

**SYSTEMS, DEVICES, AND METHODS FOR RAIL-BASED AND OTHER ELECTRIC
VEHICLES WITH MODULAR CASCADED ENERGY SYSTEMS**

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of, and priority to, U.S. Provisional Application No. 63/025,099, filed May 14, 2020, U.S. Provisional Application No. 63/029,368, filed May 22, 2020, and U.S. Provisional Application No. 63/084,293, filed September 28, 2020, all of which are incorporated by reference herein in their entireties and for all purposes.

FIELD

[0002] The subject matter described herein relates generally to systems, devices, and methods for rail-based and other electric vehicles having modular cascaded energy systems.

BACKGROUND

[0003] For electric vehicles that operate on a rail, power to drive the electric motors is provided by a charge source. This charge source is typically in the form of a high-voltage conductor that is present along a span of track. The charge source can be an overhead line, such as a catenary, a ground-level power supply such as third rail, or a belowground supplies such as a conduit. The rail-based EV receives power from this charge source by means of a conductive element (e.g., a pantograph or plow) that remains in continuous contact with the charge source as the EV is moving. In some cases, the rail-based EV uses a static approach and extends a conductor into contact with the charge source when the vehicle is at rest, charges while the vehicle is not moving, and withdraws the conductor from contact with the charge source prior to resuming movement.

[0004] Charge source lines that run continually alongside the rail require additional physical space and infrastructure, can be unaesthetic, can pose risks to the public in the environment, and are costly to build and maintain in a safe manner. Conventional rail-based EVs can be configured with an energy storage system that stores power for operating the motors and allows the rail-based EV to traverse spans of rail where no charge source is present. However, these rail-based EVs can suffer from limitations in range, limitations in lifespan of the energy sources, and lack of flexibility in implementation for rail-based EVs with numerous motors and auxiliary loads requiring electric power.

[0005] As such, needs exist for improved energy systems for use in rail-based electric vehicles and related vehicles and stationary applications.

SUMMARY

[0006] Example embodiments of systems, devices, and methods are provided herein for electric vehicles that are subject to intermittent charging, such as rail-based electric vehicles, having one or more modular cascaded energy systems. The one or more modular systems can be configured to supply multiphase, single phase, and/or DC power to numerous motor and auxiliary loads of the EV. If multiple systems or subsystems are present in the EV, they can be interconnected to exchange energy between them in numerous different ways, such as through lines designated for carrying power from the intermittently connected charge source or through the presence of modules interconnected between arrays of the subsystems. The subsystems can be configured as subsystems that supply power for motor loads alone, motor loads in combination with auxiliary loads, and auxiliary loads alone.

[0007] Each module of the subsystems can be configured with multiple converters and one or more energy sources such that the modules can receive relatively high voltage signals from the intermittently connected charge source and modify that voltage with one or more converters to charge the one or more energy sources, and also such that the modules can utilize another converter two convert the DC voltage from the one or more energy sources into an AC output voltage for powering the one or more loads of the EV. The charging can occur while the EV is moving, such as with a rail-based EV receiving power from an overhead, ground-level, or belowground charge source. The embodiments are applicable to other applications as well.

[0008] Other systems, devices, methods, features and advantages of the subject matter described herein will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features and advantages be included within this description, be within the scope of the subject matter described herein, and be protected by the accompanying claims. In no way should the features of the example embodiments be construed as limiting the appended claims, absent express recitation of those features in the claims.

BRIEF DESCRIPTION OF FIGURES

[0009] The details of the subject matter set forth herein, both as to its structure and operation, may be apparent by study of the accompanying figures, in which like reference numerals refer to like parts. The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the subject matter. Moreover, all illustrations are intended to convey concepts, where relative sizes, shapes and other detailed attributes may be illustrated schematically rather than literally or precisely.

[0010] FIGs. 1A-1C are block diagrams depicting example embodiments of a modular energy system.

[0011] FIGs. 1D-1E are block diagrams depicting example embodiments of control devices for an energy system.

[0012] FIGs. 1F-1G are block diagrams depicting example embodiments of modular energy systems coupled with a load and a charge source.

[0013] FIGs. 2A-2B are block diagrams depicting example embodiments of a module and control system within an energy system.

[0014] FIG. 2C is a block diagram depicting an example embodiment of a physical configuration of a module.

[0015] FIG. 2D is a block diagram depicting an example embodiment of a physical configuration of a modular energy system.

[0016] FIGs. 3A-3C are block diagrams depicting example embodiments of modules having various electrical configurations.

[0017] FIGs. 4A-4F are schematic views depicting example embodiments of energy sources.

[0018] FIGs. 5A-5C are schematic views depicting example embodiments of energy buffers.

[0019] FIGs. 6A-6C are schematic views depicting example embodiments of converters.

[0020] FIGs. 7A-7E are block diagrams depicting example embodiments of modular energy systems having various topologies.

[0021] FIG. 8A is a plot depicting an example output voltage of a module.

[0022] FIG. 8B is a plot depicting an example multilevel output voltage of an array of modules.

[0023] FIG. 8C is a plot depicting an example reference signal and carrier signals usable in a pulse width modulation control technique.

[0024] FIG. 8D is a plot depicting example reference signals and carrier signals usable in a pulse width modulation control technique.

[0025] FIG. 8E is a plot depicting example switch signals generated according to a pulse width modulation control technique.

[0026] FIG. 8F is a plot depicting an example multilevel output voltage generated by superposition of output voltages from an array of modules under a pulse width modulation control technique.

[0027] FIGs. 9A-9B are block diagrams depicting example embodiments of controllers for a modular energy system.

[0028] FIG. 10A is a block diagram depicting an example embodiment of a multiphase modular energy system having interconnection module.

[0029] FIG. 10B is a schematic diagram depicting an example embodiment of an interconnection module in the multiphase embodiment of FIG. 10A.

[0030] FIG. 10C is a block diagram depicting an example embodiment of a modular energy system having two subsystems connected together by interconnection modules.

[0031] FIG. 10D is a block diagram depicting an example embodiment of a three-phase modular energy system having interconnection modules supplying auxiliary loads.

[0032] FIG. 10E is a schematic view depicting an example embodiment of the interconnection modules in the multiphase embodiment of FIG. 10D.

[0033] FIG. 10F is a block diagram depicting another example embodiment of a three-phase modular energy system having interconnection modules supplying auxiliary loads.

[0034] FIG. 11A is an illustration depicting an example route of an electric rail-based vehicle.

[0035] FIG. 11B is a block diagram depicting an example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

[0036] FIG. 11C is a side diagram depicting an example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

[0037] FIG. 11D is a block diagram depicting another example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

[0038] FIG. 11E is a side diagram depicting another example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

[0039] FIG. 11F is a block diagram depicting another example embodiment of an electrical layout of a modular energy system for an electric rail-based vehicle.

[0040] FIGs. 12A-12B are block diagrams depicting example embodiments of modules for use in a modular energy system.

[0041] FIGs. 13A-13C are schematic diagrams depicting example embodiments of modules for use in a modular energy system.

[0042] FIGs. 14A-14B are block diagrams depicting example embodiments of modular energy system topologies.

[0043] FIGs. 14C-14D are schematic diagrams depicting example embodiments of interconnection modules for use in a modular energy system.

[0044] FIG. 15 is a block diagram depicting an example embodiment of a modular energy system topology.

[0045] FIG. 16 is a schematic diagram depicting another example embodiment of an interconnection module.

DETAILED DESCRIPTION

[0046] Before the present subject matter is described in detail, it is to be understood that this disclosure is not limited to the particular embodiments described, as such may, of course, vary. The terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting, since the scope of the present disclosure will be limited only by the appended claims.

[0047] Before describing the example embodiments pertaining to modular energy systems implemented within rail-based and other applications relying on intermittent charging, it is first useful to describe these underlying systems in greater detail. With reference to FIGs. 1A through 10F, the following sections describe various applications in which embodiments of the modular energy systems can be implemented, embodiments of control systems or devices for the modular

energy systems, configurations of the modular energy system embodiments with respect to charging sources and loads, embodiments of individual modules, embodiments of topologies for arrangement of the modules within the systems, embodiments of control methodologies, embodiments of balancing operating characteristics of modules within the systems, and embodiments of the use of interconnection modules.

Examples of Applications

[0048] Stationary applications are those in which the modular energy system is located in a fixed location during use, although it may be capable of being transported to alternative locations when not in use. The module-based energy system resides in a static location while providing electrical energy for consumption by one or more other entities, or storing or buffering energy for later consumption. Examples of stationary applications in which the embodiments disclosed herein can be used include, but are not limited to: energy systems for use by or within one or more residential structures or locales, energy systems for use by or within one or more industrial structures or locales, energy systems for use by or within one or more commercial structures or locales, energy systems for use by or within one or more governmental structures or locales (including both military and non-military uses), energy systems for charging the mobile applications described below (e.g., a charge source or a charging station), and systems that convert solar power, wind, geothermal energy, fossil fuels, or nuclear reactions into electricity for storage. Stationary applications often supply loads such as grids and microgrids, motors, and data centers. A stationary energy system can be used in either a storage or non-storage role.

[0049] Mobile applications, sometimes referred to as traction applications, are generally ones where a module-based energy system is located on or within an entity, and stores and provides electrical energy for conversion into motive force by a motor to move or assist in moving that entity. Examples of mobile entities with which the embodiments disclosed herein can be used include, but are not limited to, electric and/or hybrid entities that move over or under land, over or under sea, above and out of contact with land or sea (e.g., flying or hovering in the air), or through outer space. Examples of mobile entities with which the embodiments disclosed herein can be used include, but are not limited to, vehicles, trains, trams, ships, vessels, aircraft, and spacecraft. Examples of mobile vehicles with which the embodiments disclosed herein can be used include, but are not limited to, those having only one wheel or track, those having only two-

wheels or tracks, those having only three wheels or tracks, those having only four wheels or tracks, and those having five or more wheels or tracks. Examples of mobile entities with which the embodiments disclosed herein can be used include, but are not limited to, a car, a bus, a truck, a motorcycle, a scooter, an industrial vehicle, a mining vehicle, a flying vehicle (e.g., a plane, a helicopter, a drone, etc.), a maritime vessel (e.g., commercial shipping vessels, ships, yachts, boats or other watercraft), a submarine, a locomotive or rail-based vehicle (e.g., a train, a tram, etc.), a military vehicle, a spacecraft, and a satellite.

[0050] In describing embodiments herein, reference may be made to a particular stationary application (e.g., grid, micro-grid, data centers, cloud computing environments) or mobile application (e.g., an electric car). Such references are made for ease of explanation and do not mean that a particular embodiment is limited for use to only that particular mobile or stationary application. Embodiments of systems providing power to a motor can be used in both mobile and stationary applications. While certain configurations may be more suitable to some applications over others, all example embodiments disclosed herein are capable of use in both mobile and stationary applications unless otherwise noted.

Examples of Module-based Energy Systems

[0051] FIG. 1A is a block diagram depicts an example embodiment of a module-based energy system 100. Here, system 100 includes control system 102 communicatively coupled with N converter-source modules 108-1 through 108-N, over communication paths or links 106-1 through 106-N, respectively. Modules 108 are configured to store energy and output the energy as needed to a load 101 (or other modules 108). In these embodiments, any number of two or more modules 108 can be used (e.g., N is greater than or equal to two). Modules 108 can be connected to each other in a variety of manners as will be described in more detail with respect to FIGs. 7A-7E. For ease of illustration, in FIGs. 1A-1C, modules 108 are shown connected in series, or as a one dimensional array, where the Nth module is coupled to load 101.

[0052] System 100 is configured to supply power to load 101. Load 101 can be any type of load such as a motor or a grid. System 100 is also configured to store power received from a charge source. FIG. 1F is a block diagram depicting an example embodiment of system 100 with a power input interface 151 for receiving power from a charge source 150 and a power output interface for outputting power to load 101. In this embodiment system 100 can receive and store

power over interface 151 at the same time as outputting power over interface 152. FIG. 1G is a block diagram depicting another example embodiment of system 100 with a switchable interface 154. In this embodiment, system 100 can select, or be instructed to select, between receiving power from charge source 150 and outputting power to load 101. System 100 can be configured to supply multiple loads 101, including both primary and auxiliary loads, and/or receive power from multiple charge sources 150 (e.g., a utility-operated power grid and a local renewable energy source (e.g., solar)).

[0053] FIG. 1B depicts another example embodiment of system 100. Here, control system 102 is implemented as a master control device (MCD) 112 communicatively coupled with N different local control devices (LCDs) 114-1 through 114-N over communication paths or links 115-1 through 115-N, respectively. Each LCD 114-1 through 114-N is communicatively coupled with one module 108-1 through 108-N over communication paths or links 116-1 through 116-N, respectively, such that there is a 1:1 relationship between LCDs 114 and modules 108.

[0054] FIG. 1C depicts another example embodiment of system 100. Here, MCD 112 is communicatively coupled with M different LCDs 114-1 to 114-M over communication paths or links 115-1 to 115-M, respectively. Each LCD 114 can be coupled with and control two or more modules 108. In the example shown here, each LCD 114 is communicatively coupled with two modules 108, such that M LCDs 114-1 to 114-M are coupled with 2M modules 108-1 through 108-2M over communication paths or links 116-1 to 116-2M, respectively.

[0055] Control system 102 can be configured as a single device (e.g., FIG. 1A) for the entire system 100 or can be distributed across or implemented as multiple devices (e.g., FIGs. 1B-1C). In some embodiments, control system 102 can be distributed between LCDs 114 associated with the modules 108, such that no MCD 112 is necessary and can be omitted from system 100.

[0056] Control system 102 can be configured to execute control using software (instructions stored in memory that are executable by processing circuitry), hardware, or a combination thereof. The one or more devices of control system 102 can each include processing circuitry 120 and memory 122 as shown here. Example implementations of processing circuitry and memory are described further below.

[0057] Control system 102 can have a communicative interface for communicating with devices 104 external to system 100 over a communication link or path 105. For example, control

system 102 (e.g., MCD 112) can output data or information about system 100 to another control device 104 (e.g., the Electronic Control Unit (ECU) or Motor Control Unit (MCU) of a vehicle in a mobile application, grid controller in a stationary application, etc.).

[0058] Communication paths or links 105, 106, 115, 116, and 118 (FIG. 2B) can each be wired (e.g., electrical, optical) or wireless communication paths that communicate data or information bidirectionally, in parallel or series fashion. Data can be communicated in a standardized (e.g., IEEE, ANSI) or custom (e.g., proprietary) format. In automotive applications, communication paths 115 can be configured to communicate according to FlexRay or CAN protocols. Communication paths 106, 115, 116, and 118 can also provide wired power to directly supply the operating power for control system 102 from one or more modules 108. For example, the operating power for each LCD 114 can be supplied only by the one or more modules 108 to which that LCD 114 is connected and the operating power for MCD 112 can be supplied indirectly from one or more of modules 108 (e.g., such as through a car's power network).

[0059] Control system 102 is configured to control one or more modules 108 based on status information received from the same or different one or more of modules 108. Control can also be based on one or more other factors, such as requirements of load 101. Controllable aspects include, but are not limited to, one or more of voltage, current, phase, and/or output power of each module 108.

