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(54) **Title**: METHODS, SYSTEMS, AND DEVICES FOR IMPROVED ELECTRIC VEHICLE CHARGING
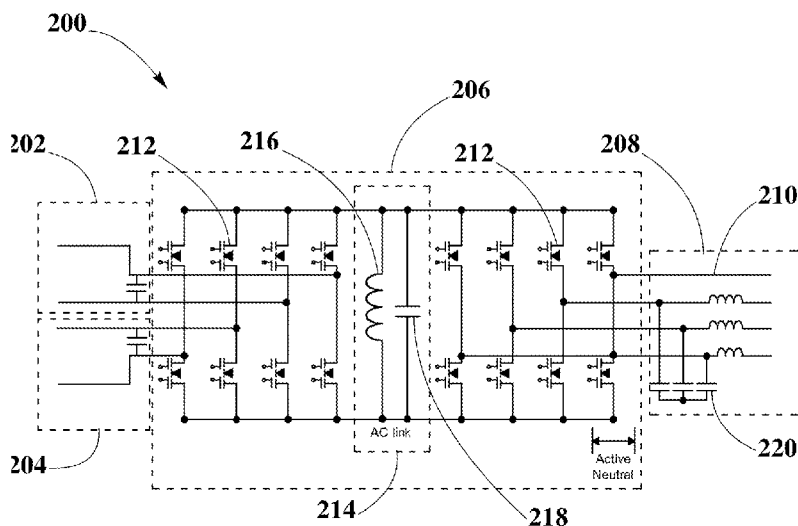
(57) **Abstract**: A car charging station in
which battery buffering includes at least
approximately as much energy as is re-
quired to charge one car rapidly. This is
particularly advantageous when a photo-
voltaic array is connected through a power
converter to charge the battery, and also to
provide a lower rate of charge directly to
the vehicle charge connections. Advant-
ageously, a mains power connection can
also be made through yet another port of
the same multiport power converter.

FIG. 1

METHODS, SYSTEMS, AND DEVICES FOR IMPROVED ELECTRIC VEHICLE CHARGING

CROSS-REFERENCE

[0001]   Priority is claimed from US Provisional 61/778,680 filed March 13, 2013, which is hereby incorporated by reference.

BACKGROUND

[0002]   The present application relates to electric vehicles, and more particularly to level III charging of electric vehicles.

[0003]   Note that the points discussed below may reflect the hindsight gained from the disclosed inventions, and are not necessarily admitted to be prior art.

[0004]   A new kind of power converter was disclosed in U.S. Patent No. 7,599,196 entitled "Universal power conversion methods," which is incorporated by reference into the present application in its entirety. This patent describes a bidirectional (or multidirectional) power converter which pumps power into and out of a link inductor which is shunted by a capacitor.

[0005]   The switch arrays at the ports are operated to achieve zero-voltage switching by totally isolating the link inductor+capacitor combination at times when its voltage is desired to be changed. (When the inductor+capacitor combination is isolated at such times, the inductor's current will change the voltage of the capacitor, as in a resonant circuit. This can even change the sign of the voltage, without loss of energy.) This architecture has subsequently been referred to as a "current-modulating" or "Power Packet Switching" architecture. Bidirectional power switches are

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used to provide a full bipolar (reversible) connection from each of multiple lines, at each port, to the rails connected to the link inductor and its capacitor. The basic operation of this architecture is shown, in the context of the three-phase to three-phase example of patent Figure 1, in the sequence of drawings from patent Fig. 12a to patent Fig. 12j.

[0006]   The ports of this converter can be AC or DC, and will normally be bidirectional (at least for AC ports). Individual lines of each port are each connected to a "phase leg," i.e. a pair of switches which permit that line to be connected to either of two "rails" (i.e. the two conductors which are connected to the two ends of the link inductor). It is important to note that these switches are bidirectional, so that there are four current flows possible in each phase leg: the line can source current to either rail, or can sink current from either rail.

[0007]   Many different improvements and variations are shown in the basic patent. For example, variable-frequency drive is shown (for controlling a three-phase motor from a three-phase power line), DC and single-phase ports are shown (patent Fig. 21), as well as three- and four-port systems, applications to photovoltaic systems (patent Fig. 23), applications to Hybrid Electric vehicles (patent Fig. 24), applications to power conditioning (patent Fig. 29), half-bridge configurations (patent Figs. 25 and 26), systems where a transformer is included (to segment the rails, and allow different operating voltages at different ports) (patent Fig. 22), and power combining (patent Fig. 28).

[0008]   Improvements   and   modifications   of   this   basic architecture have also been disclosed in U.S. Patents 8,391,033, 8,295,069, 8,531,858, and 8,461,718, all of which are hereby incorporated by reference.

