover duration t.sub.SCR. The software crash recover duration t.sub.SCR is typically longer than checkpoint duration of t.sub.CP1. Once the software has recovered at time T**2**, the power level of the power signal **12** returns to performing training processing for Training Job **1** at the load power high value LP.sub.H1.

[0036] Training Job **1** completes at time T**3**, and the model training process enters a stand-by state. The stand-by state is a low power state in which training processing is stopped and minimal to no processing is performed. As a result, at time T**3**, the power level of the power signal **12** drops to a load power stand-by value LP.sub.SB, which is lower than the load power software crash recovery value LP.sub.SCR, for a stand-by duration t.sub.SB. The stand-by state is exited at time T**4**, and Training Job **2** then begins.

[0037] As can be seen in FIG. **2**, the power consumption during software crashes, recoveries, and stand-by states exhibit even further variations in power consumption, in addition to the variations due to training processing and checkpoint processing. The power signal **12** suddenly drops to the load power software crash recovery value LP.sub.SCR in response to a software crash and returns to the load power high value LP.sub.H1 upon recovery. Further, power consumption drops again to the load power stand-by value LP.sub.SB in response to model training process entering the stand-by state.

[0038] The present disclosure is directed to system architectures and control methods that employ fuel cell-based power generation as the primary energy source. The system includes various supporting modules and technologies that cater to the power load demands of various applications, such as large model training data centers. Namely, the system provides a microgrid architecture that combines a fuel cell system as the primary power source with other supporting technologies for energy storage and energy dissipation. The supporting technologies maintain a constant power draw from the fuel cell system, or at least reduce the magnitude of power swings that the fuel cell system experiences.

[0039] FIG. **3** shows a system **14** according to an embodiment disclosed herein. The system **14** provides a fuel cell-based microgrid that caters to processes with highly variable power consumption levels.

[0040] The system **14** includes a fuel cell power system **16**, a first energy storage system **18**, a second energy storage system **20**, a load bank **22**, a power converter **24**, a load interface converter **26**, and a controller **28**. The fuel cell power system **16**, the first energy storage system **18**, the second energy storage system **20**, the load bank **22**, and the load interface converter **26** are coupled to each other by a power bus **15**, and communicatively coupled to the controller **28**.

[0041] The fuel cell power system **16** includes one or more fuel cell power modules that act as the primary power source for loads connected to the system **14** (e.g., the primary load connected to the load interface converter **26**). For example, FIG. **4** shows a fuel cell power system **16** according to an embodiment disclosed herein.

[0042] In this example, the fuel cell power system **16** is a modular fuel cell power system that provides flexible system installation and operation. Modules allow scaling of installed generating capacity, reliable generation of power, flexibility of fuel processing, and flexibility of power output voltages and frequencies. This design also provides an easy means of scale up to meet specific requirements of customer installations. The modular design also allows the use of available fuels

and required voltages and frequencies which may vary by customer and/or by geographic region.

[0043] The fuel cell power system **16** includes one or more fuel cell power modules **30** and one or more power conditioning (i.e., electrical output) modules **32**. In embodiments, the power conditioning modules **32** are configured to deliver direct current (DC). In alternative embodiments, the power conditioning modules **32** are configured to deliver alternating current (AC). In these embodiments, the power conditioning modules **32** include a mechanism to convert DC to AC, such as an inverter.

[0044] In FIG. **4**, the exemplary fuel cell power system **16** includes a row of seven fuel cell power modules **30** and one power conditioning module **32** disposed on a pad **34**. However, the fuel cell power system **16** may include any number of fuel cell power modules and power conditioning modules and any number of rows of modules. For example, the fuel cell power system **16** may include two rows of fuel cell power modules **30** arranged back to back/end to end.

[0045] Each of the fuel cell power modules **30** is configured to house one or more hot boxes **36**. Each hot box **36** contains one or more stacks or columns of fuel cells, such as one or more stacks or columns of SOFCs comprised of fuel cells (anode, cathode, and electrolyte) separated by conductive interconnect plates.

[0046] The fuel cell stacks may include externally and/or internally manifolded stacks. For example, the stacks may be internally manifolded for fuel and air with fuel and air risers extending through openings in the fuel cell layers and/or in the interconnect plates between the fuel cells. Alternatively, the fuel cell stacks may be internally manifolded for fuel and externally manifolded for air, where only the fuel inlet and exhaust risers extend through openings in the fuel cell layers and/or in the interconnect plates between the fuel cells.

[0047] The fuel cells may have a cross flow (where oxidant and fuel flow roughly perpendicular to each other on opposite sides of the fuel cells), counter flow parallel (where oxidant and fuel flow roughly parallel to each other but in opposite directions on opposite sides of the fuel cells), or co-flow parallel (where air and fuel flow roughly parallel to each other in the same direction on opposite sides of the fuel cells) configuration.

[0048] The power conditioning module **32** may include components for converting the fuel cell stack generated DC power to AC power (e.g., DC/DC and DC/AC converters), electrical connectors for AC power output to the grid, circuits for managing electrical transients, and a system controller (e.g., a computer or dedicated control logic device or circuit). The power conditioning module **32** may be designed to convert DC power from the fuel cell modules to different AC voltages and frequencies. Designs for 208V, 60 Hz; 480V, 60 Hz; 415V, 50 Hz and other common voltages and frequencies may be provided.

[0049] The linear array of fuel cell power modules **30** is readily scaled. For example, more or fewer fuel cell power modules **30** may be provided depending on the power needs of the building or other facility serviced by the fuel cell power system **16**. The fuel cell power modules **30** and input/output modules may also be provided in other ratios. For example, in other exemplary embodiments, more or fewer fuel cell power modules **30** may be provided.

[0050] The fuel cell power system **16** is configured in a way to ease servicing of the components of the fuel cell power system **16**.

[0051] For example, the fuel cell power system **16** may include access doors **38**. All of the routinely or high serviced components, such as the consumable components, may also be placed in a single module to reduce amount of time required for service operations.

[0052] As another example, when one fuel cell power module **30** is taken offline (i.e., no power is generated by the stacks in the hot box **36** in the offline fuel cell power module **30**), the remaining fuel cell power modules **30** and the power conditioning module **32** are not taken offline. Furthermore, the fuel cell power system **16** may contain more than one of each type of module **30**, **32**. When at least one module of a particular type is taken offline, the remaining modules of the same type are not taken offline. Thus, in a system including a plurality of modules, each of the

modules **30** or **32** may be electrically disconnected, removed from the fuel cell power system **16** and/or serviced or repaired without stopping an operation of the other modules in the system, allowing the fuel cell power system **16** to continue to generate electricity. The entire fuel cell power system **16** does not have to be shut down if one stack of fuel cells in one hot box **36** malfunctions or is taken offline for servicing. Moreover, the fuel cell system **16** can include redundant modules that can be brought on-line when other modules are being serviced or replaced.

[0053] Returning to FIG. **3**, the first energy storage system **18** and the second energy storage system **20** are energy or power storage systems that are used to reduce the magnitude of power swings that the fuel cell power system **16** experiences. The first energy storage system **18** and the second energy storage system **20** act as power buffers that store excess power for supply to the power bus **15** when load power (e.g., power consumption of the primary load connected to the load interface converter **26**) is lower than an intended power level of the fuel cell power system **16**. In addition, the first energy storage system **18** and/or the second energy storage system **20** provide power to the power bus **15** when there is a shortage of power on the power bus **15** (e.g., load power is more than the power output of the fuel cell power system **16**). Although two energy storage systems are shown in FIG. **3**, the system **14** may include any number of energy storage systems. Various operation methods for the first energy storage system **18** and the second energy storage system **20** will be discussed in further detail below.