[0060] Status information of every module 108 in system 100 can be communicated to control system 102, which can independently control every module 108-1...108-N. Other variations are possible. For example, a particular module 108 (or subset of modules 108) can be controlled based on status information of that particular module 108 (or subset), based on status information of a different module 108 that is not that particular module 108 (or subset), based on status information of all modules 108 other than that particular module 108 (or subset) based on status information of that particular module 108 (or subset) and status information of at least one other module 108 that is not that particular module 108 (or subset), or based on status information of all modules 108 in system 100.

[0061] The status information can be information about one or more aspects, characteristics, or parameters of each module 108. Types of status information include, but are not limited to, the following aspects of a module 108 or one or more components thereof (e.g., energy source,

energy buffer, converter, monitor circuitry): State of Charge (SOC) (e.g., the level of charge of an energy source relative to its capacity, such as a fraction or percent) of the one or more energy sources of the module, State of Health (SOH) (e.g., a figure of merit of the condition of an energy source compared to its ideal conditions) of the one or more energy sources of the module, temperature of the one or more energy sources or other components of the module, capacity of the one or more energy sources of the module, voltage of the one or more energy sources and/or other components of the module, current of the one or more energy sources and/or other components of the module, and/or the presence of absence of a fault in any one or more of the components of the module.

[0062] LCDs 114 can be configured to receive the status information from each module 108, or determine the status information from monitored signals or data received from or within each module 108, and communicate that information to MCD 112. In some embodiments, each LCD 114 can communicate raw collected data to MCD 112, which then algorithmically determines the status information on the basis of that raw data. MCD 112 can then use the status information of modules 108 to make control determinations accordingly. The determinations may take the form of instructions, commands, or other information (such as a modulation index described herein) that can be utilized by LCDs 114 to either maintain or adjust the operation of each module 108.

[0063] For example, MCD 112 may receive status information and assess that information to determine a difference between at least one module 108 (e.g., a component thereof) and at least one or more other modules 108 (e.g., comparable components thereof). For example, MCD 112 may determine that a particular module 108 is operating with one of the following conditions as compared to one or more other modules 108: with a relatively lower or higher SOC, with a relatively lower or higher SOH, with a relatively lower or higher capacity, with a relatively lower or higher voltage, with a relatively lower or higher current, with a relatively lower or higher temperature, or with or without a fault. In such examples, MCD 112 can output control information that causes the relevant aspect (e.g., output voltage, current, power, temperature) of that particular module 108 to be reduced or increased (depending on the condition). In this manner, the utilization of an outlier module 108 (e.g., operating with a relatively lower SOC or higher temperature), can be reduced so as to cause the relevant parameter of that module 108 (e.g., SOC or temperature) to converge towards that of one or more other modules 108.

[0064] The determination of whether to adjust the operation of a particular module 108 can be made by comparison of the status information to predetermined thresholds, limits, or conditions, and not necessarily by comparison to statuses of other modules 108. The predetermined thresholds, limits, or conditions can be static thresholds, limits, or conditions, such as those set by the manufacturer that do not change during use. The predetermined thresholds, limits, or conditions can be dynamic thresholds, limits, or conditions, that are permitted to change, or that do change, during use. For example, MCD 112 can adjust the operation of a module 108 if the status information for that module 108 indicates it to be operating in violation (e.g., above or below) of a predetermined threshold or limit, or outside of a predetermined range of acceptable operating conditions. Similarly, MCD 112 can adjust the operation of a module 108 if the status information for that module 108 indicates the presence of an actual or potential fault (e.g., an alarm, or warning) or indicates the absence or removal of an actual or potential fault. Examples of a fault include, but are not limited to, an actual failure of a component, a potential failure of a component, a short circuit or other excessive current condition, an open circuit, an excessive voltage condition, a failure to receive a communication, the receipt of corrupted data, and the like. Depending on the type and severity of the fault, the faulty module's utilization can be decreased to avoid damaging the module, or the module's utilization can be ceased altogether.

[0065] MCD 112 can control modules 108 within system 100 to achieve or converge towards a desired target. The target can be, for example, operation of all modules 108 at the same or similar levels with respect to each other, or within predetermined thresholds limits, or conditions. This process is also referred to as balancing or seeking to achieve balance in the operation or operating characteristics of modules 108. The term "balance" as used herein does not require absolute equality between modules 108 or components thereof, but rather is used in a broad sense to convey that operation of system 100 can be used to actively reduce disparities in operation between modules 108 that would otherwise exist.

[0066] MCD 112 can communicate control information to LCD 114 for the purpose of controlling the modules 108 associated with the LCD 114. The control information can be, e.g., a modulation index and a reference signal as described herein, a modulated reference signal, or otherwise. Each LCD 114 can use (e.g., receive and process) the control information to generate switch signals that control operation of one or more components (e.g., a converter) within the

associated module(s) 108. In some embodiments, MCD 112 generates the switch signals directly and outputs them to LCD 114, which relays the switch signals to the intended module component.

[0067] All or a portion of control system 102 can be combined with a system external control device 104 that controls one or more other aspects of the mobile or stationary application. When integrated in this shared or common control device (or subsystem), control of system 100 can be implemented in any desired fashion, such as one or more software applications executed by processing circuitry of the shared device, with hardware of the shared device, or a combination thereof. Non-exhaustive examples of external control devices 104 include: a vehicular ECU or MCU having control capability for one or more other vehicular functions (e.g., motor control, driver interface control, traction control, etc.); a grid or micro-grid controller having responsibility for one or more other power management functions (e.g., load interfacing, load power requirement forecasting, transmission and switching, interface with charge sources (e.g., diesel, solar, wind), charge source power forecasting, back up source monitoring, asset dispatch, etc.); and a data center control subsystem (e.g., environmental control, network control, backup control, etc.).

[0068] FIGs. 1D and 1E are block diagrams depicting example embodiments of a shared or common control device (or system) 132 in which control system 102 can be implemented. In FIG. 1D, common control device 132 includes master control device 112 and external control device 104. Master control device 112 includes an interface 141 for communication with LCDs 114 over path 115, as well as an interface 142 for communication with external control device 104 over internal communication bus 136. External control device 104 includes an interface 143 for communication with master control device 112 over bus 136, and an interface 144 for communication with other entities (e.g., components of the vehicle or grid) of the overall application over communication path 136. In some embodiments, common control device 132 can be integrated as a common housing or package with devices 112 and 104 implemented as discrete integrated circuit (IC) chips or packages contained therein.

[0069] In FIG. 1E, external control device 104 acts as common control device 132, with the master control functionality implemented as a component 112 within device 104. This component 112 can be or include software or other program instructions stored and/or hardcoded within memory of device 104 and executed by processing circuitry thereof. The component can

also contain dedicated hardware. The component can be a self-contained module or core, with one or more internal hardware and/or software interfaces (e.g., application program interface (API)) for communication with the operating software of external control device 104. External control device 104 can manage communication with LCDs 114 over interface 141 and other devices over interface 144. In various embodiments, device 104 / 132 can be integrated as a single IC chip, can be integrated into multiple IC chips in a single package, or integrated as multiple semiconductor packages within a common housing.

[0070] In the embodiments of FIGs. 1D and 1E, the master control functionality of system 102 is shared in common device 132, however, other divisions of shared control or permitted. For example, part of the master control functionality can be distributed between common device 132 and a dedicated MCD 112. In another example, both the master control functionality and at least part of the local control functionality can be implemented in common device 132 (e.g., with remaining local control functionality implemented in LCDs 114). In some embodiments, all of control system 102 is implemented in common device (or subsystem) 132. In some embodiments, local control functionality is implemented within a device shared with another component of each module 108, such as a Battery Management System (BMS).

Examples of Modules within Cascaded Energy Systems

[0071] Module 108 can include one or more energy sources and a power electronics converter and, if desired, an energy buffer. FIGs. 2A-2B are block diagrams depicting additional example embodiments of system 100 with module 108 having a power converter 202, an energy buffer 204, and an energy source 206. Converter 202 can be a voltage converter or a current converter. The embodiments are described herein with reference to voltage converters, although the embodiments are not limited to such. Converter 202 can be configured to convert a direct current (DC) signal from energy source 204 into an alternating current (AC) signal and output it over power connection 110 (e.g., an inverter). Converter 202 can also receive an AC or DC signal over connection 110 and apply it to energy source 204 with either polarity in a continuous or pulsed form. Converter 202 can be or include an arrangement of switches (e.g., power transistors) such as a half bridge or full bridge (H-bridge). In some embodiments converter 202 includes only switches and the converter (and the module as a whole) does not include a transformer.

[0072] Converter 202 can be also (or alternatively) be configured to perform AC to DC conversion (e.g., a rectifier) such as to charge a DC energy source from an AC source, DC to DC conversion, and/or AC to AC conversion (e.g., in combination with an AC-DC converter). In some embodiments, such as to perform AC-AC conversion, converter 202 can include a transformer, either alone or in combination with one or more power semiconductors (e.g., switches, diodes, thyristors, and the like). In other embodiments, such as those where weight and cost is a significant factor, converter 202 can be configured to perform the conversions with only power switches, power diodes, or other semiconductor devices and without a transformer.

[0073] Energy source 206 is preferably a robust energy storage device capable of outputting direct current and having an energy density suitable for energy storage applications for electrically powered devices. The fuel cell can be a single fuel cell, multiple fuel cells connected in series or parallel, or a fuel cell module. Two or more energy sources can be included in each module, and the two or more sources can include two batteries of the same or different type, two capacitors of the same or different type, two fuel cells of the same or different type, one or more batteries combined with one or more capacitors and/or fuel cells, and one or more capacitors combined with one or more fuel cells.

[0074] Energy source 206 can be an electrochemical battery, such as a single battery cell or multiple battery cells connected together in a battery module or array, or any combination thereof. FIGs. 4A-4D are schematic diagrams depicting example embodiments of energy source 206 configured as a single battery cell 402 (FIG. 4A), a battery module with a series connection of multiple (e.g., four) cells 402 (FIG. 4B), a battery module with a parallel connection of single cells 402 (FIG. 4C), and a battery module with a parallel connection with legs having multiple (e.g., two) cells 402 each (FIG. 4D). Examples of batteries types include solid state batteries, liquid electrotype based batteries, liquid phase batteries as well as flow batteries such as lithium (Li) metal batteries, Li ion batteries, Li air batteries, sodium ion batteries, potassium ion batteries, magnesium ion batteries, alkaline batteries, nickel metal hydride batteries, nickel sulfate batteries, lead acid batteries, zinc-air batteries, and others. Some examples of Li ion battery types include Li cobalt oxide (LCO), Li manganese oxide (LMO), Li nickel manganese cobalt oxide (NMC), Li iron phosphate (LFP), Lithium nickel cobalt aluminum oxide (NCA), and Li titanate (LTO).

[0075] Energy source 206 can also be a high energy density (HED) capacitor, such as an ultracapacitor or supercapacitor. An HED capacitor can be configured as a double layer capacitor (electrostatic charge storage), pseudocapacitor (electrochemical charge storage), hybrid capacitor (electrostatic and electrochemical), or otherwise, as opposed to a solid dielectric type of a typical electrolytic capacitor. The HED capacitor can have an energy density of 10 to 100 times (or higher) that of an electrolytic capacitor, in addition to a higher capacity. For example, HED capacitors can have a specific energy greater than 1.0 watt hours per kilogram (Wh/kg), and a capacitance greater than 10-100 farads (F). As with the batteries described with respect to FIGs. 4A-4D, energy source 206 can be configured as a single HED capacitor or multiple HED capacitors connected together in an array (e.g., series, parallel, or a combination thereof).

[0076] Energy source 206 can also be a fuel cell. Examples of fuel cells include proton-exchange membrane fuel cells (PEMFC), phosphoric acid fuel cells (PAFC), solid acid fuel cells, alkaline fuel cells, high temperature fuel cells, solid oxide fuel cells, molten electrolyte fuel cells, and others. As with the batteries described with respect to FIGs. 4A-4D, energy source 206 can be configured as a single fuel cell or multiple fuel cells connected together in an array (e.g., series, parallel, or a combination thereof). The aforementioned examples of batteries, capacitors, and fuel cells are not intended to form an exhaustive list, and those of ordinary skill in the art will recognize other variants that fall within the scope of the present subject matter.

[0077] Energy buffer 204 can dampen or filter fluctuations in current across the DC line or link (e.g., $+V_{DCL}$ and $-V_{DCL}$ as described below), to assist in maintaining stability in the DC link voltage. These fluctuations can be relatively low (e.g., kilohertz) or high (e.g., megahertz) frequency fluctuations or harmonics caused by the switching of converter 202, or other transients. These fluctuations can be absorbed by buffer 204 instead of being passed to source 206 or to ports IO3 and IO4 of converter 202.

[0078] Power connection 110 is a connection for transferring energy or power to, from and through module 108. Module 108 can output energy from energy source 206 to power connection 110, where it can be transferred to other modules of the system or to a load. Module 108 can also receive energy from other modules 108 or a charging source (DC charger, single phase charger, multi-phase charger). Signals can also be passed through module 108 bypassing energy source 206. The routing of energy or power into and out of module 108 is performed by converter 202 under the control of LCD 114 (or another entity of system 102).

[0079] In the embodiment of FIG. 2A, LCD 114 is implemented as a component separate from module 108 (e.g., not within a shared module housing) and is connected to and capable of communication with converter 202 via communication path 116. In the embodiment of FIG. 2B, LCD 114 is included as a component of module 108 and is connected to and capable of communication with converter 202 via internal communication path 118 (e.g., a shared bus or discrete connections). LCD 114 can also be capable of receiving signals from, and transmitting signals to, energy buffer 204 and/or energy source 206 over paths 116 or 118.

[0080] Module 108 can also include monitor circuitry 208 configured to monitor (e.g., collect, sense, measure, and/or determine) one or more aspects of module 108 and/or the components thereof, such as voltage, current, temperature or other operating parameters that constitute status information (or can be used to determine status information by, e.g., LCD 114). A main function of the status information is to describe the state of the one or more energy sources 206 of the module 108 to enable determinations as to how much to utilize the energy source in comparison to other sources in system 100, although status information describing the state of other components (e.g., voltage, temperature, and/or presence of a fault in buffer 204, temperature and/or presence of a fault in converter 202, presence of a fault elsewhere in module 108, etc.) can be used in the utilization determination as well. Monitor circuitry 208 can include one or more sensors, shunts, dividers, fault detectors, Coulomb counters, controllers or other hardware and/or software configured to monitor such aspects. Monitor circuitry 208 can be separate from the various components 202, 204, and 206, or can be integrated with each component 202, 204, and 206 (as shown in FIGs. 2A-2B), or any combination thereof. In some embodiments, monitor circuitry 208 can be part of or shared with a Battery Management System (BMS) for a battery energy source 204. Discrete circuitry is not needed to monitor each type of status information, as more than one type of status information can be monitored with a single circuit or device, or otherwise algorithmically determined without the need for additional circuits.

[0081] LCD 114 can receive status information (or raw data) about the module components over communication paths 116, 118. LCD 114 can also transmit information to module components over paths 116, 118. Paths 116 and 118 can include diagnostics, measurement, protection, and control signal lines. The transmitted information can be control signals for one or more module components. The control signals can be switch signals for converter 202 and/or one or more signals that request the status information from module components. For example,

LCD 114 can cause the status information to be transmitted over paths 116, 118 by requesting the status information directly, or by applying a stimulus (e.g., voltage) to cause the status information to be generated, in some cases in combination with switch signals that place converter 202 in a particular state.

[0082] The physical configuration or layout of module 108 can take various forms. In some embodiments, module 108 can include a common housing in which all module components, e.g., converter 202, buffer 204, and source 206, are housed, along with other optional components such as an integrated LCD 114. In other embodiments, the various components can be separated in discrete housings that are secured together. FIG. 2C is a block diagram depicting an example embodiment of a module 108 having a first housing 220 that holds an energy source 206 of the module and accompanying electronics such as monitor circuitry 208 (not shown), a second housing 222 that holds module electronics such as converter 202, energy buffer 204, and other accompany electronics such as monitor circuitry (not shown), and a third housing 224 that holds LCD 114 (not shown) for the module 108. Electrical connections between the various module components can proceed through the housings 220, 222, 224 and can be exposed on any of the housing exteriors for connection with other devices such as other modules 108 or MCD 112.

[0083] Modules 108 of system 100 can be physically arranged with respect to each other in various configurations that depend on the needs of the application and the number of loads. For example, in a stationary application where system 100 provides power for a microgrid, modules 108 can be placed in one or more racks or other frameworks. Such configurations may be suitable for larger mobile applications as well, such as maritime vessels. Alternatively, modules 108 can be secured together and located within a common housing, referred to as a pack. A rack or a pack may have its own dedicated cooling system shared across all modules. Pack configurations are useful for smaller mobile applications such as electric cars. System 100 can be implemented with one or more racks (e.g., for parallel supply to a microgrid) or one or more packs (e.g., serving different motors of the vehicle), or combination thereof. FIG. 2D is a block diagram depicting an example embodiment of system 100 configured as a pack with nine modules 108 electrically and physically coupled together within a common housing 230.

[0084] Examples of these and further configurations are described in Int'l. Publ. No. 2020/205574, which is incorporated by reference herein in its entirety for all purposes.

[0085] FIGs. 3A-3C are block diagrams depicting example embodiments of modules 108 having various electrical configurations. These embodiments are described as having one LCD 114 per module 108, with the LCD 114 housed within the associated module, but can be configured otherwise as described herein. FIG. 3A depicts a first example configuration of a module 108A within system 100. Module 108A includes energy source 206, energy buffer 204, and converter 202A. Each component has power connection ports (e.g., terminals, connectors) into which power can be input and/or from which power can be output, referred to herein as IO ports. Such ports can also be referred to as input ports or output ports depending on the context.

[0086] Energy source 206 can be configured as any of the energy source types described herein (e.g., a battery as described with respect to FIGs. 4A-4D, an HED capacitor, a fuel cell, or otherwise). Ports IO1 and IO2 of energy source 206 can be connected to ports IO1 and IO2, respectively, of energy buffer 204. Energy buffer 204 can be configured to buffer or filter high and low frequency energy pulsations arriving at buffer 204 through converter 202, which can otherwise degrade the performance of module 108. The topology and components for buffer 204 are selected to accommodate the maximum permissible amplitude of these high frequency voltage pulsations. Several (non-exhaustive) example embodiments of energy buffer 204 are depicted in the schematic diagrams of FIGs. 5A-5C. In FIG. 5A, buffer 204 is an electrolytic and/or film capacitor C_{EB} , in FIG. 5B buffer 204 is a Z-source network 710, formed by two inductors L_{EB1} and L_{EB2} and two electrolytic and/or film capacitors C_{EB1} and C_{EB2} , and in FIG. 5C buffer 204 is a quasi Z-source network 720, formed by two inductors L_{EB1} and L_{EB2} , two electrolytic and/or film capacitors C_{EB1} and C_{EB2} and a diode D_{EB} .

[0087] Ports IO3 and IO4 of energy buffer 204 can be connected to ports IO1 and IO2, respectively, of converter 202A, which can be configured as any of the power converter types described herein. FIG. 6A is a schematic diagram depicting an example embodiment of converter 202A configured as a DC-AC converter that can receive a DC voltage at ports IO1 and IO2 and switch to generate pulses at ports IO3 and IO4. Converter 202A can include multiple switches, and here converter 202A includes four switches S3, S4, S5, S6 arranged in a full bridge configuration. Control system 102 or LCD 114 can independently control each switch via control input lines 118-3 to each gate.

[0088] The switches can be any suitable switch type, such as power semiconductors like the metal-oxide-semiconductor field-effect transistors (MOSFETs) shown here, insulated gate

bipolar transistors (IGBTs), or gallium nitride (GaN) transistors. Semiconductor switches can operate at relatively high switching frequencies, thereby permitting converter 202 to be operated in pulse-width modulated (PWM) mode if desired, and to respond to control commands within a relatively short interval of time. This can provide a high tolerance of output voltage regulation and fast dynamic behavior in transient modes.

[0089] In this embodiment, a DC line voltage V_{DCL} can be applied to converter 202 between ports IO1 and IO2. By connecting V_{DCL} to ports IO3 and IO4 by different combinations of switches S3, S4, S5, S6, converter 202 can generate three different voltage outputs at ports IO3 and IO4: $+V_{DCL}$, 0, and $-V_{DCL}$. A switch signal provided to each switch controls whether the switch is on (closed) or off (open). To obtain $+V_{DCL}$, switches S3 and S6 are turned on while S4 and S5 are turned off, whereas $-V_{DCL}$ can be obtained by turning on switches S4 and S5 and turning off S3 and S6. The output voltage can be set to zero (including near zero) or a reference voltage by turning on S3 and S5 with S4 and S6 off, or by turning on S4 and S6 with S3 and S5 off. These voltages can be output from module 108 over power connection 110. Ports IO3 and IO4 of converter 202 can be connected to (or form) module IO ports 1 and 2 of power connection 110, so as to generate the output voltage for use with output voltages from other modules 108.

[0090] The control or switch signals for the embodiments of converter 202 described herein can be generated in different ways depending on the control technique utilized by system 100 to generate the output voltage of converter 202. In some embodiments, the control technique is a PWM technique such as space vector pulse-width modulation (SVPWM) or sinusoidal pulse-width modulation (SPWM), or variations thereof. FIG. 8A is a graph of voltage versus time depicting an example of an output voltage waveform 802 of converter 202. For ease of description, the embodiments herein will be described in the context of a PWM control technique, although the embodiments are not limited to such. Other classes of techniques can be used. One alternative class is based on hysteresis, examples of which are described in Int'l Publ. Nos. WO 2018/231810A1, WO 2018/232403A1, and WO 2019/183553A1, which are incorporated by reference herein for all purposes.

[0091] Each module 108 can be configured with multiple energy sources 206 (e.g., two, three, four, or more). Each energy source 206 of module 108 can be controllable (switchable) to supply power to connection 110 (or receive power from a charge source) independent of the other sources 206 of the module. For example, all sources 206 can output power to connection

110 (or be charged) at the same time, or only one (or a subset) of sources 206 can supply power (or be charged) at any one time. In some embodiments, the sources 206 of the module can exchange energy between them, e.g., one source 206 can charge another source 206. Each of the sources 206 can be configured as any energy source described herein (e.g., battery, HED capacitor, fuel cell). Each of the sources 206 can be the same type (e.g., each can be a battery), or a different type (e.g., a first source can be a battery and a second source can be an HED capacitor, or a first source can be a battery having a first type (e.g., NMC) and a second source can be a battery having a second type (e.g., LFP).

[0092] FIG. 3B is a block diagram depicting an example embodiment of a module 108B in a dual energy source configuration with a primary energy source 206A and secondary energy source 206B. Ports IO1 and IO2 of primary source 202A can be connected to ports IO1 and IO2 of energy buffer 204. Module 108B includes a converter 202B having an additional IO port. Ports IO3 and IO4 of buffer 204 can be connected ports IO1 and IO2, respectively, of converter 202B. Ports IO1 and IO2 of secondary source 206B can be connected to ports IO5 and IO2, respectively, of converter 202B (also connected to port IO4 of buffer 204).

[0093] In this example embodiment of module 108B, primary energy source 202A, along with the other modules 108 of system 100, supplies the average power needed by the load. Secondary source 202B can serve the function of assisting energy source 202 by providing additional power at load power peaks, or absorbing excess power, or otherwise.

[0094] As mentioned both primary source 206A and secondary source 206B can be utilized simultaneously or at separate times depending on the switch state of converter 202B. If at the same time, an electrolytic and/or a film capacitor (C_{ES}) can be placed in parallel with source 206B as depicted in FIG. 4E to act as an energy buffer for the source 206B, or energy source 206B can be configured to utilize an HED capacitor in parallel with another energy source (e.g., a battery or fuel cell) as depicted in FIG. 4F.

[0095] FIGs. 6B and 6C are schematic views depicting example embodiments of converters 202B and 202C, respectively. Converter 202B includes switch circuitry portions 601 and 602A. Portion 601 includes switches S3 through S6 configured as a full bridge in similar manner to converter 202A, and is configured to selectively couple IO1 and IO2 to either of IO3 and IO4, thereby changing the output voltages of module 108B. Portion 602A includes switches S1 and S2 configured as a half bridge and coupled between ports IO1 and IO2. A coupling inductor L_c

is connected between port IO5 and a node1 present between switches S1 and S2 such that switch portion 602A is a bidirectional converter that can regulate (boost or buck) voltage (or inversely current). Switch portion 602A can generate two different voltages at node1, which are $+V_{DCL2}$ and 0, referenced to port IO2, which can be at virtual zero potential. The current drawn from or input to energy source 202B can be controlled by regulating the voltage on coupling inductor L_C , using, for example, a pulse-width modulation technique or a hysteresis control method for commutating switches S1 and S2. Other techniques can also be used.

[0096] Converter 202C differs from that of 202B as switch portion 602B includes switches S1 and S2 configured as a half bridge and coupled between ports IO5 and IO2. A coupling inductor L_C is connected between port IO1 and a node1 present between switches S1 and S2 such that switch portion 602B is configured to regulate voltage.

[0097] Control system 102 or LCD 114 can independently control each switch of converters 202B and 202C via control input lines 118-3 to each gate. In these embodiments and that of FIG. 6A, LCD 114 (not MCD 112) generates the switching signals for the converter switches. Alternatively, MCD 112 can generate the switching signals, which can be communicated directly to the switches, or relayed by LCD 114.

[0098] In embodiments where a module 108 includes three or more energy sources 206, converters 202B and 202C can be scaled accordingly such that each additional energy source 206B is coupled to an additional IO port leading to an additional switch circuitry portion 602A or 602B, depending on the needs of the particular source. For example a dual source converter 202 can include both switch portions 202A and 202B.

[0099] Modules 108 with multiple energy sources 206 are capable of performing additional functions such as energy sharing between sources 206, energy capture from within the application (e.g., regenerative braking), charging of the primary source by the secondary source even while the overall system is in a state of discharge, and active filtering of the module output. Examples of these functions are described in more detail in Int'l. Publ. No. WO 2020/205574, filed March 27, 2020, and titled Module-Based Energy Systems Capable Of Cascaded And Interconnected Configurations, And Methods Related Thereto, and Int'l. Publ. No. WO 2019/183553, filed March 22, 2019, and titled Systems and Methods for Power Management and Control, both of which are incorporated by reference herein in their entireties for all purposes.

[00100] Each module 108 can be configured to supply one or more auxiliary loads with its one or more energy sources 206. Auxiliary loads are loads that require lower voltages than the primary load 101. Examples of auxiliary loads can be, for example, an on-board electrical network of an electric vehicle, or an HVAC system of an electric vehicle. The load of system 100 can be, for example, one of the phases of the electric vehicle motor or electrical grid. This embodiment can allow a complete decoupling between the electrical characteristics (terminal voltage and current) of the energy source and those of the loads.

[00101] FIG. 3C is a block diagram depicting an example embodiment of a module 108C configured to supply power to a first auxiliary load 301 and a second auxiliary load 302, where module 108C includes an energy source 206, energy buffer 204, and converter 202B coupled together in a manner similar to that of FIG. 3B. First auxiliary load 301 requires a voltage equivalent to that supplied from source 206. Load 301 is coupled to IO ports 3 and 4 of module 108C, which are in turn coupled to ports IO1 and IO2 of source 206. Source 206 can output power to both power connection 110 and load 301. Second auxiliary load 302 requires a constant voltage lower than that of source 206. Load 302 is coupled to IO ports 5 and 6 of module 108C, which are coupled to ports IO5 and IO2, respectively, of converter 202B. Converter 202B can include switch portion 602 having coupling inductor L_c coupled to port IO5 (FIG. 6B). Energy supplied by source 206 can be supplied to load 302 through switch portion 602 of converter 202B. It is assumed that load 302 has an input capacitor (a capacitor can be added to module 108C if not), so switches S1 and S2 can be commutated to regulate the voltage on and current through coupling inductor L_c and thus produce a stable constant voltage for load 302. This regulation can step down the voltage of source 206 to the lower magnitude voltage is required by load 302.

[00102] Module 108C can thus be configured to supply one or more first auxiliary loads in the manner described with respect to load 301, with the one or more first loads coupled to IO ports 3 and 4. Module 108C can also be configured to supply one or more second auxiliary loads in the manner described with respect to load 302. If multiple second auxiliary loads 302 are present, then for each additional load 302 module 108C can be scaled with additional dedicated module output ports (like 5 and 6), an additional dedicated switch portion 602, and an additional converter IO port coupled to the additional portion 602.

[00103] Energy source 206 can thus supply power for any number of auxiliary loads (e.g., 301 and 302), as well as the corresponding portion of system output power needed by primary load 101. Power flow from source 206 to the various loads can be adjusted as desired.

[00104] Module 108 can be configured as needed with two or more energy sources 206 (FIG. 3B) and to supply first and/or second auxiliary loads (FIG. 3C) through the addition of a switch portion 602 and converter port IO5 for each additional source 206B or second auxiliary load 302. Additional module IO ports (e.g., 3, 4, 5, 6) can be added as needed. Module 108 can also be configured as an interconnection module to exchange energy (e.g., for balancing) between two or more arrays, two or more packs, or two or more systems 100 as described further herein. This interconnection functionality can likewise be combined with multiple source and/or multiple auxiliary load supply capabilities.

[00105] Control system 102 can perform various functions with respect to the components of modules 108A, 108B, and 108C. These functions can include management of the utilization (amount of use) of each energy source 206, protection of energy buffer 204 from over-current, over-voltage and high temperature conditions, and control and protection of converter 202.

[00106] For example, to manage (e.g., adjust by increasing, decreasing, or maintaining) utilization of each energy source 206, LCD 114 can receive one or more monitored voltages, temperatures, and currents from each energy source 206 (or monitor circuitry). The monitored voltages can be at least one of, preferably all, voltages of each elementary component independent of the other components (e.g., each individual battery cell, HED capacitor, and/or fuel cell) of the source 206, or the voltages of groups of elementary components as a whole (e.g., voltage of the battery array, HED capacitor array, and/or fuel cell array). Similarly the monitored temperatures and currents can be at least one of, preferably all, temperatures and currents of each elementary component independent of the other components of the source 206, or the temperatures and currents of groups of elementary components as a whole, or any combination thereof. The monitored signals can be status information, with which LCD 114 can perform one or more of the following: calculation or determination of a real capacity, actual State of Charge (SOC) and/or State of Health (SOH) of the elementary components or groups of elementary components; set or output a warning or alarm indication based on monitored and/or calculated status information; and/or transmission of the status information to MCD 112. LCD 114 can receive control information (e.g., a modulation index, synchronization signal) from

MCD 112 and use this control information to generate switch signals for converter 202 that manage the utilization of the source 206.