[0054] In one embodiment, the fuel cell power system **16**, the first energy storage system **18**, and the second energy storage system **20** are integrated at a DC level, thus making the power bus **15** a DC power bus and the system **14** a DC-coupled system.

[0055] The types of storage systems that may be used for the first energy storage system **18** and the second energy storage system **20** include, for example, ultracapacitors, supercapacitors, different types of battery technologies, rotary storage systems like flywheels, and thermal storage systems.

[0056] The first energy storage system **18** and the second energy storage system **20** are different types of storage systems to achieve optimum performance of the system **14**. In one embodiment, the first energy storage system **18** is an energy storage system that stores a low total amount of power, but is able to achieve fast charging and discharging times. In contrast, the second energy storage system **20** is an energy storage system that stores a large total amount of power (e.g., greater than the total amount of power of the first energy storage system **18**), but has slow charging and discharging times (e.g., slower than the charging and discharging times of the first energy storage system **18**). With storage systems with different characteristics, the first energy storage system **18** or the second energy storage system **20** is selected depending on the current power consumption of the primary load. In one embodiment, the first energy storage system **18** is used to supplement the power generated by the fuel cell power system **16** and store excess power generated by the fuel cell power system **16**. The second energy storage system **20** is also used to store excess power generated by the fuel cell power system **16** but in cases where the first energy storage system **18** is fully charged (e.g., charged to a level greater than a determined threshold value) or where there are large amounts of excess power (e.g., a stand-by state).

[0057] The load bank **22** is a controllable load bank that converts excess power on the power bus **15** to heat energy. The amount of power the load bank **22** consumes depends on the excess power available from the fuel cell power system **16** after catering to the primary load connected to the load interface converter **26**, as well as the first energy storage system **18** and the second energy storage system **20** at any instant. The heat energy generated by the load bank **22**, as well as any heat energy generated by the fuel cell power system **16**, may be vented to the surrounding environment or reused for various purposes, such as being captured using combined heat and power (CHP) equipment for heating, ventilation, and air conditioning (HVAC) and other heating loads of a building. The heat generated by the load bank **22** as well as fuel cell power system **16** may be supplied to a steam generator, thermoelectric generator, water heater, absorption chiller, Rankine cycle device, or a combination thereof, or the like. For example, an absorption chiller can use the

heat from the load bank **22** and the fuel cell power system **16** to drive a thermodynamic process whereby water is chilled and distributed for HVAC needs. In this manner, absorption chillers can provide needed cooling capability to various industrial facilities (hospitals, universities, hotels, warehouses, manufacturing facilities, etc.) without significantly contributing to peak electric demand. In this particular case, an absorption chiller can be utilized to cool processing systems that are used to train AI models. Alternatively, heat generated from load bank **22** and/or fuel cell power system **16** may be retained in thermal storage units utilizing molten salt, molten silicon, molten aluminum, graphite thermal media, thermochemical materials, phase change materials, and the like. Heat stored in thermal storage media can be discharged to generate electricity when needed through use of a suitable heat engine (e.g., steam turbine, thermophotovoltaics, etc.). Electricity generated by the heat engine can be used for multiple purposes (e.g., supplying the first energy storage system **18**, the second energy storage system **20**, or any other load as needed).

[0058] The power converter **24** is a bidirectional power converter that connects a secondary load to the power bus **15** (e.g., the power converter **24** is a DC to AC converter in case the system **14** is a DC-coupled system and the secondary load is an AC system). The secondary load is an additional load, such as the utility power grid or another connected microgrid, besides the primary load connected to the load interface converter **26**. The fuel cell power system **16** does not act as the primary power source for the secondary load.

[0059] The power converter **24** allows the secondary load to act as an energy source and storage in addition to the first energy storage system **18** and the second energy storage system **20**. For example, when there is excess power on the power bus **15**, the power converter **24** exports the excess power to the secondary load. Conversely, when there is a shortage of power on the power bus **15**, the power converter **24** brings power from the secondary load to the power bus **15**.

[0060] The load interface converter **26** provides power to the primary load. The primary load may be either an AC or a DC type. In case the system **14** is a DC-coupled system and the load is an AC type, the load interface converter **26** will be a DC-AC converter that converts DC power on the power bus **15** to AC power for the primary load. Conversely, in case the system **14** is a DC-coupled system and the primary load is a DC type, the load interface converter **26** will be a DC-DC converter that converts DC power on the power bus **15** to DC voltage used by the primary load.

[0061] The primary load connected to the load interface converter **26** is mainly powered by the system **14**, more specifically, by the fuel cell power system **16**. Stated differently, the primary load receives the majority of its power from the fuel cell power system **16**. In one embodiment, the primary load is a data center that performs training processes for AI models. As discussed above with respect to FIGS. **1** and **2**, power consumption profiles of training processes for AI models are particularly challenging for the fuel cell power system **16** due to their highly variable loads, and, thus, would greatly benefit from the system **14**. However, the primary load may be any type of load that has variable power consumption besides AI models.

[0062] The controller **28** is communicatively coupled to and controls the various functions of the fuel cell power system **16**, the first energy storage system **18**, the second energy storage system **20**, the load bank **22**, the power converter **24**, and the load interface converter **26**. The controller **28** manages the power balance between different generation modules (e.g., the fuel cell power system **16**), storage modules (e.g., the first energy storage system **18** and the second energy storage system **20**), and loads (e.g., the load bank **22**, the secondary load connected to the power converter **24**, the primary load connected to the load interface converter **26**) of the system **14** in real time.

[0063] The controller **28** continuously measures the current state of charge (SOC) (e.g., current stored charge) of the first energy storage system **18** and the second energy storage system **20**; the power output from the fuel cell power system **16**, the first energy storage system **18**, the second energy storage system **20**, and the secondary load to the power bus **15**; and the power input to the first energy storage system **18**, the second energy storage system **20**, the load bank **22**, the secondary load, and the primary load from the power bus **15**. The controller **28** manages power

flows to and from (e.g., sets power levels input to and output from) each of the fuel cell power system **16**, the first energy storage system **18**, the second energy storage system **20**, the load bank **22**, the secondary load, and the primary load, based on the measurements by the controller **28**. Various operation methods for the controller **28** will be discussed in further detail below.

[0064] The controller **28** may be any type of processor, signal processor, or controller that is able to process data; and may include one or more processors. For example, the controller **28** may be an industrial personal computer (PC), a programmable logic controller (PLC), microcontroller, digital signal processor (DSP), field programmable gate arrays (FPGAs), or other similar technologies.

[0065] The system **14** provides various levels of support for the fuel cell power system **16** to cater to the continuously varying loads of the primary load (e.g., the data center performing training processes for AI models). The system **14** can be configured to maintain a constant power draw from the fuel cell power system **16**, or at least reduce the magnitude of power swings that the fuel cell power system **16** experiences.

[0066] In one embodiment, the controller **28** controls the fuel cell power system **16** to follow the entire load cycle of the primary load. The output of the fuel cell power system **16** increases and decreases in power along with the primary load. Further, in cases where the fuel cell power system **16** is unable to ramp up or increase at the same rate as the primary load demands, an energy storage system provides additional energy to supplement the power provided by the fuel cell power system **16**. In addition, during training processing, the fuel cell power system **16** provides power greater than the power consumption of the primary load in order to recharge the energy storage system.

[0067] For example, FIG. **5** shows power signals for the primary load, the fuel cell power system **16**, and an energy storage system in case the fuel cell power system **16** follows an entire load cycle of the primary load according to an embodiment disclosed herein.

[0068] A power signal **40** indicates power consumption of the primary load, a power signal **42** indicates the power output of the fuel cell power system **16**, a power signal **44** indicates the power output of an energy storage system, and a power signal **46** indicates the SOC of the energy storage system. The vertical axis is an amplitude axis and the horizontal axis is a time axis. Each of the power signals are shown relative to an amplitude value equal to zero.

[0069] The energy storage system may be either the first energy storage system **18** or the second energy storage system **20** depending on the desired energy storage system type. In one embodiment, in case the first energy storage system **18** stores a low total amount of power but has fast charging and discharging times and the second energy storage system **20** stores a large total amount of power but has slow charging and discharging times, the energy storage system in FIG. **5** is the first energy storage system **18**.

[0070] The controller **28** controls the fuel cell power system **16** to follow the entire load of the primary load. For example, referring to FIG. **5**, the controller **28** instructs the fuel cell power system **16** to output power such that the power signal **42**, which is the power output of the fuel cell power system **16**, follows the power signal **40**, which is the power consumption of the primary load. The power signal **40** drops from a load power high value LP_H to a load power low value LP_L at time T**1** and then returns to the load power high value LP_H at time T**2**. Similarly, the power signal **42** is set to drop from a fuel cell power high value FP_H to a fuel cell power low value FP_L at time T**1**, and set again to the fuel cell power high value FP_H at time T**2**. The fuel cell power high value FP_H is substantially equal to the load power high value L_{PH}, and the fuel cell power low value FP_L is substantially equal to the load power low value LP_L.

[0071] In some cases, the fuel cell power system **16** is unable to ramp up or increase power at the same rate as the primary load demands. Namely, the fuel cell power system **16** increases output power at a slower rate than a power consumption increase rate of the primary load. In this situation, additional energy provided by the energy storage system is used to supplement the power provided by the fuel cell power system **16** during the ramp up period. For example, referring to FIG. **5**, there

is a ramp up period between time T**2** and time T**3**, and the power signal **42**, which is the power output of the fuel cell power system **16**, is unable to immediately increase to the fuel cell power high value FP.sub.H. As such, the controller **28** instructs the energy storage system to output additional power to compensate for the shortcoming of the fuel cell power system **16**. Between times T**2** and T**3**, the power signal **44**, which is the power output of the energy storage system, is set such that the total output power of the fuel cell power system **16** and the energy storage system is substantially equal to the power consumption of the primary load. Stated differently, between times T**2** and T**3**, the power signal **44** is equal to the difference between the power signal **40** and the power signal **42**. The power balance between the primary load, the fuel cell power system **16**, and the energy storage system is governed by the following equation:

[00001]

EnergyStorageSystemOutput = PrimaryLoadPowerConsumption - FuelCellPowerSystemOutput

[0072] It is also possible to use energy provided by the secondary load in place of or in addition to the power provided by the energy storage system, to supplement the power provided by the fuel cell power system **16** during the ramp up period.

[0073] As the fuel cell power system **16** ramps up to catch up to the primary load, the output from the energy storage system comes down. The energy storage system stops supplying power to the primary load as soon as the fuel cell power system **16** matches the primary load. For example, referring to FIG. **5**, as the power signal **42** increases to catch up to the power signal **40** between times T**2** and T**3**, the power signal **44** proportionally decreases. When the power signal **42** reaches the power signal **40** at time T**3**, the power signal **44** is set to zero.

[0074] To recharge the energy storage system after supplying power to the primary load, the fuel cell power system **16** provides power greater than the power consumption of the primary load. The excess power from the fuel cell power system **16** is used to recharge the energy storage system for later use. Stated differently, a portion of the power generated by the fuel cell power system **16** is diverted to the energy storage system. For example, referring to FIG. **5**, the energy storage system is discharged between times T**2** and T**3** by an amount indicated by discharge region **48**. At time T**3**, the power signal **42**, which is the power output of the fuel cell power system **16**, is set higher than the power signal **40**, which is the power consumption of the primary load. The additional power indicated by charge region **50** is used to recharge the energy storage system. The discharging of the energy storage system is shown as a positive value in the power signal **44**, which is the power output of the energy storage system. The charging of the energy storage system is shown as a negative value in the power signal **44**. This is also shown by power signal **46**, which is the SOC of the energy storage system. The power signal **46** decreases between times T**2** and T**3** as the energy storage system is discharged, and starts to increase at time T**3** as the energy storage system is recharged by the fuel cell power system **16**.

[0075] Controlling the fuel cell power system **16** to follow the entire load cycle of the primary load is straightforward to implement. For example, an energy storage system with relatively low capacity may be used because the energy storage system is used to support the fuel cell power system **16** for relatively brief ramp up periods, as fuel cell power systems can take about **60** seconds to ramp up from no load to a full load.

[0076] In another embodiment, the controller **28** controls the fuel cell power system **16** to follow a portion of the load cycle of the primary load. The output of the fuel cell power system **16** increases and decreases in power along with the primary load, but is allowed to follow a determined percentage of a load power swing (i.e., a change in power) of the primary load in order to minimize the impact on the life of the fuel cell power system **16**. In addition, during checkpoint processing, excess power generated by the fuel cell power system **16** is stored away or dissipated to maintain the power balance on the power bus **15**.

[0077] For example, FIG. **6** shows power signals for the primary load, the fuel cell power system **16**, and the energy storage system in case the fuel cell power system **16** follows a portion of a load

cycle of the primary load according to an embodiment disclosed herein.

[0078] A power signal **52** indicates power consumption of the primary load connected to the load interface converter **26**, a power signal **54** indicates the power output of the fuel cell power system **16**, a power signal **56** indicates the power output of the energy storage system, a power signal **58** indicates the SOC of the energy storage system, and a power signal **60** indicates excess power generated by the fuel cell power system **16**. The vertical axis is an amplitude axis and the horizontal axis is a time axis. Each of the power signals are shown relative to an amplitude value equal to zero.

[0079] As discussed above, the energy storage system may be either the first energy storage system **18** or the second energy storage system **20** depending on the desired energy storage system type. In one embodiment, the energy storage system in FIG. **6** is the first energy storage system **18**, which stores a low total amount of power but has fast charging and discharging times; and the second energy storage system **20**, which stores a large total amount of power but has slow charging and discharging times, is used in addition to the first energy storage system **18** to store excess power when the first energy storage system **18** is fully charged.