[00107] To protect energy buffer 204, LCD 114 can receive one or more monitored voltages, temperatures, and currents from energy buffer 204 (or monitor circuitry). The monitored voltages can be at least one of, preferably all, voltages of each elementary component of buffer 204 (e.g., of C_{EB} , C_{EB1} , C_{EB2} , L_{EB1} , L_{EB2} , D_{EB}) independent of the other components, or the voltages of groups of elementary components or buffer 204 as a whole (e.g., between IO1 and IO2 or between IO3 and IO4). Similarly the monitored temperatures and currents can be at least one of, preferably all, temperatures and currents of each elementary component of buffer 204 independent of the other components, or the temperatures and currents of groups of elementary components or of buffer 204 as a whole, or any combination thereof. The monitored signals can be status information, with which LCD 114 can perform one or more of the following: set or output a warning or alarm indication; communicate the status information to MCD 112; or control converter 202 to adjust (increase or decrease) the utilization of source 206 and module 108 as a whole for buffer protection.

[00108] To control and protect converter 202, LCD 114 can receive the control information from MCD 112 (e.g., a modulated reference signal, or a reference signal and a modulation index), which can be used with a PWM technique in LCD 114 to generate the control signals for each switch (e.g., S1 through S6). LCD 114 can receive a current feedback signal from a current sensor of converter 202, which can be used for overcurrent protection together with one or more fault status signals from driver circuits (not shown) of the converter switches, which can carry information about fault statuses (e.g., short circuit or open circuit failure modes) of all switches of converter 202. Based on this data, LCD 114 can make a decision on which combination of switching signals to be applied to manage utilization of module 108, and potentially bypass or disconnect converter 202 (and the entire module 108) from system 100.

[00109] If controlling a module 108C that supplies a second auxiliary load 302, LCD 114 can receive one or more monitored voltages (e.g., the voltage between IO ports 5 and 6) and one or more monitored currents (e.g., the current in coupling inductor L_C , which is a current of load 302) in module 108C. Based on these signals, LCD 114 can adjust the switching cycles (e.g., by adjustment of modulation index or reference waveform) of S1 and S2 to control (and stabilize) the voltage for load 302.

Examples of Cascaded Energy System Topologies

[00110] Two or more modules 108 can be coupled together in a cascaded array that outputs a voltage signal formed by a superposition of the discrete voltages generated by each module 108 within the array. FIG. 7A is a block diagram depicting an example embodiment of a topology for system 100 where N modules 108-1, 108-2 . . . 108-N are coupled together in series to form a serial array 700. In this and all embodiments described herein, N can be any integer greater than one. Array 700 includes a first system IO port SIO1 and a second system IO port SIO2 across which is generated an array output voltage. Array 700 can be used as a DC or single phase AC energy source for DC or AC single-phase loads, which can be connected to SIO1 and SIO2 of array 700. FIG. 8A is a plot of voltage versus time depicting an example output signal produced by a single module 108 having a 48 volt energy source. FIG. 8B is a plot of voltage versus time depicting an example single phase AC output signal generated by array 700 having six 48V modules 108 coupled in series.

[00111] System 100 can be arranged in a broad variety of different topologies to meet varying needs of the applications. System 100 can provide multi-phase power (e.g., two-phase, three-phase, four-phase, five-phase, six-phase, etc.) to a load by use of multiple arrays 700, where each array can generate an AC output signal having a different phase angle.

[00112] FIG. 7B is a block diagram depicting system 100 with two arrays 700-PA and 700-PB coupled together. Each array 700 is one-dimensional, formed by a series connection of N modules 108. The two arrays 700-PA and 700-PB can each generate a single-phase AC signal, where the two AC signals have different phase angles PA and PB (e.g., 180 degrees apart). IO port 1 of module 108-1 of each array 700-PA and 700-PB can form or be connected to system IO ports SIO1 and SIO2, respectively, which in turn can serve as a first output of each array that can provide two phase power to a load (not shown). Or alternatively ports SIO1 and SIO2 can be connected to provide single phase power from two parallel arrays. IO port 2 of module 108-N of each array 700- PA and 700- PB can serve as a second output for each array 700- PA and 700- PB on the opposite end of the array from system IO ports SIO1 and SIO2, and can be coupled together at a common node and optionally used for an additional system IO port SIO3 if desired, which can serve as a neutral. This common node can be referred to as a rail, and IO port 2 of modules 108-N of each array 700 can be referred to as being on the rail side of the arrays.

[00113] FIG. 7C is a block diagram depicting system 100 with three arrays 700-PA, 700-PB, and 700-PC coupled together. Each array 700 is one-dimensional, formed by a series connection of N modules 108. The three arrays 700-1 and 700-2 can each generate a single-phase AC signal, where the three AC signals have different phase angles PA, PB, PC (e.g., 120 degrees apart). IO port 1 of module 108-1 of each array 700-PA, 700-PB, and 700-PC can form or be connected to system IO ports SIO1, SIO2, and SIO3, respectively, which in turn can provide three phase power to a load (not shown). IO port 2 of module 108-N of each array 700-PA, 700-PB, and 700-PC can be coupled together at a common node and optionally used for an additional system IO port SIO4 if desired, which can serve as a neutral.

[00114] The concepts described with respect to the two-phase and three-phase embodiments of FIGs. 7B and 7C can be extended to systems 100 generating still more phases of power. For example, a non-exhaustive list of additional examples includes: system 100 having four arrays 700, each of which is configured to generate a single phase AC signal having a different phase angle (e.g., 90 degrees apart); system 100 having five arrays 700, each of which is configured to generate a single phase AC signal having a different phase angle (e.g., 72 degrees apart); and system 100 having six arrays 700, each array configured to generate a single phase AC signal having a different phase angle (e.g., 60 degrees apart).

[00115] System 100 can be configured such that arrays 700 are interconnected at electrical nodes between modules 108 within each array. FIG. 7D is a block diagram depicting system 100 with three arrays 700-PA, 700-PB, and 700-PC coupled together in a combined series and delta arrangement. Each array 700 includes a first series connection of M modules 108, where M is two or greater, coupled with a second series connection of N modules 108, where N is two or greater. The delta configuration is formed by the interconnections between arrays, which can be placed in any desired location. In this embodiment, IO port 2 of module 108-(M+N) of array 700-PC is coupled with IO port 2 of module 108-M and IO port 1 of module 108-(M+1) of array 700-PA, IO port 2 of module 108-(M+N) of array 700-PB is coupled with IO port 2 of module 108-M and IO port 1 of module 108-(M+1) of array 700-PC, and IO port 2 of module 108-(M+N) of array 700-PA is coupled with IO port 2 of module 108-M and IO port 1 of module 108-(M+1) of array 700-PB.

[00116] FIG. 7E is a block diagram depicting system 100 with three arrays 700-PA, 700-PB, and 700-PC coupled together in a combined series and delta arrangement. This embodiment is

similar to that of FIG. 7D except with different cross connections. In this embodiment, IO port 2 of module 108-M of array 700-PC is coupled with IO port 1 of module 108-1 of array 700-PA, IO port 2 of module 108-M of array 700-PB is coupled with IO port 1 of module 108-1 of array 700-PC, and IO port 2 of module 108-M of array 700-PA is coupled with IO port 1 of module 108-1 of array 700-PB. The arrangements of FIGs. 7D and 7E can be implemented with as little as two modules in each array 700. Combined delta and series configurations enable an effective exchange of energy between all modules 108 of the system (interphase balancing) and phases of power grid or load, and also allows reducing the total number of modules 108 in an array 700 to obtain the desired output voltages.

[00117] In the embodiments described herein, although it is advantageous for the number of modules 108 to be the same in each array 700 within system 100, such is not required and different arrays 700 can have differing numbers of modules 108. Further, each array 700 can have modules 108 that are all of the same configuration (e.g., all modules are 108A, all modules are 108B, all modules are 108C, or others) or different configurations (e.g., one or more modules are 108A, one or more are 108B, and one or more are 108C, or otherwise). As such, the scope of topologies of system 100 covered herein is broad.

Example Embodiments of Control Methodologies

[00118] As mentioned, control of system 100 can be performed according to various methodologies, such as hysteresis or PWM. Several examples of PWM include space vector modulation and sine pulse width modulation, where the switching signals for converter 202 are generated with a phase shifted carrier technique that continuously rotates utilization of each module 108 to equally distribute power among them.

[00119] FIGs. 8C-8F are plots depicting an example embodiment of a phase-shifted PWM control methodology that can generate a multilevel output PWM waveform using incrementally shifted two-level waveforms. An X-level PWM waveform can be created by the summation of $(X-1)/2$ two-level PWM waveforms. These two-level waveforms can be generated by comparing a reference waveform V_{ref} to carriers incrementally shifted by $360^\circ/(X-1)$. The carriers are triangular, but the embodiments are not limited to such. A nine-level example is shown in FIG. 8C (using four modules 108). The carriers are incrementally shifted by $360^\circ/(9-1) = 45^\circ$ and compared to V_{ref} . The resulting two-level PWM waveforms are shown in FIG. 8E. These two-

level waveforms may be used as the switching signals for semiconductor switches (e.g., S1 through S6) of converters 202. As an example with reference to FIG. 8E, for a one-dimensional array 700 including four modules 108 each with a converter 202, the 0° signal is for control of S3 and the 180° signal for S6 of the first module 108-1, the 45° signal is for S3 and the 225° signal for S6 of the second module 108-2, the 90° signal is for S3 and the 270° signal is for S6 of the third module 108-3, and the 135° signal is for S3 and the 315° signal is for S6 of the fourth module 108-4. The signal for S3 is complementary to S4 and the signal for S5 is complementary to S6 with sufficient dead-time to avoid shoot through of each half-bridge. FIG. 8F depicts an example single phase AC waveform produced by superposition (summation) of output voltages from the four modules 108.

[00120] An alternative is to utilize both a positive and a negative reference signal with the first $(N-1)/2$ carriers. A nine-level example is shown in FIG. 8D. In this example, the 0° to 135° switching signals (FIG. 8E) are generated by comparing $+V_{ref}$ to the 0° to 135° carriers of FIG. 8D and the 180° to 315° switching signals are generated by comparing $-V_{ref}$ to the 0° to 135° carriers of FIG. 8D. However, the logic of the comparison in the latter case is reversed. Other techniques such as a state machine decoder may also be used to generate gate signals for the switches of converter 202.

[00121] In multi-phase system embodiments, the same carriers can be used for each phase, or the set of carriers can be shifted as a whole for each phase. For example, in a three phase system with a single reference voltage (V_{ref}), each array 700 can use the same number of carriers with the same relative offsets as shown in FIGs. 8C and 8D, but the carriers of the second phase are shift by 120 degrees as compared to the carriers of the first phase, and the carriers of the third phase are shifted by 240 degrees as compared to the carriers of the first phase. If a different reference voltage is available for each phase, then the phase information can be carried in the reference voltage and the same carriers can be used for each phase. In many cases the carrier frequencies will be fixed, but in some example embodiments, the carrier frequencies can be adjusted, which can help to reduce losses in EV motors under high current conditions.

[00122] The appropriate switching signals can be provided to each module by control system 102. For example, MCD 112 can provide V_{ref} and the appropriate carrier signals to each LCD 114 depending upon the module or modules 108 that LCD 114 controls, and the LCD 114 can

then generate the switching signals. Or all LCDs 114 in an array can be provided with all carrier signals and the LCD can select the appropriate carrier signals.

[00123] The relative utilizations of each module 108 can adjusted based on status information to perform balancing or of one or more parameters as described herein. Balancing of parameters can involve adjusting utilization to minimize parameter divergence over time as compared to a system where individual module utilization adjustment is not performed. The utilization can be the relative amount of time a module 108 is discharging when system 100 is in a discharge state, or the relative amount of time a module 108 is charging when system 100 is in a charge state.

[00124] As described herein, modules 108 can be balanced with respect to other modules in an array 700, which can be referred to as intra-array or intraphase balancing, and different arrays 700 can be balanced with respect to each other, which can be referred to as interarray or interphase balancing. Arrays 700 of different subsystems can also be balanced with respect to each other. Control system 102 can simultaneously perform any combination of intraphase balancing, interphase balancing, utilization of multiple energy sources within a module, active filtering, and auxiliary load supply.

[00125] FIG. 9A is a block diagram depicting an example embodiment of an array controller 900 of control system 102 for a single-phase AC or DC array. Array controller 900 can include a peak detector 902, a divider 904, and an intraphase (or intra-array) balance controller 906. Array controller 900 can receive a reference voltage waveform (V_r) and status information about each of the N modules 108 in the array (e.g., state of charge (SOC_i), temperature (T_i), capacity (Q_i), and voltage (V_i)) as inputs, and generate a normalized reference voltage waveform (V_{rn}) and modulation indexes (M_i) as outputs. Peak detector 902 detects the peak (V_{pk}) of V_r , which can be specific to the phase that controller 900 is operating with and/or balancing. Divider 904 generates V_{rn} by dividing V_r by its detected V_{pk} . Intraphase balance controller 906 uses V_{pk} along with the status information (e.g., SOC_i , T_i , Q_i , V_i , etc.) to generate modulation indexes M_i for each module 108 within the array 700 being controlled.

[00126] The modulation indexes and V_{rn} can be used to generate the switching signals for each converter 202. The modulation index can be a number between zero and one (inclusive of zero and one). For a particular module 108, the normalized reference V_{rn} can be modulated or scaled by M_i , and this modulated reference signal (V_{rnm}) can be used as V_{ref} (or $-V_{ref}$)

according to the PWM technique described with respect to FIGs. 8C-8F, or according to other techniques. In this manner, the modulation index can be used to control the PWM switching signals provided to the converter switching circuitry (e.g., S3-S6 or S1-S6), and thus regulate the operation of each module 108. For example, a module 108 being controlled to maintain normal or full operation may receive an M_i of one, while a module 108 being controlled to less than normal or full operation may receive an M_i less than one, and a module 108 controlled to cease power output may receive an M_i of zero. This operation can be performed in various ways by control system 102, such as by MCD 112 outputting V_{rn} and M_i to the appropriate LCDs 114 for modulation and switch signal generation, by MCD 112 performing modulation and outputting the modulated V_{rnm} to the appropriate LCDs 114 for switch signal generation, or by MCD 112 performing modulation and switch signal generation and outputting the switch signals to the LCDs or the converters 202 of each module 108 directly. V_{rn} can be sent continually with M_i sent at regular intervals, such as once for every period of the V_{rn} , or one per minute, etc.