[0080] The controller **28** controls the fuel cell power system **16** to follow a portion of the load of the primary load. For example, referring to FIG. **6**, the controller **28** instructs the fuel cell power system **16** to output power such that the power signal **54** follows a determined portion or percentage of a swing of the power signal **52**, which is the power consumption of the primary load. The power signal **52** drops from a load power high value LP.sub.H to a load power low value LP.sub.L at time T**1** and then returns to the load power high value LP.sub.H at time T**2**. Similarly, the power signal **54** is set to drop from a fuel cell power high value FP.sub.H to a fuel cell power low value FP.sub.L at time T**1**, and set again to the fuel cell power high value FP.sub.H at time T**2**. However, the fuel cell power high value FP.sub.H is lower than the load power high value L.sub.PH, and the fuel cell power low value FP.sub.L is greater than the load power low value LP.sub.L.

[0081] During checkpoint processing between times T**1** and T**2**, the power signal **52**, which is the power consumption of the primary load, is at its lowest value (the load power low value LP.sub.L). The power signal **54**, which is the power output of the fuel cell power system **16**, is set to the fuel cell power low value FP.sub.L, which is higher than the load power low value LP.sub.L, in order to reduce the drop of the power swing of the fuel cell power system **16**, and, thus, minimize the impact on the life of the fuel cell power system **16**.

[0082] Since the fuel cell power low value FP.sub.L is higher than the load power low value LP.sub.L, the fuel cell power low value FP.sub.L generates excess power (e.g., excess power equal to the difference between the fuel cell power low value FP.sub.L and the load power low value LP.sub.L). The power signal **60** indicates excess power generated by the fuel cell power system **16**, and increases to above zero between times T**1** and T**2**. The excess power is either stored away or dissipated to maintain the power balance on the power bus **15**, and, thus, keep voltage levels of the power bus **15** within acceptable limits.

[0083] The first preference to manage the excess power is to store the excess power in the energy storage system (e.g., one or both of the first energy storage system **18** and the second energy storage system **20**). The charging of the energy storage system is shown as a negative value in the power signal **56**, which is the power output of the energy storage system, between times T**1** and T**2**, as well as the increase in the power signal **58**, which is the SOC of the energy storage system, from SOC.sub.Min to SOC.sub.Max between times T**1** and T**2**. The energy storage system is charged by an amount indicated by charge region **62**.

[0084] In case the energy storage system is unable to store any more of the excess power (e.g., the first energy storage system **18** is fully charged or experiencing a partial or full failure), the excess power is exported to another energy storage system (e.g., the second energy storage system **20**).

[0085] In case all the energy storage systems are unable to store any more of the excess power, the

excess power is then exported to the secondary load through the power converter **24**. For example, in case the secondary load is the utility power grid or another connected microgrid, the excess power is converted by the power converter **24** for use by the utility power grid or microgrid.

[0086] In case there is still excess power after the energy storage system and the secondary load, the excess power is diverted to the load bank **22** for conversion to heat energy. As discussed above, the heat energy may be vented to the surrounding environment or reused for various purposes, such as being captured using CHP equipment for HVAC and other heating loads of a building. The amount of excess energy dissipated through the secondary load and the load bank **22** is indicated by dissipation region **64**.

[0087] In case of failure of the load bank **22**, the fuel cell power system **16** may be ramped down to a lower output power.

[0088] During training processing prior to time T**1** and after time T**2**, the power signal **52**, which is the power consumption of the primary load, is at its highest value (the load power high value LP.sub.H). The power signal **54**, which is the power output of the fuel cell power system **16**, is set to the fuel cell power high value FP.sub.H, which is lower than the load power high value L.sub.PH, to ensure that the energy storage system is not fully charged and has some capacity to store the excess power from checkpoint processing as discussed above. For example, similar to the embodiment discussed above with respect to FIG. **5**, the energy storage system is used to supplement the power provided by the fuel cell power system **16** during the ramp up period (e.g., between times T**2** and T**3** in FIG. **6**) because the fuel cell power system **16** is unable to ramp up at the same rate as the primary load. However, the energy consumed by the energy storage system during the ramp up period may not completely drain the energy storage system. Consequently, the energy storage system may be unable to take the excess power from the checkpoint processing. To avoid this, the fuel cell power system **16** outputs power lower than the load of the primary load (e.g., the fuel cell power high value FP.sub.H is set lower than the load power high value LP.sub.H), and the difference between the output power of the fuel cell power system **16** and the load of the primary load is compensated by the energy storage system. As a result, the energy storage system is slightly drained during training processing (e.g., the power signal **56**, which is the power output of the energy storage system, is positive) and almost completely drained at a subsequent checkpoint processing (e.g., the power signal **58**, which is the SOC of the energy storage system, is fully discharged at SOC.sub.Min). The energy storage system is discharged by an amount indicated by discharge region **66**.

[0089] In case the energy storage system is completely drained (e.g., reaches SOC.sub.Min) during training processing and before reaching checkpoint processing, the controller **28** reduces the amount of power dissipated to the load bank **22** and then to the secondary load. If there is still a deficit in power on the power bus **15** for the primary load, the controller **28** increases the output power of the fuel cell power system **16** to the load power high value L.sub.PH.

[0090] When transitioning from training processing to checkpoint processing, the load drop of the primary load (e.g., the drop from the load power high value LP.sub.H to the load power low value LP.sub.L at time T**1** in FIG. **6**) is almost instantaneous. As such, the response time of the energy storage system is critical in order to properly handle excess power generated by the fuel cell power system **16** at the load drop of the primary load. For optimum performance, the energy storage system should have a large amount of storage to store excess power generated by the fuel cell power system **16** and a fast response rate to immediately store the excess power at the load drop. To achieve this, different types of energy storages are used. For example, in one embodiment, the first energy storage system **18** stores a low total amount of power but has fast charging and discharging times, and the second energy storage system **20** stores a large total amount of power but has slow charging and discharging times. The first energy storage system **18**, which is capable of fast charging times, is used to handle excess power at the load drop. Once the first energy storage system **18** is fully charged, the second energy storage system **20**, which has large capacity, is used

to store any remaining excess power.

[0091] Alternatively, the controller **28** controls the fuel cell power system **16** to follow the load cycle of the primary load as discussed above with respect to FIG. **6**. However, the output of the fuel cell power system **16** is ramped down instead of immediately dropped. For example, FIG. **7** shows power signals for the primary load, the fuel cell power system **16**, and the energy storage system in case the fuel cell power system **16** follows a portion of a load cycle of the primary load according to another embodiment disclosed herein.

[0092] FIG. **7** shows the power signal **52** indicating power consumption of the primary load connected to the load interface converter **26**, the power signal **54** indicating the power output of the fuel cell power system **16**, the power signal **56** indicating the power output of the energy storage system, the power signal **58** indicating the SOC of the energy storage system, and the power signal **60** indicating excess power generated by the fuel cell power system **16**, which are discussed above with respect to FIG. **6**.

[0093] In contrast to the embodiment shown in FIG. **6**, the controller **28** sets the power signal **54** of the fuel cell power system **16** to ramp down from the fuel cell power high value FP.sub.H to the fuel cell power low value FP.sub.L between times T**1** and T**4**. The ramp down of the fuel cell power system **16** eases the demand on the energy storage system and allows the energy storage system to have slower charging times. In addition, excess power during the ramp down of the fuel cell power system **16** is diverted to the secondary load and the load bank **22** (shown as dissipation region **64** between times T**1** and T**4**). This approach reduces the overall cost of having multiple different energy storage systems while still improving performance of the fuel cell power system **16**.

[0094] In another embodiment, the controller **28** controls the fuel cell power system **16** to output a constant power level. The output of the fuel cell power system **16** does not increase or decrease in power along with the primary load, but remains the same.

[0095] For example, FIG. **8** shows power signals for the primary load, the fuel cell power system **16**, and the energy storage system in case the fuel cell power system **16** remains at a constant power level according to an embodiment disclosed herein.

[0096] A power signal **68** indicates power consumption of the primary load, a power signal **70** indicates the power output of the fuel cell power system **16**, a power signal **72** indicates the power output of the energy storage system, a power signal **74** indicates the SOC of the energy storage system, and a power signal **76** indicates excess power generated by the fuel cell power system **16**. The vertical axis is an amplitude axis and the horizontal axis is a time axis. Each of the power signals are shown relative to an amplitude value equal to zero.

[0097] As discussed above, the energy storage system may be either the first energy storage system **18** or the second energy storage system **20** depending on the desired energy storage system type. In one embodiment, the energy storage system in FIG. **8** is the first energy storage system **18**, which stores a low total amount of power but has fast charging and discharging times; and the second energy storage system **20**, which stores a large total amount of power but has slow charging and discharging times, is used in addition to the first energy storage system **18** to store excess power when the first energy storage system **18** is fully charged.

[0098] The operating modes and control sections in this embodiment are similar to that of the embodiment discussed above with respect to FIG. **6**. For example, excess power is stored to the energy storage system (indicated by charge region **78**) and then to the secondary load and the load bank **22** (indicated by dissipation region **80**) during checkpoint processing, and the energy storage system is used to supplement the power provided by the fuel cell power system **16** (indicated by discharge region **82**) during training processing.

[0099] In contrast to the embodiment discussed above with respect to FIG. **6**, the controller **28** instead controls the fuel cell power system **16** to output a constant power level. For example, referring to FIG. **8**, the power signal **68**, which is the power consumption of the primary load, drops from a load power high value LP.sub.H to a load power low value LP.sub.L at time T**1** and then

returns to the load power high value LP.sub.H at time T**2**. Regardless, the controller **28** instructs the fuel cell power system **16** to output power such that the power signal **70** remains at the same level FP. In one embodiment, the fuel cell power system **16** outputs a constant power that is less than the load power high value LP.sub.H and greater than the load power low value LP.sub.L.

[0100] The fuel cell power system **16** does not follow the load power variations of the primary load, and outputs substantially constant average load power within desired limits throughout any change in load of the primary load (e.g., checkpoint and training processing). By keeping the fuel cell power system **16** at a substantially constant power output level, the load behavior of the primary load has no impact on the life of the fuel cell power system **16**.

[0101] As discussed above with respect to FIG. **2**, model training processes also undergo software crashes and recoveries and stand-by states that cause additional fluctuations in the load. For example, the load decreases significantly when a software crash occurs and increases significantly upon recovering, and decreases to near zero upon the model training entering a stand-by state.

[0102] A software crash (and recovery process) is an unplanned event that occurs sporadically. Further, the duration of the recovery could last from seconds to several minutes depending on the cause of the software crash. Consequently, software crashes and recoveries are difficult to manage ahead of time similar to training and checkpoint processing discussed above. As such, during a software crash and recovery process, excess power and output power of the fuel cell power system **16** are dynamically handled. In one embodiment, the controller **28** monitors the power balance between the fuel cell power system **16**, the first energy storage system **18**, the second energy storage system **20**, the load bank **22**, the secondary load, and the primary load in real time. In response to detecting excess power on the power bus **15**, the controller **28** stores the excess power to the first energy storage system **18** and/or the second energy storage system **20**, then directs excess power to the secondary load in case the first energy storage system **18** and/or the second energy storage system **20** are full, and then to the load bank **22** if the system is unable to export power to the secondary load. In case the secondary load and/or load bank are unable to accommodate excess power from fuel cell power system **16** (e.g., due to being full or due to failure), the controller **28** decreases the output power of the fuel cell power system **16** to a lower level as a last resort.

[0103] A stand-by state is a planned event, but may last several hours to several days between training jobs. The excess power generated by the fuel cell power system **16** during the stand-by state is stored in the first energy storage system **18** and the second energy storage system **20** when the first energy storage system **18** is fully charged. However, extended durations of the stand-by state may make it unpractical for excess power to be stored in energy storage systems alone. As such, for stand-by states with extended durations, once the first energy storage system **18** and the second energy storage system **20** are fully charged, the controller **28** directs excess power to the secondary load, directs excess power to the load bank **22**, decreases the output power of the fuel cell power system **16** to a lower level, or performs a combination thereof.

[0104] FIGS. **9**, **9**A, and **9**B show a method **84** of managing the power balance of the system **14** according to an embodiment disclosed herein. The method **84** is performed by the controller **28**, which monitors and manages the power balance between the fuel cell power system **16**, the first energy storage system **18**, the second energy storage system **20**, the load bank **22**, the secondary load connected to the power converter **24**, and the primary load connected to the load interface converter **26**.

[0105] In block **86**, the controller **28** determines powers and statuses of all of the components of the system **14**. The controller **28** measures the current SOCs of the first energy storage system **18** and the second energy storage system **20**; the power output from the fuel cell power system **16**, the first energy storage system **18**, the second energy storage system **20**, and the secondary load to the power bus **15**; and the power provided to the first energy storage system **18**, the second energy storage system **20**, the load bank **22**, the secondary load, and the primary load from the power bus

15.

[0106] In block **88**, the controller **28** determines the total amount of power on the power bus **15**. In one embodiment, the controller **28** determines the total amount of power by adding all incoming power from the fuel cell power system **16**, the first energy storage system **18**, the second energy storage system **20**, and the secondary load; and subtracting all outgoing power to the first energy storage system **18**, the second energy storage system **20**, the load bank **22**, the secondary load, and the primary load.

[0107] In block **90**, the controller **28** determines or detects if there is excess power on the power bus **15**. In one embodiment, the controller **28** determines there is excess power on the power bus **15** in case the total amount of power on the power bus **15** from block **88** is greater than or equal to a determined excess threshold value. In case the controller **28** determines there is not excess power on the power bus **15** (e.g., the total amount of power is less than the excess threshold value), the method **84** moves to block **92**. Conversely, in case the controller **28** determines there is excess power on the power bus **15** (e.g., the total amount of power is greater than or equal to the excess threshold value), the method **84** moves to block **94**. In one embodiment, the excess threshold value is equal to, greater than, or within a threshold value of a current power consumption of the primary load.

[0108] In block **92**, the controller **28** determines or detects if there is a deficit in power on the power bus **15**. In one embodiment, the controller **28** determines there is a deficit in power on the power bus **15** in case the total amount of power on the power bus **15** from block **88** is less than or equal to a determined deficit threshold value. In case the controller **28** determines there is not a deficit in power on the power bus **15** (e.g., the total amount of power is greater than the deficit threshold value), the method **84** moves to block **96**. Conversely, in case the controller **28** determines there is a deficit in power on the power bus **15** (e.g., the total amount of power is less than or equal to the deficit threshold value), the method **84** moves to block **98**. In one embodiment, the deficit threshold value is less than a current power consumption of the primary load and less than the excess threshold value.

[0109] In block **96**, the method **84** is repeated and restarts at block **86**.

[0110] Blocks **98**, **100**, **102**, **104**, **106**, **108**, **110**, **112**, and **114** discussed below are performed in order to reduce the deficit in power on the power bus **15**.