[00127] Controller 906 can generate an M_i for each module 108 using any type or combination of types of status information (e.g., SOC, temperature (T), Q, SOH, voltage, current) described herein. For example, when using SOC and T, a module 108 can have a relatively high M_i if SOC is relatively high and temperature is relatively low as compared to other modules 108 in array 700. If either SOC is relatively low or T is relatively high, then that module 108 can have a relatively low M_i , resulting in less utilization than other modules 108 in array 700. Controller 906 can determine M_i such that the sum of module voltages does not exceed V_{pk} . For example, V_{pk} can be the sum of the products of the voltage of each module's source 206 and M_i for that module (e.g., $V_{pk} = M_1V_1 + M_2V_2 + M_3V_3 \dots + M_NV_N$, etc). A different combination of modulation indexes, and thus respective voltage contributions by the modules, may be used but the total generated voltage should remain the same.

[00128] Controller 900 can control operation, to the extent it does not prevent achieving the power output requirements of the system at any one time (e.g., such as during maximum acceleration of an EV), such that SOC of the energy source(s) in each module 108 remains balanced or converges to a balanced condition if they are unbalanced, and/or such that temperature of the energy source(s) or other component (e.g., energy buffer) in each module remains balanced or converges to a balanced condition if they are unbalanced. Power flow in and out of the modules can be regulated such that a capacity difference between sources does not

cause an SOC deviation. Balancing of SOC and temperature can indirectly cause some balancing of SOH. Voltage and current can be directly balanced if desired, but in many embodiments the main goal of the system is to balance SOC and temperature, and balancing of SOC can lead to balance of voltage and current in a highly symmetric systems where modules are of similar capacity and impedance.

[00129] Since balancing all parameters may not be possible at the same time (e.g., balancing of one parameter may further unbalance another parameter), a combination of balancing any two or more parameters (SOC, T, Q, SOH, V, I) may be applied with priority given to either one depending on the requirements of the application. Priority in balancing can be given to SOC over other parameters (T, Q, SOH, V, I), with exceptions made if one of the other parameters (T, Q, SOH, V, I) reaches a severe unbalanced condition outside a threshold.

[00130] Balancing between arrays 700 of different phases (or arrays of the same phase, e.g., if parallel arrays are used) can be performed concurrently with intra-phase balancing. FIG. 9B depicts an example embodiment of an Ω -phase (or Ω -array) controller 950 configured for operation in an Ω -phase system 100, having at least Ω arrays 700, where Ω is any integer greater than one. Controller 950 can include one interphase (or interarray) controller 910 and Ω intraphase balance controllers 906-PA . . . 906-P Ω for phases PA through P Ω , as well as peak detector 902 and divider 904 (FIG. 9A) for generating normalized references V_{rnPA} through V_{rnP Ω} from each phase-specific reference V_{rPA} through V_{rP Ω} . Intraphase controllers 906 can generate M_i for each module 108 of each array 700 as described with respect to FIG. 9A. Interphase balance controller 910 is configured or programmed to balance aspects of modules 108 across the entire multi-dimensional system, for example, between arrays of different phases. This may be achieved through injecting common mode to the phases (e.g., neutral point shifting) or through the use of interconnection modules (described herein) or through both. Common mode injection involves introducing a phase and amplitude shift to the reference signals V_{rPA} through V_{rP Ω} to generate normalized waveforms V_{rnPA} through V_{rnP Ω} to compensate for unbalance in one or more arrays, and is described further in Int'l. Publ. No. WO 2020/205574 incorporated herein.

[00131] Controllers 900 and 950 (as well as balance controllers 906 and 910) can be implemented in hardware, software or a combination thereof within control system 102.

Controllers 900 and 950 can be implemented within MCD 112, distributed partially or fully among LCDs 114, or may be implemented as discrete controllers independent of MCD 112 and LCDs 114.

Example Embodiments of Interconnection (IC) Modules

[00132] Modules 108 can be connected between the modules of different arrays 700 for the purposes of exchanging energy between the arrays, acting as a source for an auxiliary load, or both. Such modules are referred to herein as interconnection (IC) modules 108IC. IC module 108IC can be implemented in any of the already described module configurations (108A, 108B, 108C) and others to be described herein. IC modules 108IC can include any number of one or more energy sources, an optional energy buffer, switch circuitry for supplying energy to one or more arrays and/or for supplying power to one or more auxiliary loads, control circuitry (e.g., a local control device), and monitor circuitry for collecting status information about the IC module itself or its various loads (e.g., SOC of an energy source, temperature of an energy source or energy buffer, capacity of an energy source, SOH of an energy source, voltage and/or current measurements pertaining to the IC module, voltage and/or current measurements pertaining to the auxiliary load(s), etc.).

[00133] FIG. 10A is a block diagram depicting an example embodiment of a system 100 capable of producing Ω -phase power with Ω arrays 700-PA through 700-P Ω , where Ω can be any integer greater than one. In this and other embodiments, IC module 108IC can be located on the rail side of arrays 700 such that the arrays 700 to which module 108IC are connected (arrays 700-PA through 700-P Ω in this embodiment) are electrically connected between module 108IC and outputs (e.g., SIO1 and SIO Ω) to the load. Here, module 108IC has Ω IO ports for connection to IO port 2 of each module 108-N of arrays 700-PA through 700-P Ω . In the configuration depicted here, module 108IC can perform interphase balancing by selectively connecting the one or more energy sources of module 108IC to one or more of the arrays 700-PA through 700-P Ω (or to no output, or equally to all outputs, if interphase balancing is not required). System 100 can be controlled by control system 102 (not shown, see FIG. 1A).

[00134] FIG. 10B is a schematic diagram depicting an example embodiment of module 108IC. In this embodiment module 108IC includes an energy source 206 connected with energy buffer 204 that in turn is connected with switch circuitry 603. Switch circuitry 603 can include

switch circuitry units 604-PA through 604-P Ω for independently connecting energy source 206 to each of arrays 700-PA through 700-P Ω , respectively. Various switch configurations can be used for each unit 604, which in this embodiment is configured as a half-bridge with two semiconductor switches S7 and S8. Each half bridge is controlled by control lines 118-3 from LCD 114. This configuration is similar to module 108A described with respect to FIG. 3A. As described with respect to converter 202, switch circuitry 603 can be configured in any arrangement and with any switch types (e.g., MOSFET, IGBT, Silicon, GaN, etc.) suitable for the requirements of the application.

[00135] Switch circuitry units 604 are coupled between positive and negative terminals of energy source 206 and have an output that is connected to an IO port of module 108IC. Units 604-PA through 604-P Ω can be controlled by control system 102 to selectively couple voltage +V_{IC} or -V_{IC} to the respective module I/O ports 1 through Ω . Control system 102 can control switch circuitry 603 according to any desired control technique, including the PWM and hysteresis techniques mentioned herein. Here, control circuitry 102 is implemented as LCD 114 and MCD 112 (not shown). LCD 114 can receive monitoring data or status information from monitor circuitry of module 108IC. This monitoring data and/or other status information derived from this monitoring data can be output to MCD 112 for use in system control as described herein. LCD 114 can also receive timing information (not shown) for purposes of synchronization of modules 108 of the system 100 and one or more carrier signals (not shown), such as the sawtooth signals used in PWM (FIGs. 8C-8D).

[00136] For interphase balancing, proportionally more energy from source 206 can be supplied to any one or more of arrays 700-PA through 700-P Ω that is relatively low on charge as compared to other arrays 700. Supply of this supplemental energy to a particular array 700 allows the energy output of those cascaded modules 108-1 thru 108-N in that array 700 to be reduced relative to the unsupplied phase array(s).

[00137] For example, in some example embodiments applying PWM, LCD 114 can be configured to receive the normalized voltage reference signal (V_{rn}) (from MCD 112) for each of the one or more arrays 700 that module 108IC is coupled to, e.g., V_{rnPA} through V_{rnP Ω} . LCD 114 can also receive modulation indexes Mi_{PA} through Mi_{P Ω} for the switch units 604-PA through 604-P Ω for each array 700, respectively, from MCD 112. LCD 114 can modulate (e.g.,

multiply) each respective V_{rn} with the modulation index for the switch section coupled directly to that array (e.g., V_{rnA} multiplied by MiA) and then utilize a carrier signal to generate the control signal(s) for each switch unit 604. In other embodiments, MCD 112 can perform the modulation and output modulated voltage reference waveforms for each unit 604 directly to LCD 114 of module 108IC. In still other embodiments, all processing and modulation can occur by a single control entity that can output the control signals directly to each unit 604.

[00138] This switching can be modulated such that power from energy source 206 is supplied to the array(s) 700 at appropriate intervals and durations. Such methodology can be implemented in various ways.

[00139] Based on the collected status information for system 100, such as the present capacity (Q) and SOC of each energy source in each array, MCD 112 can determine an aggregate charge for each array 700 (e.g., aggregate charge for an array can be determined as the sum of capacity times SOC for each module of that array). MCD 112 can determine whether a balanced or unbalanced condition exists (e.g., through the use of relative difference thresholds and other metrics described herein) and generate modulation indexes $MiPA$ through $MiP\Omega$ accordingly for each switch unit 604-PA through 604-P Ω .

[00140] During balanced operation, Mi for each switch unit 604 can be set at a value that causes the same or similar amount of net energy over time to be supplied by energy source 206 and/or energy buffer 204 to each array 700. For example, Mi for each switch unit 604 could be the same or similar, and can be set at a level or value that causes the module 108IC to perform a net or time average discharge of energy to the one or more arrays 700-PA through 700-P Ω during balanced operation, so as to drain module 108IC at the same rate as other modules 108 in system 100. In some embodiments, Mi for each unit 604 can be set at a level or value that does not cause a net or time average discharge of energy during balanced operation (causes a net energy discharge of zero). This can be useful if module 108IC has a lower aggregate charge than other modules in the system.

[00141] When an unbalanced condition occurs between arrays 700, then the modulation indexes of system 100 can be adjusted to cause convergence towards a balanced condition or to minimize further divergence. For example, control system 102 can cause module 108IC to discharge more to the array 700 with low charge than the others, and can also cause modules

108-1 through 108-N of that low array 700 to discharge relatively less (e.g., on a time average basis). The relative net energy contributed by module 108IC increases as compared to the modules 108-1 through 108-N of the array 700 being assisted, and also as compared to the amount of net energy module 108IC contributes to the other arrays. This can be accomplished by increasing M_i for the switch unit 604 supplying that low array 700, and by decreasing the modulation indexes of modules 108-1 through 108-N of the low array 700 in a manner that maintains V_{out} for that low array at the appropriate or required levels, and maintaining the modulation indexes for other switch units 604 supplying the other higher arrays relatively unchanged (or decreasing them).

[00142] The configuration of module 108IC in FIGs. 10A-10B can be used alone to provide interphase or interarray balancing for a single system, or can be used in combination with one or more other modules 108IC each having an energy source and one or more switch portions 604 coupled to one or more arrays. For example, a module 108IC with Ω switch portions 604 coupled with Ω different arrays 700 can be combined with a second module 108IC having one switch portion 604 coupled with one array 700 such that the two modules combine to service a system 100 having $\Omega+1$ arrays 700. Any number of modules 108IC can be combined in this fashion, each coupled with one or more arrays 700 of system 100.

[00143] Furthermore, IC modules can be configured to exchange energy between two or more subsystems of system 100. FIG. 10C is a block diagram depicting an example embodiment of system 100 with a first subsystem 1000-1 and a second subsystem 1000-2 interconnected by IC modules. Specifically, subsystem 1000-1 is configured to supply three-phase power, PA, PB, and PC, to a first load (not shown) by way of system I/O ports SIO1, SIO2, and SIO3, while subsystem 1000-2 is configured to supply three-phase power PD, PE, and PF to a second load (not shown) by way of system I/O ports SIO4, SIO5, and SIO6, respectively. For example, subsystems 1000-1 and 1000-2 can be configured as different packs supplying power for different motors of an EV or as different racks supplying power for different microgrids.

[00144] In this embodiment each module 108IC is coupled with a first array of subsystem 1000-1 (via IO port 1) and a first array of subsystem 1000-2 (via IO port 2), and each module 108IC can be electrically connected with each other module 108IC by way of I/O ports 3 and 4, which are coupled with the energy source 206 of each module 108IC as described with respect to

module 108C of FIG. 3C. This connection places sources 206 of modules 108IC-1, 108IC-2, and 108IC-3 in parallel, and thus the energy stored and supplied by modules 108IC is pooled together by this parallel arrangement. Other arrangements such as series connections can also be used. Modules 108IC are housed within a common enclosure of subsystem 1000-1, however the interconnection modules can be external to the common enclosure and physically located as independent entities between the common enclosures of both subsystems 1000.

[00145] Each module 108IC has a switch unit 604-1 coupled with IO port 1 and a switch unit 604-2 coupled with I/O port 2, as described with respect to FIG. 10B. Thus, for balancing between subsystems 1000 (e.g., interpack or inter-rack balancing), a particular module 108IC can supply relatively more energy to either or both of the two arrays to which it is connected (e.g., module 108IC-1 can supply to array 700-PA and/or array 700-PD). The control circuitry can monitor relative parameters (e.g., SOC and temperature) of the arrays of the different subsystems and adjust the energy output of the IC modules to compensate for imbalances between arrays or phases of different subsystems in the same manner described herein as compensating for imbalances between two arrays of the same rack or pack. Because all three modules 108IC are in parallel, energy can be efficiently exchanged between any and all arrays of system 100. In this embodiment, each module 108IC supplies two arrays 700, but other configurations can be used including a single IC module for all arrays of system 100 and a configuration with one dedicated IC module for each array 700 (e.g., six IC modules for six arrays, where each IC module has one switch unit 604). In all cases with multiple IC modules, the energy sources can be coupled together in parallel so as to share energy as described herein.

[00146] In systems with IC modules between phases, interphase balancing can also be performed by neutral point shifting (or common mode injection) as described above. Such a combination allows for more robust and flexible balancing under a wider range of operating conditions. System 100 can determine the appropriate circumstances under which to perform interphase balancing with neutral point shifting alone, interphase energy injection alone, or a combination of both simultaneously.

[00147] IC modules can also be configured to supply power to one or more auxiliary loads 301 (at the same voltage as source 206) and/or one or more auxiliary loads 302 (at voltages stepped down from source 302). FIG. 10D is a block diagram depicting an example embodiment

of a three-phase system 100 A with two modules 108IC connected to perform interphase balancing and to supply auxiliary loads 301 and 302. FIG. 10E is a schematic diagram depicting this example embodiment of system 100 with emphasis on modules 108IC-1 and 108IC-2. Here, control circuitry 102 is again implemented as LCD 114 and MCD 112 (not shown). The LCDs 114 can receive monitoring data from modules 108IC (e.g., SOC of ES1, temperature of ES1, Q of ES1, voltage of auxiliary loads 301 and 302, etc.) and can output this and/or other monitoring data to MCD 112 for use in system control as described herein. Each module 108IC can include a switch portion 602A (or 602B described with respect to FIG. 6C) for each load 302 being supplied by that module, and each switch portion 602 can be controlled to maintain the requisite voltage level for load 302 by LCD 114 either independently or based on control input from MCD 112. In this embodiment, each module 108IC includes a switch portion 602A connected together to supply the one load 302, although such is not required.