[0111] In block **98**, the controller **28** determines if power output to the load bank **22** can be reduced. In one embodiment, the controller **28** determines power output to the load bank **22** can be reduced in case the power output to the load bank **22** is greater than or equal to a determined load bank threshold value. In case the controller **28** determines power output to the load bank **22** can be reduced (e.g., the power output to the load bank **22** is greater than or equal to the load bank threshold value), the method **84** moves to block **100**. Conversely, in case the controller **28** determines power output to the load bank **22** cannot be reduced (e.g., the power output to the load bank **22** is less than the load bank threshold value), the method **84** moves to block **102**.

[0112] In block **100**, the controller **28** reduces the power output to the load bank **22** from the power bus **15**. As a result, power increases on the power bus **15**, and the additional power is used to compensate for the deficit in power. For example, the additional power originally diverted to the load bank **22** is used to provide power to the primary load, charge the first energy storage system **18**, charge the second energy storage system **20**, or a combination thereof. Once instructions are provided to reduce power to the load bank, the method **84** proceeds to block **96**, where the method **84** is repeated and restarts at block **86**.

[0113] In block **102**, the controller **28** determines if power output to the secondary load connected to the power converter **24** can be reduced. As discussed above, the secondary load may be a utility power grid or another connected microgrid capable of both storing, using, and/or generating power. In one embodiment, the controller **28** determines power output to the secondary load can be reduced in case the power output to the secondary load is greater than or equal to a determined

secondary load threshold value. In case the controller **28** determines power output to the secondary load can be reduced (e.g., the power output to the secondary load is greater than or equal to the secondary load threshold value), the method **84** moves to block **104**. Conversely, in case the controller **28** determines power output to the secondary load cannot be reduced (e.g., the power output to the secondary load is less than the secondary load threshold value), the method **84** moves to block **106**.

[0114] In block **104**, the controller **28** reduces the power output to the secondary load from the power bus **15**. As a result, power increases on the power bus **15**, and the additional power is used to compensate for the deficit in power. For example, the additional power originally diverted to the secondary load is used to provide power to the primary load, charge the first energy storage system **18**, charge the second energy storage system **20**, or a combination thereof. Once instructions are provided to reduce power output to the secondary load, the method **84** proceeds to block **96**, where the method **84** is repeated and restarts at block **86**.

[0115] In block **106**, the controller **28** determines if the discharging power from the first energy storage system **18** or the second energy storage system **20** can be increased. Stated differently, the controller **28** determines whether additional power can be provided from the first energy storage system **18** or the second energy storage system **20** to the power bus **15**. In one embodiment, the controller **28** determines the discharging power from the first energy storage system **18** can be increased in case the SOC of the first energy storage system **18** is greater than or equal to a determined first SOC threshold value, and determines the discharging power from the second energy storage system **20** can be increased in case the SOC of the second energy storage system **20** is greater than or equal to a determined second SOC threshold value. In case the controller **28** determines the discharging power from the first energy storage system **18** or the second energy storage system **20** can be increased (e.g., the SOC is greater than or equal to the corresponding SOC threshold value), the method **84** moves to block **108**. Conversely, in case the controller **28** determines the discharging power from the first energy storage system **18** or the second energy storage system **20** cannot be increased (e.g., the SOC is less than the corresponding SOC threshold value), the method **84** moves to block **110**. The first SOC threshold value and the second SOC threshold value may be equal or different values.

[0116] In block **108**, the controller **28** increases the discharging power from the first energy storage system **18** to the power bus **15** in response to determining the discharging power from the first energy storage system **18** can be increased, and increases the discharging power from the second energy storage system **20** in response to determining the discharging power from the second energy storage system **20** can be increased. As a result, power increases on the power bus **15**, and the additional power is used to compensate for the deficit in power. For example, the additional power is used to provide power to the primary load. Once instructions are provided to increase the discharging power from the first energy storage system **18** and/or the second energy storage system **20**, the method **84** proceeds to block **96**, where the method **84** is repeated and restarts at block **86**.

[0117] In block **110**, the controller **28** determines if power imported from the secondary load can be increased. Stated differently, the controller **28** determines whether additional power can be provided from the secondary load to the power bus **15**. In one embodiment, the controller **28** determines power imported from the secondary load can be increased in case the available power of the secondary load (e.g., the total amount of power stored by the secondary load or the current amount of power being generated by the secondary load) is greater than or equal to a determined available power threshold value. In case the controller **28** determines power imported from the secondary load can be increased (e.g., the available power of the secondary load is greater than or equal to the determined available power threshold value), the method **84** moves to block **112**. Conversely, in case the controller **28** determines power imported from the secondary load cannot be increased (e.g., the available power of the secondary load is less than the determined available power threshold value), the method **84** moves to block **114**.

[0118] In block **112**, the controller **28** increases the power imported from the secondary load to the power bus **15**. As a result, power increases on the power bus **15**, and the additional power is used to compensate for the deficit in power. For example, the additional power is used to provide power to the primary load, charge the first energy storage system **18**, charge the second energy storage system **20**, or a combination thereof. The method **84** then moves to block **96**, where the method **84** is repeated and restarts at block **86**.

[0119] In block **114**, the controller **28** increases the power output of the fuel cell power system **16** to the power bus **15** in order to compensate for the deficit on the power bus **15**. The additional power is used to provide power to the primary load, charge the first energy storage system **18**, charge the second energy storage system **20**, or a combination thereof. The method **84** then moves to block **96**, where the method **84** is repeated and restarts at block **86**.

[0120] As a result of blocks **98**, **100**, **102**, **104**, **106**, **108**, **110**, **112**, and **114**, the fuel cell power system **16** is used as a last resort to compensate a deficit in power on the power bus **15**. The power output of fuel cell power system **16** is increased in case the deficit cannot be compensated by adjusting powers of the load bank **22**, the secondary load, the first energy storage system **18**, and the second energy storage system **20**. Accordingly, power swings in the output of the fuel cell power system **16** are reduced, and degradation of the life of the fuel cell power system **16** is minimized.

[0121] Returning to block **90**, as discussed above, the method **84** moves to block **94** in case the controller **28** determines there is excess power on the power bus **15**. Blocks **94**, **116**, **118**, **120**, **122**, **124**, and **126** discussed below are performed in order to manage the excess power on the power bus **15**.

[0122] In block **94**, the controller **28** determines if the charging power to the first energy storage system **18** or the second energy storage system **20** can be increased. Stated differently, the controller **28** determines whether additional power can be stored to the first energy storage system **18** or the second energy storage system **20**. In one embodiment, the controller **28** determines the charging power to the first energy storage system **18** can be increased in case the SOC of the first energy storage system **18** is less than or equal to a determined first SOC threshold value, and determines the charging power to the second energy storage system **20** can be increased in case the SOC of the second energy storage system **20** is less than or equal to a determined second SOC threshold value. In case the controller **28** determines the charging power to the first energy storage system **18** or the second energy storage system **20** can be increased (e.g., the SOC is less than or equal to the corresponding SOC threshold value), the method **84** moves to block **116**. Conversely, in case the controller **28** determines the charging power to the first energy storage system **18** or the second energy storage system **20** cannot be increased (e.g., the SOC is greater than the corresponding SOC threshold value), the method **84** moves to block **118**. The first SOC threshold value and the second SOC threshold value may be equal or different values.