[00148] FIG. 10F is a block diagram depicting another example embodiment of a three-phase system configured to supply power to one or more auxiliary loads 301 and 302 with modules 108IC-1, 108IC-2, and 108IC-3. In this embodiment, modules 108IC-1 and 108IC-2 are configured in the same manner as described with respect to FIGS. 10D-10E. Module 108IC-3 is configured in a purely auxiliary role and does not actively inject voltage or current into any array 700 of system 100. In this embodiment, module 108IC-3 can be configured like module 108C of FIG. 3B, having a converter 202B,C (FIGS. 6B-6C) with one or more auxiliary switch portions 602A, but omitting switch portion 601. As such, the one or more energy sources 206 of module 108IC-3 are interconnected in parallel with those of modules 108IC-1 and 108IC-2, and thus this embodiment of system 100 is configured with additional energy for supplying auxiliary loads 301 and 302, and for maintaining charge on the sources 206A of modules 108IC-1 and 108IC-2 through the parallel connection with the source 206 of module 108IC-3.

[00149] The energy source 206 of each IC module can be at the same voltage and capacity as the sources 206 of the other modules 108-1 through 108-N of the system, although such is not required. For example, a relatively higher capacity can be desirable in an embodiment where one module 108IC applies energy to multiple arrays 700 (FIG. 10A) to allow the IC module to discharge at the same rate as the modules of the phase arrays themselves. If the module 108IC is also supplying an auxiliary load, then an even greater capacity may be desired so as to permit the

IC module to both supply the auxiliary load and discharge at relatively the same rate as the other modules.

Example Embodiments of Topologies for Applications with Intermittent Charging

[00150] Example embodiments pertaining to modular energy systems 100 used in applications with intermittently available charge sources are described with reference to FIGs. 11A-16.

These embodiments can be implemented with all aspects of system 100 described with respect to FIGs. 1A-10F unless stated otherwise or logically implausible. As such, the many variations already described will not be repeated with respect to the following embodiments. These example embodiments are particularly suited for mobile applications, such as electric vehicles that operate on a rail (rail-based EVs) like trains, trams, trolleys, and other rolling stock, where the charge source is intermittently available. The embodiments can be used with other vehicles as well, such as cars, buses, trucks, maritime vehicles (e.g., electric ferries), planes, etc., and even in some stationary applications. Thus, for ease of description the example embodiments will be described in the context of a rail-based EV, particularly an electric tram or train, with the understanding that the embodiments have much wider applicability to other vehicles and applications.

[00151] The example embodiments can be implemented in a variety of configurations to store and deliver energy while the electric tram is moving through sections of rail where no charge source is available. FIG. 11A is an illustration depicting a portion of an example route of an electric tram 1100 traveling on rails 1105, where tram 1100 is traveling from a first location Stop-A to a second location Stop-B. A charge source is available within Zone-A surrounding Stop-A, and a charge source is also available within Zone-B surrounding Stop-B. The charge source can be positioned overhead, at ground-level or below ground. When within Zone-A and Zone-B, tram 1100 can extend an electrical contact device (e.g., a pantograph for a catenary) to connect to the charge source and, whether moving or stationary, can receive power for operating the loads of tram 1100 and for charging the energy sources 206 of system 100. Zone-N demarcates the length of rails 1105 between Zone-A and Zone-B where no charge source is available. When traveling through Zone-N, the contact device can be retracted and tram 1100 uses the energy stored within its one or more systems 100 to supply power for all loads within tram 1100.

[00152] Tram 1100 can be configured with one or more iterations of system 100, each with its own control system 102, and each iteration of system 100 can supply one or more loads, such as motor loads and auxiliary loads. The tram can have a single iteration of system 100 with one or more subsystems 1000 that supplies power for all loads of all cars. The one or more subsystems 1000 can share one control system 102 (e.g., a single MCD 112 for all subsystems 1000) or can have independent control systems 102. The cars can each have one or more subsystems 1000 of system 100 for supplying the loads within that car, or the cars can rely wholly on power supplied by a subsystem 1000 in another car. A combination of approaches can be used where a particular car has a subsystem 1000 for supplying certain loads of that particular car and that particular car can also have other loads that receive power from another subsystem 1000 in a different car.

[00153] FIG. 11B is a block diagram depicting an example embodiment of an electric tram 1100 having two cars 1101 and 1102 with an interconnection 1103 therebetween. System 100 is located in first car 1101, which has a retractable conductor 1104 for receiving charge from charge source 150 when conductor 1104 is in contact with source 150. System 100 can be configured to supply high-voltage multiphase power to one or more motors within each car 1101 and 1102. Here, system 100 has multiple arrays (not shown) for providing three-phase power (PA, PB, PC) over lines 1111 to motors 1110-1A through 1110-XA of car 1101, where X can be any integer two or greater. Lines 1111 continue through interconnection 1103 to car 1102 where the three-phase power can be supplied to motors 1110-1B through 1110-XB of car 1102.

[00154] System 100 can also be configured to supply multiple voltages for auxiliary loads having different power requirements, including multiphase power, single phase power, and DC power at one or more voltages each. Examples of auxiliary loads can include compressors for HVAC systems, a battery thermal management system (BTMS), onboard electrical networks for powering all automated aspects of tram 1100, and others. Here, system 100 is configured to supply three-phase power (PD, PE, PF) to three-phase auxiliary load 1112-1 over lines 1113, single phase (SP) power (line (L), neutral (N)) to single phase auxiliary load 1114-1 over lines 1115, DC voltage at a first level to auxiliary load 301-1 over lines 1117, and DC voltage at a second level to auxiliary load 302-1 over lines 1119 (see, e.g., power supply for loads 301 and 302 as described with respect to FIGs. 10D and 10E). Lines 1113, 1115, 1117, and 1119 continue through interconnection 1103 to supply similar loads 1112-2, 1114-2, 301-2, and 302-2

within car 1102. Here, supply for the loads within car 1101 is provided in parallel fashion via the same lines for the loads within car 1102. In other embodiments, different lines can be used to supply the various loads within each car 1101 and 1102 in non-parallel fashion depending on the needs of the implementation.

[00155] One or more motors 1110 (e.g., one, two, three, four, or more) can be secured to or associated with a bogie, and the rail-based vehicle can have multiple (e.g., two or more) such bogies for every car. Placement of system 100 and its subsystems 1000 can be in close proximity to motors 1110 or elsewhere as described herein. FIG. 11C is a side view depicting an example embodiment of tram 1100 with an electrical layout of that described with respect to FIG. 11A. Here, each car includes two bogies 1120 having two motors 1110, each configured to provide motive force for driving an axle 1122. System 100 is physically located in car 1101 and can be placed in a position that would reside above the passenger's heads as shown here or below the passenger's feet or floor in an alternative embodiment. Each car includes auxiliary loads 1112, 1114, 301 and 302. All motors 1110 and auxiliary loads are supplied by system 100 via the arrows shown (individual lines 1111, 1113, 1115, 1117, and 1119 are omitted for clarity).

[00156] FIG. 11D is a block diagram depicting another example embodiment of electric tram 1100, but with multiple subsystems 1000. Each subsystem 1000 can be configured as a separate pack with a common housing. In this example, car 1101 includes a first subsystem 1000-1 for supplying power for motors 1110-1 and 1110-2 over a set of lines 1111-1 and a second subsystem 1000-2 for supplying power for motors 1110-3 and 1110-4 over a set of lines 1111-2. Car 1102 includes a third subsystem 1000-3 for supplying power for motors 1110-5 and 1110-6 over a set of lines 1111-3 and a fourth subsystem 1000-4 for supplying power for motors 1110-7 and 1110-8 over a set of lines 1111-4. Car 1102 also includes a fifth subsystem 1000-5 for supplying multiphase and/or single phase power for one or more auxiliary loads. Here, subsystem 1000-5 supplies three-phase power to auxiliary load 1112 over lines 1113 and single phase power to auxiliary load 1114 over lines 1115. Each of subsystems 1000-1 through 1000-5 can be configured to supply DC power for loads 301 and 302 by way of one or more modules 108IC or 108C (see, e.g., FIG. 3C and FIGs. 10A-10F).

[00157] Each subsystem 1000 can be connected to sets of shared lines for sharing DC power, and these lines can cross between cars 1101 and 1102 through interconnection 1103. Lines 1130 can carry high-voltage positive and negative DC signals, DC_CS+ and DC_CS-, respectively,

from charge source 150, for supplying charge voltage to all of the modules 108 of each system 100 when tram 1100 is connected to a charge source 150. The shared lines can also exchange lower DC voltages for supply to auxiliary loads 301 and 302. Lines 1131 can carry positive and negative DC signals, DC1+ and DC1-, respectively, for supplying a lower DC voltage to auxiliary loads 301. For example, these lines can be similar to the lines interconnecting ports 3 and 4 of IC modules 108IC (and 108C) as described with respect to FIGs. 3C, 10D, and 10E, and can carry the voltage of the energy sources 206 of the interconnected modules 108. Lines 1132 can carry positive and negative DC signals, DC2+ and DC2-, respectively, for supplying a lower DC voltage to auxiliary loads 302. For example, these lines can be similar to the lines interconnecting ports 5 and 6 of IC modules 108IC (and 108C) as described with respect to FIGs. 3C, 10D, and 10E, and can carry a regulated stepped down voltage from sources 206.

[00158] FIG. 11E is a side view depicting another example embodiment of tram 1100 with an electrical layout of that described with respect to FIG. 11C. Here, each of subsystems 1000-1 through 1000-4 supplies power for two motors 1110 associated with axles 1122 of a bogie 1120. Subsystem 1000-5 in car 1102 supplies power for loads 1112 and 1114, which are also positioned in car 1102, but can be located in other cars as well. Each of subsystems 1000 is connected to shared lines 1130 for charging and energy exchange, as well as lines 1131 for energy exchange and supplying loads 301, and lines 1132 for supplying loads 302. As with the embodiment of FIG. 11B, each of subsystems 1000-1 through 1000-5 can be placed in a position that would reside above the passenger's heads (as shown here) or below the passenger's feet, or elsewhere.

[00159] FIG. 11F is a block diagram depicting another example embodiment of electric tram 1100 with multiple subsystems 1000, but with an auxiliary power converter 1150 instead of auxiliary subsystem 1000-5. Auxiliary converter 1150 can convert the high voltage available on DC lines 1130 into single and/or multiphase power for one or more auxiliary loads of tram 1100. In this embodiment, converter 1150 is configured to provide three phase power for three-phase load 1112 over lines 1152 and to provide single phase power for single phase load 1114 over lines 1154. When connected to charge source 150, auxiliary converter 1150 can use the DC voltage provided by source 150 over lines 1130 to power loads 1112 and 1114. As described with respect to FIG. 12B, when not connected to source 150, the other subsystems 1000-1 through 1000-4 can provide the power to auxiliary converter 1150 over lines 1130 by outputting

DC voltages from ports 7 and 8 to lines 1130 using bidirectional DC-DC converters 1210. The DC output voltages from each module 108 can be summed on the DC lines 1130 to provide sufficient voltage to power auxiliary converter 1150.

[00160] The embodiments of FIGs. 11B-11F are described with respect to tram 1100 having two cars 1101 and 1102, but can be extended to rolling stock having any number of cars (one, three, four, and more), with any combination of subsystems within each car (e.g., supplying one or more motors 1110, one or more loads 1112, one or more loads 1114, one or more loads 301, and/or one or more loads 302).

[00161] The embodiments of FIGs. 11D-11F can also include one or more conventional high voltage battery packs connected between lines 1130 (DC_CS+ and DC_CS-) like subsystems 1000. The conventional battery pack can include multiple batteries (e.g., Li ion) or HED capacitors connected in series, and is not configured as a modular cascaded multi-level converter. The conventional battery pack can be used to provide supplementary power for any subsystem 1000 (through the shared DC lines 1130), for auxiliary converter 1150, directly for a motor load 1110 (if connected through an inverter), directly for DC auxiliary loads 301 and 302 (e.g., connected through a DC-DC converter), and/or directly for AC auxiliary loads 1112 and/or 1114 (if connected through a DC-AC converter). The conventional battery pack can be charged by charge source 150 through a DC-DC converter interposed in series on lines 1130 between the convention pack and charge source 150. Alternatively, the interposed DC-DC converter can be omitted and the conventional pack can be selectively disconnected from lines 1130 with switches (e.g., contactors) when charge source 150 is connected and, after disconnection of source 150, the battery pack can be reconnected to lines 1130 and charged by one or more subsystems 1000.

[00162] Modules 108A-C and 108IC described herein can be used within tram 1100.

Additional example embodiments of module configurations are also described. FIG. 12A is a block diagram depicting an example embodiment of module 108D configured for use within system 100 of tram 1100. In all the embodiments described herein module 108D can include any number of energy sources 206, such as one or more batteries, one or more high energy density (HED) capacitors, and/or one or more fuel cells. If multiple batteries are included those batteries can have the same or different electrochemistries as described herein. Similarly, different types of high-energy density capacitors and fuel cells can be used. Each battery can be a single cell or multiple cells connected in series, parallel or a combination thereof to arrive at the desired

voltage and current characteristics. As shown in FIG. 12A, module 108 includes a first source 206A and a second source 206B, in the sources can be batteries of different types (e.g., such as an LTO battery and an LFP battery) or one can be a battery and the other can be an HED capacitor, or any other combination as described herein.

[00163] Module 108D includes converter 202B or 202C coupled with energy sources 206A and 206B in a manner similar to that described with respect to module 108B of FIG. 3B. Energy source 206A is coupled with energy buffer 204, which in turn is coupled with a unidirectional isolated DC-DC converter 1200. Module 108D includes I/O ports 7 and 8 that connect with the charge source signals DC_CS+ and DC_CS- respectively, via lines 1130. These signals are input to DC-AC converter 1202 of converter 1200 where they are converted to high-frequency AC form and then input to transformer and rectifier section 1204.

[00164] Transformer and rectifier section 1204 can include a high-frequency transformer and one phase diode rectifier. The DC voltage on ports 7 and 8 may be a voltage that is lower than the total voltage supplied by the charge source as subsystem 1000 may include many such modules 108 receiving charge simultaneously. Transformer and rectifier section 1204 can modify the voltage of the AC signal from converter 1202, if necessary, and convert the AC signal back into DC form to charge sources 206A and 206B. Section 1204 also provides high-voltage isolation to the other components 202, 204, 206 and 114 of module 108D.

[00165] Unidirectionality is provided by virtue of the diode rectifier which permits current to be received from charge source 150 and passed to buffer 204 but does not permit outputting current in the opposite manner. For example, upon braking if the vehicle has an energy recovery system then the current from braking can be transferred back to each module 108 through power connection 110 and routed to either of sources 206A and 206B by way of converter 202B,C. Presence of unidirectional DC-DC isolated converter 1200 (diode rectifier) will prevent that recovered energy from passing through module 108D back to the charge source via lines 1130.

[00166] LCD 114 can monitor the status of converter 1200, particularly converter 1202 and section 1204, over data connections 118-5 and 118-6, respectively. As with the other components of module 108E, monitor circuitry for converter 1202 and section 1204 can be included to measure currents, voltages, temperatures, faults, and the like. These connections 118-5 and 118-6 can also supply control signals to control switching of converter 1202 and to control any active elements within section 1204. Isolation of LCD 114 can be maintained by

isolation circuitry present on lines 118-5 and 118-6 (e.g., isolated gate drivers and isolated sensors).