[0123] In block **116**, the controller **28** increases the charging power from the power bus **15** to the first energy storage system **18** in response to determining the charging power to the first energy storage system **18** can be increased, and increases the charging power to the second energy storage system **20** in response to determining the charging power to the second energy storage system **20** can be increased. As a result, excess power on the power bus **15** is utilized and diverted to the first energy storage system **18** and/or the second energy storage system **20**. As discussed above, the energy stored in the first energy storage system **18** and the second energy storage system **20** is also used to supplement the power provided by the fuel cell power system **16**. Once instructions are provided to increase the charging power to the first energy storage system **18** and/or the second energy storage system **20**, the method **84** proceeds to block **96**, where the method **84** is repeated and restarts at block **86**.

[0124] In block **118**, the controller **28** determines if power exported to the secondary load can be increased. Stated differently, the controller **28** determines whether additional power can be

provided to the secondary load from the power bus **15**. In one embodiment, the controller **28** determines power exported to the secondary load can be increased in case available power of the secondary load (e.g., the total amount of power stored by the secondary load or the current amount of power being generated by the secondary load) is less than or equal to a determined available power threshold value. In case the controller **28** determines power exported to the secondary load can be increased (e.g., the available power of the secondary load is less than or equal to the determined available power threshold value), the method **84** moves to block **120**. Conversely, in case the controller **28** determines power exported to the secondary load cannot be increased (e.g., the available power of the secondary load is greater than the determined available power threshold value), the method **84** moves to block **122**.

[0125] In block **120**, the controller **28** increases the power exported from the power bus **15** to the secondary load. As a result, excess power on the power bus **15** is diverted to the secondary load. The energy provided to the secondary load may be later used to supplement the power provided by the fuel cell power system **16** or used by the secondary load for its own processing. Once instructions are provided to increase the power to the secondary load, the method **84** proceeds to block **96**, where the method **84** is repeated and restarts at block **86**.

[0126] In block **122**, the controller **28** determines if power output to the load bank **22** from the power bus **15** can be increased. In one embodiment, the controller **28** determines power output to the load bank **22** can be increased in case the power output to the load bank **22** is less than or equal to a determined load bank threshold value. In case the controller **28** determines power output to the load bank **22** can be increased (e.g., the power output to the load bank **22** is less than or equal to the load bank threshold value), the method **84** moves to block **124**. Conversely, in case the controller **28** determines power output to the load bank **22** cannot be increased (e.g., the power output to the load bank **22** is greater than the load bank threshold value), the method **84** moves to block **126**.

[0127] In block **124**, the controller **28** increases the power output from the power bus **15** to the load bank **22**. As a result, excess power on the power bus **15** is diverted to the load bank **22**. As discussed above, the load bank **22** converts the excess power to heat energy, which may be left to a surrounding environment or captured using CHP equipment for HVAC and other heating loads of a building. The method **84** then moves to block **96**, where the method **84** is repeated and restarts at block **86**.

[0128] In block **126**, the controller **28** decreases the power output of the fuel cell power system **16** to the power bus **15** in order to reduce the amount of power on the power bus **15**. The method **84** then moves to block **96**, where the method **84** is repeated and restarts at block **86**.

[0129] As a result of blocks **94**, **116**, **118**, **120**, **122**, **124**, and **126**, the fuel cell power system **16** is used as a last resort to reduce the excess power on the power bus **15**. The power output of fuel cell power system **16** is decreased in case the excess power cannot be reduced by adjusting powers of the load bank **22**, the secondary load, the first energy storage system **18**, and the second energy storage system **20**. Accordingly, power swings in the output of the fuel cell power system **16** are reduced, and degradation on the life of the fuel cell power system **16** is minimized.

[0130] The various embodiments disclosed herein provide a system architecture and control methods that employ fuel cell-based power generation as the primary energy source. The system utilizes energy storage systems, load banks, and other types of loads to supplement power output by the fuel cell system, as well as store any excess power generated by the fuel cell system. As a result of the various supporting modules and technologies, swings in the power output by the fuel cell system are minimized and the life of the fuel cell power modules may be extended.

[0131] A system may be summarized as including: a fuel cell power system configured to output a first power signal having a first power level to a load having a power consumption level; and a first energy storage system configured to: output a second power signal to the load in case the first power level is less than the power consumption level; and receive a third power signal from the fuel cell power system in case the first power level is greater than the power consumption level.

[0132] The load may include processing systems for training artificial intelligence models.

[0133] The system may further include: a controller configured to determine the first power level of the first power signal and the power consumption level of the load; and set power levels of the second power signal and the third power signal based on the first power level and the power consumption level.

[0134] The system may further include: a load bank configured to convert power generated by the fuel cell power system to heat energy in case the first power level is greater than the power consumption level.

[0135] The system may further include: a converter configured to convert power generated by the fuel cell power system to power for a grid external to the system in case the first power level is greater than the power consumption level.

[0136] The system may further include: a converter configured to convert power generated by the fuel cell power system to power for the load.

[0137] The system may further include: a second energy storage system having slower discharging and charging times than the first energy storage system and greater power capacity than the first energy storage system, the second energy storage system configured to receive a fourth power signal from the fuel cell power system in case the first power level is greater than the power consumption level and the first energy storage system is charged.

[0138] The fuel cell power system may include a plurality of power modules, each of the plurality of power modules including a hot box.

[0139] Each hot box may include one or more fuel cell stacks.

[0140] The one or more fuel cell stacks may include solid oxide fuel cells interleaved with conductive interconnects.

[0141] A system may be summarized as including: a fuel cell power system configured to output a first power signal to a load; and an energy storage system configured to: output a second power signal to the load in case a power level of the first power signal is smaller than a power consumption of the load; and store power generated by the fuel cell power system in case the power level of the first power signal is larger than the power consumption of the load.

[0142] The load may include processing systems for training one or more artificial intelligence models, the energy storage system may output the second power signal to the load in response to checkpoint processing being performed for the one or more artificial intelligence models, and the energy storage system may store the power generated by the fuel cell power system in response to training processing being performed for the one or more artificial intelligence models.

[0143] The fuel cell power system may be configured to: decrease the power level of the first power signal in response to a decrease in the power consumption of the load; and increase the power level of the first power signal in response to an increase in the power consumption of the load.

[0144] The energy storage system may output the second power signal in case the power level of the first power signal is increased at a first rate and the power consumption of the load is increased at a second rate faster than the first rate, and a power level of the second power signal may be set based on a difference between power levels of the power consumption of the load and the first power signal.

[0145] The energy storage system may store the power generated by the fuel cell power system in case the power level of the first power signal is decreased at a first rate and the power consumption of the load is decreased at a second rate faster than the first rate.

[0146] The system may further include: a load bank configured to convert power generated by the fuel cell power system to heat energy in case the power level of the first power signal is larger than the power consumption of the load.

[0147] The system may further include: a converter configured to convert power generated by the fuel cell power system to power for a grid external to the system in case the power level of the first

power signal is larger than the power consumption of the load.

[0148] The first power signal may have a substantially constant power level.

[0149] Heat energy generated by the fuel cell power system may be supplied to an absorption chiller to cool processing systems.

[0150] Heat energy generated by the load bank, or the fuel cell power system, or both the load bank and the fuel cell power system may be supplied to a steam generator, a thermoelectric generator, a water heater, an absorption chiller, a Rankine cycle device, or a combination thereof.