[00167] FIG. 12B is a block diagram depicting an example embodiment of a module 108E. Module 108E is configured similarly to that of module 108D but has a bidirectional DC-DC isolated converter 1210 instead of converter 1200, and can perform bidirectional energy exchange between sources 206 (or power connection 110) and ports 7 and 8 connected to lines 1130. Bidirectional converter 1210 can route current from ports 7 and 8 to charge sources 206A and 206B (through converter 202B,C), route current from ports 7 and 8 to power the load (by output from converter 202B,C to ports 1 and 2), route current from sources 206A and/or 206B (with converter 202B,C) to ports 7 and 8 for powering one or more high voltage auxiliary loads via auxiliary converter 1150 (FIG. 11F), and route current from sources 206A and/or 206B (via converter 202B,C) to ports 7 and 8 for charging other modules 108 of system 100 by way of lines 1130.

[00168] Bidirectional converter 1210 is connected between I/O ports 7 and 8 and buffer 204 includes DC-AC converter 1202, connected to transformer 1206, which in turn is connected to AC-DC converter 1208. Converter 1202 can convert the DC voltage at ports 7 and 8 into a high-frequency AC voltage, which transformer 1206 can modify to a lower voltage if needed, and output that modified AC voltage to AC-DC converter 1208, which can convert the AC signal back into DC form for provision to sources 206A, 206B, or module ports 1 and 2. Transformer 1206 can also isolate module components 202, 204, 206, 1208, and 114 from the high voltage at ports 7 and 8. As with the other components of module 108E, monitor circuitry for converter 1202, transformer 1206, and converter 1208 can be included to measure currents, voltages, temperatures, faults, and the like. LCD 114 can monitor the status of converter 1210, particularly converter 1202, transformer 1206 (e.g., monitor circuitry or an active component associated therewith), and converter 1208, over data connections 118-5, 118-7, and 118-8, respectively. These connections 118-5 and 118-6 can also supply control signals to control switching of converter 1202 and to control any controllable elements associated with transformer 1206. Isolation of LCD 114 can be maintained by isolation circuitry present on lines 118-5 and 118-6 (e.g., isolated gate drivers and isolated sensors).

[00169] Furthermore, for electrochemical battery sources 206, the length of the charge pulses applied to sources 206 by AC-DC converter 1208 can be maintained to have a certain length,

e.g., less than 5 milliseconds, to promote the occurrence of the electrochemical storage reaction in the cells without the occurrence of significant side reactions that can lead to degradation. The charge methodology can incorporate active feedback from each energy source to ensure that battery degradation, if detected, is mitigated by lowering voltage or pausing the charge routine for that module, or otherwise. Such pulses can be applied at high C rates (e.g., 5C-15C and greater) to enable fast charging of the sources 206. The duration and frequency of the charge pulses can be controlled by control system 102. Examples of such techniques that can be used with all embodiments described herein are described in Int'l Publ. No. WO 2020/243655, filed May 29, 2020, and titled Advanced Battery Charging on Modular Levels of Energy Storage Systems, which is incorporated by reference herein for all purposes.

[00170] FIG. 13A is a schematic diagram depicting an example embodiment of module 108D. Converter 202B is coupled with secondary source 206B, and in other embodiments can be configured like converter 202C (FIG. 6C). Buffer 204 is configured here as a capacitor. I/O ports 7 and 8 are coupled to an LC filter 1302, which is in turn coupled to bidirectional converter 1210, specifically DC-AC converter 1202, which is configured as a full bridge converter with switches S10, S11, S12, and S13. LC filter 1302 can be a distributed DC filter that can filter harmonics from and to the DC lines 1130, provide a current slowing function if desired, and/or perform other functions. The full bridge outputs from nodes N1 and N2 are connected to a primary winding of transformer 1206 within section 1204. A secondary winding of transformer 1206 is coupled with nodes N3 and N4 of the diode rectifier of section 1204, having diodes D1-D4. The switches of converter 1202 can be semiconductor switches configured as MOSFETs, IGBT's, GaN devices, or others as described herein. LCD 114 or another element of control system 102 can provide the switching signals for control of switches S1-S6 and S10-S13. Along with the other functions described herein, converter 202B can be controlled to independently route current from ports 7 and 8 to source 206B for charging, or to I/O ports 1 and 2 for powering the motor loads 1110.

[00171] FIG. 13B is a schematic diagram depicting an example embodiment of module 108E. Converter 202B is coupled with secondary source 206B, and in other embodiments can be configured like converter 202C (FIG. 6C). Buffer 204 is configured as a capacitor. I/O ports 7 and 8 are coupled to an LC filter 1302, which is in turn coupled to bidirectional converter 1210, specifically DC-AC converter 1202, which is configured as a full bridge converter with switches

S10, S11, S12, and S13. The full bridge outputs from nodes N1 and N2 are connected to a primary winding of transformer 1206. A secondary winding of transformer 1206 is coupled with nodes N3 and N4 of a second full bridge circuit configured as AC-DC converter 1208, having switches S14, S15, S16, and S17. The switches of converter 1208 can be semiconductor switches configured as MOSFETs, IGBT's, GaN devices, or others as described herein. LCD 114 or another element of control system 102 can provide the switching signals for control of switches S1-S6 and S10-S17. Along with the other functions described herein, converter 202B can be controlled to independently route current from ports 7 and 8 to source 206B for charging, or to I/O ports 1 and 2 for powering the motor loads.

[00172] FIG. 13C is a schematic diagram depicting another example embodiment of module 108E, where AC-DC converter 1208 is configured as a push-pull converter with a first terminal of source 206 connected to one side of dual secondary windings of transformer 1206 through an inductor L2, and switches S18 and S19 connected between the opposite side of dual secondary windings and a common node (e.g., node 4) coupled with the opposite terminal of source 206. The push-pull configuration only requires two switches and thus is more cost-effective than a full bridge converter, although the switches have larger voltages applied across them.

[00173] FIG. 14A is a block diagram depicting an example embodiment of subsystem 1000 configured to supply three-phase power for two motors 1110-1 and 1110-2 in parallel. This embodiment includes three serial arrays 700-PA, 700-PB, and 700-PC with modules 108 arranged in cascaded fashion with ports 1 and 2 daisy-chained between modules as described elsewhere herein. Subsystem 1000 has three arrays 700-PA, 700-PB, and 700-PC for supplying three-phase power to one or more loads 1112 by way of system ports SIO1, SIO2, and SIO3. In this embodiment and that of FIG. 14B, each of modules 108 can be configured as module 108D (FIG. 12A) or module 108E (FIGs. 12B, 13A, 13B). A neutral signal is available at SIO6(N) if desired. The DC voltage signals DC_CS+ and DC_CS- supplied from lines 1130 are supplied to subsystem 1000 by system I/O ports SIO4 and SIO5, respectively. Ports 7 and 8 of each of modules 108 are daisy-chained such that the applied charge source voltage is divided across modules 108-1 through 108-N of each array 700. As with other embodiments, subsystem 1000 can be configured with N modules 108 in each array 700, where N can be any integer two or greater.

[00174] FIG. 14B is a block diagram depicting another example embodiment of subsystem 1000 configured to supply three-phase power for motors 1110-1 and 1110-2, and also having modules 108IC-1, 108IC-2, and 108IC-3. Modules 108IC can have interconnected energy sources 206 and can be configured for interphase balancing between arrays 700 as described elsewhere herein. Modules 108IC can also be configured to supply DC voltages to lines 1131 and 1132 for one or more auxiliary loads 301 and/or one or more auxiliary loads 302. The example embodiments of FIGs. 14A and 14B can be used as any of the subsystems 1000-1 through 1000-4 as described with respect to FIGs. 11D and 11E, depending on whether each subsystem 1000 is configured to supply power for auxiliary loads and is configured with interphase balancing capability through interconnected modules 108IC.

[00175] FIGs. 14C and 14D are schematic diagrams depicting example embodiments of module 108IC configured for use with the embodiment of FIG. 14B. In this embodiment module 108IC is configured with a single switch portion 604 configured to connect IO port 1 to either positive DC voltage of source 206 (port 3) or negative DC voltage of source 206 (port 4). A switch portion 602A regulates and steps down the voltage of source 206 for provision as the auxiliary load voltage for lines 1132. A filter capacitor C3 can be placed across ports 5 and 6. Module 108IC includes bidirectional converter 1210 configured with two full bridge converters similar to that of FIG. 13A. FIG. 14D depicts another embodiment where AC-DC converter 1208 is configured as a push-pull converter similar to the embodiment of FIG. 13B.

[00176] FIG. 15 is a block diagram depicting an example embodiment of subsystem 1000-5 configured to supply multiphase, single phase, and DC power for auxiliary loads of tram 1100. Subsystem 1000-5 has three arrays 700-PD, 700-PE, and 700-PF for supplying three-phase power to one or more loads 1112 by way of system ports SIO1, SIO2, and SIO3. Subsystem 1000-5 has a fourth array 700-PG for supplying single phase power to one or more loads 1114 by way of system outputs SIO6 (SP(L)) and SIO7 (SP(N)). Subsystem 1000-5 can be configured to supply power of as many different phases as necessary through the addition of further arrays 700. A number of modules 108 within each array can be varied depending on the voltage requirements of the load. For example, although all arrays 700 are shown here as having N modules 108, the value of N can differ between arrays. Each of the N modules 108 of each array 700 can be configured like module 108D (FIG. 13A) or module 108E (FIG. 13B).

[00177] Each array 700 can also include a module 108IC having interconnected sources 206 for energy sharing and interphase balancing. Modules 108IC-1 through 108IC-3 can be configured like the embodiments described with respect to FIGs. 14A and 14B. FIG. 16 is a block diagram depicting an example embodiment of module 108IC-4 for use in single phase array 700-PD. This embodiment is similar to that of FIG. 14A, except module 108IC-4 includes two switch portions 604-1 and 604-2. Portions 604-1 and 604-2 are configured to independently connect IO ports 1 and 2, respectively, to either VDCL+ (port 3) or VDCL- (port 4). I/O port 1 can be connected to port 2 of module 108-N of array 700-PD as shown in FIG. 15. I/O port 2 can serve as a neutral for the power provided by array 700-PD. An LC circuit 1600 can be connected between ports 1 and 2 as shown to provide filtering of harmonics.

[00178] In some embodiments, a separate subsystem 1000 may not be needed to generate the requisite three-phase and single phase voltages for auxiliary loads. In such embodiments, subsystem 1000-5 can be omitted and an auxiliary power converter can be used to instead generate the three-phase in single phase auxiliary load voltages. This auxiliary converter can be connected to DC charge source lines 1130 and can receive power either from charge source 150 or the other subsystems 1000 when charge source 150 is not connected.

[00179] The use of bidirectional converters 1210 in the modules of subsystems 1000-1 through 1000-5 allows those subsystems to supply relatively higher DC voltages across lines 1130, for example in a configuration where a large auxiliary load, such as a battery thermal management system (BTMS), is powered directly from lines 1130. In such an instance the auxiliary load connected across lines 1130 can be powered directly by the charge source when connected to tram 1100 and then can be powered by one or more subsystems 1000 outputting power from sources 206 through bidirectional converters 1210 of each module 108.

[00180] The embodiments disclosed herein are not limited to operation with any particular voltage, current, or power. By way of example and for purposes of context, in one sample implementation charge source 150 may provide a voltage of 600-1000V on lines 1130. Each of subsystems 1000-1 through 1000-4 may provide multiphase voltages that are regulated and stabilized by voltage and frequency if required, in those voltages may be 300-1000V depending on the needs of the motors. An example three-phase auxiliary voltage for load 1112 can be 300-500V, regulated and stabilized as needed. An example single phase auxiliary voltage for load 1114 can be 120-240V, regulated and stabilized as needed. Example auxiliary voltages for load

301 can be 48-60V and example auxiliary voltages for load 302 can be 24-30V. Again these are examples only for purposes of context and the voltages that system 100 can provide will vary depending on the needs of the application.

[00181] To maintain a balanced overall system, the energy of sources 206 of auxiliary subsystem 1000-5 can be transferred to any of the (non-auxiliary) subsystems 1000-1 through 1000-4 by way of lines 1131 and the shared interconnection module connections, and this energy can be used either for charging those subsystems 1000-1 through 1000-4 or supply to the motors. Thus energy from auxiliary subsystem 1000-5 can be used to power one or more motors even though not directly connected to those motors, but rather indirectly connected to those motors by way of one or more other subsystems 1000-1 through 1000-4. Similarly, energy recovered through braking can be shared between subsystems 1000-1 through 1000-5 by way of lines 1131 and the shared interconnection module connections.

[00182] Various aspects of the present subject matter are set forth below, in review of, and/or in supplementation to, the embodiments described thus far, with the emphasis here being on the interrelation and interchangeability of the following embodiments. In other words, an emphasis is on the fact that each feature of the embodiments can be combined with each and every other feature unless stated otherwise.

[00183] In many embodiments, a modular energy system controllable to supply power to a load is provided, the system including: a plurality of modules connected together to output an AC voltage signal including a superposition of first output voltages from each module, where each module includes: an energy source; a first converter connected to the energy source and configured to generate the first output voltage at a first port of the module; and a second converter connected between a second port of the module and the energy source, where the second converter is configured to receive a charge signal at the second port and convert the charge signal into a second output voltage to charge the energy source.

[00184] In some embodiments, the first converter includes a plurality of switches. The system where the plurality of switches can be configured as a full bridge converter.

[00185] In some embodiments, the second converter is a DC-DC converter including a transformer configured to isolate the energy source and the first converter from the second port. The system where the second converter can include a DC-AC converter connected between the second port and the transformer. The system where the second converter can include a diode

rectifier connected between the transformer and the energy source. The system where the second converter can include an AC-DC converter connected between the transformer and the energy source. The system where the AC-DC converter can be configured as a full bridge converter or a push-pull converter. The system where the second converter can be a unidirectional converter that conducts electricity from the second port to the energy source. The system where the second converter can be a bidirectional converter that conducts electricity between the second port and the energy source.

[00186] In some embodiments, the plurality of modules are serially connected as an array and are connected to receive a total charge source voltage such that a voltage of the charge signal applied to the second port of each module is divided down from the total charge source voltage. The system where the energy source can be a first energy source, and where each module can include a second energy source. The system where the second energy source can be connected to the first converter by an inductor. The system where the first energy source can be a lithium ion battery of a first type and the second energy source can be a lithium ion battery of a second type, where the first and second types can be different. The system where the first energy source can be a battery and the second energy source can be a high energy density (HED) capacitor.

[00187] In some embodiments, each module can further include an energy buffer connected in parallel with the energy source. The system where the energy buffer can be a capacitor.

[00188] In some embodiments, the system can further include a control system configured to control switching of the first and second converters. The system where the control system can include a plurality of local control devices associated with the plurality of modules, and a master control device communicatively coupled with the plurality of local control devices. The system where the control system can be configured to control switching of the second converter of each module to exchange energy between energy sources of the modules.

[00189] In many embodiments, a modular energy system controllable to supply power to a load is provided, the system including: a first array including a first plurality of modules connected together to output a first AC voltage signal including a superposition of output voltages from the first plurality of modules; and a second array including a second plurality of modules connected together to output a second AC voltage signal including a superposition of output voltages from the second plurality of modules, where each module of the first plurality and second plurality of modules includes: an energy source; a first converter connected to the

energy source and configured to generate the output voltage at a first port of the module; and a second converter connected to a second port of the module and the energy source, where the second converter is configured to receive a charge signal at the second port and convert the charge signal into a charge voltage to charge the energy source.

[00190] In some embodiments, the system can further include a first interconnection module coupled with the first array and a second interconnection module coupled with the second array, where the first and second interconnection modules each include: a first port and a second port; an energy source; a first converter connected to the energy source and configured to generate an output voltage at the first port; and a second converter connected to the second port and the energy source, where the second converter is configured to receive a charge signal at the second port and convert the charge signal into a charge voltage to charge the energy source. The system where the energy sources of the first and second interconnection modules can be connected in parallel. The system where the first interconnection module can be configured to supply power for an auxiliary load. The system where the first interconnection module can include a third port configured to connect the energy source of the first interconnection module to an auxiliary load. The system where the first interconnection module can include a third port configured to connect the energy source of the first interconnection module through switch circuitry and an inductor of the first interconnection module to an auxiliary load external to the first interconnection module. The system can further include a control system configured to control the first converter of each of the first and second interconnection modules to balance energy between the first and second arrays. The system can further include a control system configured to control the first converter of each of the first and second interconnection modules to balance energy between the first and second arrays.

[00191] In some embodiments, the first converter can include a plurality of switches. The system where the plurality of switches can be configured as a full bridge converter.

[00192] In some embodiments, the system where the second converter can be a DC-DC converter including a transformer configured to isolate the energy source and the first converter from the second port. The system where the second converter can include a DC-AC converter connected between the second port and the transformer. The system where the second converter can include a diode rectifier connected between the transformer and the energy source. The system where the second converter can include an AC-DC converter connected between the

transformer and the energy source. The system where the AC-DC converter can be configured as a full bridge converter or a push-pull converter. The system where the second converter can be a unidirectional converter that conducts electricity from the second port to the energy source. The system where the second converter can be a bidirectional converter that conducts electricity between the second port and the energy source.

[00193] In some embodiments, the first plurality of modules are serially connected in the first array and are connected to receive a total charge source voltage such that a voltage of the charge signal applied to the second port of each module of the first array is divided down from the total charge source voltage.

[00194] In some embodiments, the energy source is a first energy source, and where each module can include a second energy source. The system where the second energy source can be connected to the first converter by an inductor. The system where the first energy source can be a lithium ion battery of a first type and the second energy source can be a lithium ion battery of a second type, where the first and second types can be different. The system where the first energy source can be a battery and the second energy source can be a high energy density (HED) capacitor.

[00195] In some embodiments, each module of the first plurality of modules, each module of the second plurality of modules, the first interconnection module, and the second interconnection module further including an energy buffer connected in parallel with the energy source. The system where the energy buffer can be a capacitor.

[00196] In some embodiments, the system further including a control system configured to control switching of the first and second converters. The system where the control system can include a plurality of local control devices associated with the plurality of modules, and a master control device communicatively coupled with the plurality of local control devices. The system where the control system can be configured to control switching of the second converter of each module to exchange energy between energy sources of the modules.

[00197] In many embodiments, a modular energy system controllable to supply power to loads of an electric vehicle in provided, the system including: a first plurality of modules connected together in first, second, and third arrays, each array configured to output an AC voltage signal including a superposition of output voltages from the modules of that array; and a second plurality of modules connected together in a fourth array configured to output an AC

voltage signal including a superposition of output voltages from the second plurality of modules, where the first plurality of modules are configured to provide three-phase power to a first auxiliary load of the electric vehicle, and where the second plurality of modules are configured to provide single phase power to a second auxiliary load of the electric vehicle.

[00198] In some embodiments, the system further including a plurality of interconnection modules connected to the first, second, third, and fourth arrays. The system where a first interconnection module of the plurality of interconnection modules can be configured to provide DC power to a third auxiliary load of the electric vehicle. The system where the first interconnection module can include an energy source and can be configured to connect the energy source to the third auxiliary load. The system where the first interconnection module can include an energy source and can be configured to connect the energy source through switch circuitry and an inductor of the first interconnection module to the third auxiliary load.

[00199] In some embodiments, all of the modules individually include: an energy source; a first converter connected to the energy source and configured to generate the output voltage at a first port of the module; and a second converter connected to a second port of the module and the energy source, where the second converter is configured to receive a charge signal at the second port and convert the charge signal into a charge voltage to charge the energy source. The system can further include a control system configured to control the first converter of each of the plurality of interconnection modules to balance energy between the first, second, third, and fourth arrays. The system where modules of the first array can be serially connected to receive a total charge source voltage such that a voltage of the charge signal applied to the second port of each module of the first array is divided down from the total charge source voltage. The system where the first array, second array, and third array can be connected in parallel to receive a total charge source voltage such that a voltage of the charge signal applied to the second port of each module of each array is divided down from the total charge source voltage.

[00200] In some embodiments, every module further includes an energy buffer. The system where the energy buffer is a capacitor.

[00201] In some embodiments, the system further including a control system configured to control each of the modules.

[00202] In many embodiments, a modular energy system controllable to supply power to a load is provided, the system including: a plurality of modules connected together to output an

AC voltage signal including a superposition of first output voltages from each module, where each module includes an energy source, a first converter connected to the energy source and configured to generate the first output voltage at a first port of the module, and a second converter connected between a second port of the module and the energy source; and a control system configured to control the first converter and the second converter of each module.

[00203] In some embodiments, the control system is configured to control the first converter of each module to output the first output voltage according to a pulse width modulation technique. The system where the control system can be configured to control the second converter of each module to charge the energy source of the module.

[00204] In some embodiments, the control system is configured to control the second converter of each module to charge the energy source of the module and concurrently control the first converter of each module to output the first output voltage. The system where at least a subset of modules of the plurality of modules can be connected together in cascaded fashion such that the first port of each module in the subset is coupled to a first port of another module in the subset and the second port of each module in the subset is coupled to a second port of another module in the subset. The system where the control system can be configured to control the second converter of a first module in the plurality of modules and the second converter of a second module in the plurality of modules to exchange energy between the energy source of the first module and the energy source of the second module.

[00205] In some embodiments, the second converter of each module of the plurality of modules is a DC-DC converter including a transformer configured to isolate the energy source and the first converter from the second port. The system where the second converter of each module of the plurality of modules can include a DC-AC converter connected between the second port and the transformer. The system where the second converter of each module of the plurality of modules can include a diode rectifier connected between the transformer and the energy source. The system where the second converter of each module of the plurality of modules can include an AC-DC converter connected between the transformer and the energy source. The system where the AC-DC converter can be configured as a full bridge converter or a push-pull converter.

[00206] In some embodiments, the energy source is a first energy source, and where each module of the plurality of modules includes a second energy source coupled with the first converter by way of an inductor.

[00207] In some embodiments, the control system includes a plurality of local control devices associated with the plurality of modules, and a master control device communicatively coupled with the plurality of local control devices.

[00208] In some embodiments, the first plurality of modules are connected together in first, second, and third arrays, each configured to output an AC voltage signal including a superposition of output voltages from the modules of that array. The system can further include a second plurality of modules connected together in fourth, fifth, and sixth arrays, each configured to output an AC voltage signal including a superposition of output voltages from the modules of that array. The system can further include a third plurality of modules connected together in a seventh array configured to output an AC voltage signal including a superposition of output voltages from the third plurality of modules. The system where the first plurality of modules can be configured to provide three-phase power to a motor of the electric vehicle, the second plurality of modules can be configured to provide three-phase power to a first auxiliary load of the electric vehicle, and the third plurality of modules can be configured to provide single phase power to a second auxiliary load of the electric vehicle. The system where the control system can be configured to control a first converter and a second converter of each module of the second and third pluralities of modules.

[00209] In some embodiments, the system further includes an auxiliary converter coupled to DC lines of the system, the auxiliary converter configured to convert DC power from the DC lines to AC power for an auxiliary load. The control system can be configured to control the second converter of each module to output a DC voltage from the second port of each module such that the output DC voltages are applied to the DC lines to power the auxiliary converter.

[00210] In many embodiments, a method of operating a rail-based electric vehicle including a modular energy storage system is provided, the method including: outputting an AC power signal, including a plurality of first output voltages from a plurality of modules, to an electric motor of the rail-based electric vehicle, where the plurality of modules each include an energy source, a first converter coupled with the energy source and configured to output the first output voltage from a first port of the module, and a second converter coupled between the energy

source and a second port of the module; applying a charge signal to electric vehicle, where voltage from the charge signal is applied to the second port of each of the plurality of modules; and controlling the second converter of each of the plurality of modules to charge the energy source of each module. The method where the electric vehicle can be moving while the charge signal is applied.

[00211] The term “module” as used herein refers to one of two or more devices or sub-systems within a larger system. The module can be configured to work in conjunction with other modules of similar size, function, and physical arrangement (e.g., location of electrical terminals, connectors, etc.). Modules having the same function and energy source(s) can be configured identical (e.g., size and physical arrangement) to all other modules within the same system (e.g., rack or pack), while modules having different functions or energy source(s) may vary in size and physical arrangement. While each module may be physically removable and replaceable with respect to the other modules of the system (e.g., like wheels on a car, or blades in an information technology (IT) blade server), such is not required. For example, a system may be packaged in a common housing that does not permit removal and replacement any one module, without disassembly of the system as a whole. However, any and all embodiments herein can be configured such that each module is removable and replaceable with respect to the other modules in a convenient fashion, such as without disassembly of the system.

[00212] The term “master control device” is used herein in a broad sense and does not require implementation of any specific protocol such as a master and slave relationship with any other device, such as the local control device.

[00213] The term “output” is used herein in a broad sense, and does not preclude functioning in a bidirectional manner as both an output and an input. Similarly, the term “input” is used herein in a broad sense, and does not preclude functioning in a bidirectional manner as both an input and an output.

[00214] The terms “terminal” and “port” are used herein in a broad sense, can be either unidirectional or bidirectional, can be an input or an output, and do not require a specific physical or mechanical structure, such as a female or male configuration.

[00215] Different reference number notations are used herein. These notations are used to facilitate the description of the present subject matter and do not limit the scope of that subject

matter. Some figures show multiple instances of the same or similar elements. Those elements may be appended with a number or a letter in a “-X” format, e.g., 123-1, 123-2, or 123-PA. This -X format does not imply that the elements must be configured identically in each instance, but is rather used to facilitate differentiation when referencing the elements in the figures. Reference to a genus number without the -X appendix (e.g., 123) broadly refers to all instances of the element within the genus.

[00216] Various aspects of the present subject matter are set forth below, in review of, and/or in supplementation to, the embodiments described thus far, with the emphasis here being on the interrelation and interchangeability of the following embodiments. In other words, an emphasis is on the fact that each feature of the embodiments can be combined with each and every other feature unless explicitly stated otherwise or logically implausible.

[00217] Processing circuitry can include one or more processors, microprocessors, controllers, and/or microcontrollers, each of which can be a discrete or stand-alone chip or distributed amongst (and a portion of) a number of different chips. Any type of processing circuitry can be implemented, such as, but not limited to, personal computing architectures (e.g., such as used in desktop PC's, laptops, tablets, etc.), programmable gate array architectures, proprietary architectures, custom architectures, and others. Processing circuitry can include a digital signal processor, which can be implemented in hardware and/or software. Processing circuitry can execute software instructions stored on memory that cause processing circuitry to take a host of different actions and control other components.

[00218] Processing circuitry can also perform other software and/or hardware routines. For example, processing circuitry can interface with communication circuitry and perform analog-to-digital conversions, encoding and decoding, other digital signal processing, multimedia functions, conversion of data into a format (e.g., in-phase and quadrature) suitable for provision to communication circuitry, and/or can cause communication circuitry to transmit the data (wired or wirelessly).

[00219] Any and all communication signals described herein can be communicated wirelessly except where noted or logically implausible. Communication circuitry can be included for wireless communication. The communication circuitry can be implemented as one or more chips and/or components (e.g., transmitter, receiver, transceiver, and/or other communication circuitry) that perform wireless communications over links under the appropriate protocol (e.g., Wi-Fi,

Bluetooth, Bluetooth Low Energy, Near Field Communication (NFC), Radio Frequency Identification (RFID), proprietary protocols, and others). One or more other antennas can be included with communication circuitry as needed to operate with the various protocols and circuits. In some embodiments, communication circuitry can share antenna for transmission over links. RF communication circuitry can include a transmitter and a receiver (e.g., integrated as a transceiver) and associated encoder logic.

[00220] Processing circuitry can also be adapted to execute the operating system and any software applications, and perform those other functions not related to the processing of communications transmitted and received.

[00221] Computer program instructions for carrying out operations in accordance with the described subject matter may be written in any combination of one or more programming languages, including an object oriented programming language such as Java, JavaScript, Smalltalk, C++, C#, Transact-SQL, XML, PHP or the like and conventional procedural programming languages, such as the “C” programming language or similar programming languages.

[00222] Memory, storage, and/or computer readable media can be shared by one or more of the various functional units present, or can be distributed amongst two or more of them (e.g., as separate memories present within different chips). Memory can also reside in a separate chip of its own.

[00223] To the extent the embodiments disclosed herein include or operate in association with memory, storage, and/or computer readable media, then that memory, storage, and/or computer readable media are non-transitory. Accordingly, to the extent that memory, storage, and/or computer readable media are covered by one or more claims, then that memory, storage, and/or computer readable media is only non-transitory. The terms “non-transitory” and “tangible” as used herein, are intended to describe memory, storage, and/or computer readable media excluding propagating electromagnetic signals, but are not intended to limit the type of memory, storage, and/or computer readable media in terms of the persistency of storage or otherwise. For example, “non-transitory” and/or “tangible” memory, storage, and/or computer readable media encompasses volatile and non-volatile media such as random access media (e.g., RAM, SRAM, DRAM, FRAM, etc.), read-only media (e.g., ROM, PROM, EPROM, EEPROM, flash, etc.) and combinations thereof (e.g., hybrid RAM and ROM, NVRAM, etc.) and variants thereof.

[00224] It should be noted that all features, elements, components, functions, and steps described with respect to any embodiment provided herein are intended to be freely combinable and substitutable with those from any other embodiment. If a certain feature, element, component, function, or step is described with respect to only one embodiment, then it should be understood that that feature, element, component, function, or step can be used with every other embodiment described herein unless explicitly stated otherwise. This paragraph therefore serves as antecedent basis and written support for the introduction of claims, at any time, that combine features, elements, components, functions, and steps from different embodiments, or that substitute features, elements, components, functions, and steps from one embodiment with those of another, even if the following description does not explicitly state, in a particular instance, that such combinations or substitutions are possible. It is explicitly acknowledged that express recitation of every possible combination and substitution is overly burdensome, especially given that the permissibility of each and every such combination and substitution will be readily recognized by those of ordinary skill in the art.

[00225] As used herein and in the appended claims, the singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise.

[00226] While the embodiments are susceptible to various modifications and alternative forms, specific examples thereof have been shown in the drawings and are herein described in detail. It should be understood, however, that these embodiments are not to be limited to the particular form disclosed, but to the contrary, these embodiments are to cover all modifications, equivalents, and alternatives falling within the spirit of the disclosure. Furthermore, any features, functions, steps, or elements of the embodiments may be recited in or added to the claims, as well as negative limitations that define the inventive scope of the claims by features, functions, steps, or elements that are not within that scope.