[0151] A method may be summarized as including: determining, by a controller, a total amount of power on a power bus that connects a fuel cell power system, one or more energy storage systems, and a load to each other; detecting, by the controller, a deficit in power on the power bus based on the total amount of power and a power consumption of the load; increasing, by the controller, power on the power bus in response to detecting the deficit; detecting, by the controller, excess power on the power bus based on the total amount of power and the power consumption of the load; and decreasing, by the controller, power on the power bus in response to detecting the excess power.

[0152] The load may include processing systems for training an artificial intelligence model.

[0153] A load bank, which is configured to convert power to heat energy, may be connected to the power bus, and the increasing of the power on the power bus may include reducing power output to the load bank from the power bus.

[0154] An external grid may be connected to the power bus, and the increasing of the power on the power bus may include reducing power output to the external grid from the power bus.

[0155] The increasing of the power on the power bus may include increasing power output from the one or more energy storage systems to the power bus.

[0156] An external grid may be connected to the power bus, and the increasing of the power on the power bus may include increasing power output from the external grid to the power bus.

[0157] The increasing of the power on the power bus may include increasing power output from the fuel cell power system to the power bus.

[0158] The decreasing of the power on the power bus may include increasing power output from the power bus to the one or more energy storage systems.

[0159] An external grid is connected to the power bus, and the decreasing of the power on the power bus may include increasing power output from the power bus to the external grid.

[0160] A load bank, which is configured to convert power to heat energy, may be connected to the power bus, and the decreasing of the power on the power bus may include increasing power output from the power bus to the load bank.

[0161] The decreasing of the power on the power bus may include reducing power output from the fuel cell power system to the power bus.

[0162] The various embodiments described above can be combined to provide further embodiments. These and other changes can be made to the embodiments in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

Claims

1. A system, comprising: a fuel cell power system configured to output a first power signal having a first power level to a load having a power consumption level; and a first energy storage system configured to: output a second power signal to the load in case the first power level is less than the power consumption level; and receive a third power signal from the fuel cell power system in case the first power level is greater than the power consumption level.

2. The system of claim 1 wherein the load includes processing systems for training artificial intelligence models.

3. The system of claim 1, further comprising: a controller configured to determine the first power level of the first power signal and the power consumption level of the load; and set power levels of the second power signal and the third power signal based on the first power level and the power consumption level.

4. The system of claim 1, further comprising: a load bank configured to convert power generated by the fuel cell power system to heat energy in case the first power level is greater than the power consumption level.

5. The system of claim 1, further comprising: a converter configured to convert power generated by the fuel cell power system to power for a grid external to the system in case the first power level is greater than the power consumption level.

6. The system of claim 1, further comprising: a converter configured to convert power generated by the fuel cell power system to power for the load.

7. The system of claim 1, further comprising: a second energy storage system having slower discharging and charging times than the first energy storage system and greater power capacity than the first energy storage system, the second energy storage system configured to receive a fourth power signal from the fuel cell power system in case the first power level is greater than the power consumption level and the first energy storage system is charged.

8. The system of claim 1 wherein the fuel cell power system includes a plurality of power modules, each of the plurality of power modules including a hot box.

9. The system of claim 8 wherein each hot box includes one or more fuel cell stacks.

10. The system of claim 9 wherein the one or more fuel cell stacks include solid oxide fuel cells interleaved with conductive interconnects.

11. A system, comprising: a fuel cell power system configured to output a first power signal to a load; and an energy storage system configured to: output a second power signal to the load in case a power level of the first power signal is smaller than a power consumption of the load; and store power generated by the fuel cell power system in case the power level of the first power signal is larger than the power consumption of the load.

12. The system of claim 11 wherein the load includes processing systems for training one or more artificial intelligence models, the energy storage system outputs the second power signal to the load in response to checkpoint processing being performed for the one or more artificial intelligence models, and the energy storage system stores the power generated by the fuel cell power system in response to training processing being performed for the one or more artificial intelligence models.

13. The system of claim 11 wherein the fuel cell power system is configured to: decrease the power level of the first power signal in response to a decrease in the power consumption of the load; and increase the power level of the first power signal in response to an increase in the power consumption of the load.

14. The system of claim 13 wherein the energy storage system outputs the second power signal in case the power level of the first power signal is increased at a first rate and the power consumption of the load is increased at a second rate faster than the first rate, and a power level of the second power signal is set based on a difference between power levels of the power consumption of the load and the first power signal.

15. The system of claim 13 wherein the energy storage system stores the power generated by the fuel cell power system in case the power level of the first power signal is decreased at a first rate and the power consumption of the load is decreased at a second rate faster than the first rate.

16. The system of claim 11, further comprising: a load bank configured to convert power generated by the fuel cell power system to heat energy in case the power level of the first power signal is larger than the power consumption of the load.

17. The system of claim 11, further comprising: a converter configured to convert power generated

by the fuel cell power system to power for a grid external to the system in case the power level of the first power signal is larger than the power consumption of the load.

18. The system of claim 11 wherein the first power signal has a substantially constant power level.

19. The system of claim 12 wherein heat energy generated by the fuel cell power system is supplied to an absorption chiller to cool processing systems.

20. The system of claim 16 wherein heat energy generated by the load bank, or the fuel cell power system, or both the load bank and the fuel cell power system is supplied to a steam generator, a thermoelectric generator, a water heater, an absorption chiller, a Rankine cycle device, or a combination thereof.

21. A method, comprising: determining, by a controller, a total amount of power on a power bus that connects a fuel cell power system, one or more energy storage systems, and a load to each other; detecting, by the controller, a deficit in power on the power bus based on the total amount of power and a power consumption of the load; increasing, by the controller, power on the power bus in response to detecting the deficit; detecting, by the controller, excess power on the power bus based on the total amount of power and the power consumption of the load; and decreasing, by the controller, power on the power bus in response to detecting the excess power.

22. The method of claim 21 wherein the load includes processing systems for training an artificial intelligence model.

23. The method of claim 21 wherein a load bank, which is configured to convert power to heat energy, is connected to the power bus, and the increasing of the power on the power bus includes reducing power output to the load bank from the power bus.

24. The method of claim 21 wherein an external grid is connected to the power bus, and the increasing of the power on the power bus includes reducing power output to the external grid from the power bus.

25. The method of claim 21 wherein the increasing of the power on the power bus includes increasing power output from the one or more energy storage systems to the power bus.

26. The method of claim 21 wherein an external grid is connected to the power bus, and the increasing of the power on the power bus includes increasing power output from the external grid to the power bus.

27. The method of claim 21 wherein the increasing of the power on the power bus includes increasing power output from the fuel cell power system to the power bus.

28. The method of claim 21 wherein the decreasing of the power on the power bus includes increasing power output from the power bus to the one or more energy storage systems.

29. The method of claim 21 wherein an external grid is connected to the power bus, and the decreasing of the power on the power bus includes increasing power output from the power bus to the external grid.

30. The method of claim 21 wherein a load bank, which is configured to convert power to heat energy, is connected to the power bus, and the decreasing of the power on the power bus includes increasing power output from the power bus to the load bank.

31. The method of claim 21 wherein the decreasing of the power on the power bus includes reducing power output from the fuel cell power system to the power bus.