[0009]   The term "converter" has sometimes been used to refer specifically to DC-to-DC converters, as distinct from DC-AC "inverters" and/or AC-AC frequency-changing "cycloconverters." However, in the present application the word converter is used more generally, to refer to all of these types and more, and especially to converters using a current-modulating or power-packet-switching architecture.

[00010]   The electric vehicle (EV) has become more common in recent years, and charging stations of different levels have developed to recharge the internal battery of electric vehicles. Conventionally, electric vehicle charging mechanisms can be divided into three charging levels: Level I, Level II, and Level III.

[00011]   Level I charging systems can take, on average, anywhere from 8 to 30 hours to fully charge an electric vehicle's internal battery. A Level I charging system can be supplied by low voltage AC lines, such as 208 VAC three-phase.

[00012]   Level II charging systems can require two to six hours to fully charge an electric vehicle's internal battery. Level III charging systems use large amounts of direct current to bypass the vehicle's on-board charger, and can take twenty to forty-five minutes to fully charge an electric vehicle's internal battery.

[00013]   While Level I charging systems can usually be fully supplied by low voltage AC lines, Level II and Level III charging systems usually require extra power, e.g. from an external battery. However, the inclusion of an external battery can require three or more power conversion stages. These additional power conversion stages can decrease efficiency, increase production costs, and increase size and weight.

SUMMARY

[00014]   The present inventors have realized that surprising synergies can result when a multiport bidirectional universal power converter is used to charge electric vehicles. In addition to decreased cost, size, and weight, the greatly increased efficiency permits various vehicle-to-grid applications, both from the electric vehicle itself and from any backup/buffer battery used in charging the vehicle.

[00015]   A multiport bidirectional universal power converter comprises an energy transfer reactance, e.g. an inductor and capacitor in parallel. The energy transfer reactance can be disconnected from external connections at various points in the charging cycle to match desired input/output signal characteristics.

[00016]   The disclosed innovations, in various embodiments, provide one or more of at least the following advantages. However, not all of these advantages result from every one of the innovations disclosed, and this list of advantages does not limit the various claimed inventions.

- Increased efficiency
- Decreased size and weight of charging systems
- Decreased production cost of charging systems
- Improved vehicle-to-grid capabilities

BRIEF DESCRIPTION OF THE DRAWINGS

[00017]   The disclosed inventions will be described with reference to the accompanying drawings, which show important sample embodiments and which are incorporated in the specification hereof by reference, wherein:

[00018]   **Figure 1** shows a schematic view for a bidirectional 3-port power conversion system, according to an exemplary embodiment.

[00019]   **Figure 2** shows a schematic view for a first level III charging mode, according to the state of the art.

[00020]   **Figure 3A** shows a simplified schematic of a sample power converter.

[00021]   **Figure 3B** shows sample voltage and current waveforms for a power cycle of a sample power converter.

[00022]   **Figure 3C** shows an exemplary finite state machine for one sample control architecture.

[00023]   **Figures 3D, 3E, and 3F** show sample embodiments of output and input voltages.

[00024]   **Figure 3G** shows one sample embodiment of a bidirectional switch.

[00025]   **Figure 3H** shows one sample embodiment of a bidirectional current-modulating power converter.

[00026]   **Figures 3I, 3J, 3K, 3L, 3M, 3N, 3O, 3P, 3Q, and 3R** show sample voltage and current waveforms on an inductor during a typical cycle while transferring power at full load from input to output.

[00027]   **Figure 3S** shows voltage and current waveforms corresponding to the full power condition of Figures 3I-3R, with the

conduction mode numbers corresponding to the mode numbers of Figures 3I-3R.

[00028]   **Figure 3T** shows an embodiment of the present inventions with a full bridge three phase cycle topology, with controls and I/O filtering, including a three phase input line reactor as needed to isolate the small but high frequency voltage ripple on the input filter capacitors from the utility.

[00029]   **Figure 3U** shows an embodiment of the present inventions with DC or Single Phase portals.

[00030]   **Figure 3V** shows an embodiment of the present inventions with a transformer/inductor.

[00031]   **Figure 3W** shows an embodiment of the present inventions in a four portal application mixing single phase AC and multiple DC portals, as can be used to advantage in a solar power application.

[00032]   **Figure 3X** shows an embodiment of the present inventions in a three portal application mixing three phase AC portals and a DC portal, as can be used to advantage in a Hybrid Electric Vehicle application.

[00033]   **Figure 3Y** shows an embodiment of the present inventions as a Half-Bridge Buck-Boost Converter in a Single Phase AC or DC Topology with BCBS.

[00034]   **Figure 3Z** show a sample embodiment in a Half-Bridge Buck-Boost Converter in a Three Phase AC Topology with BCBS.

[00035]   **Figure 3AA** shows a sample embodiment in a single phase to three phase synchronous motor drive.

[00036]   **Figure 3BB** shows a sample embodiment with dual, parallel, "power modules", each of which consists of 12 bi-directional

switches and a parallel inductor/capacitor. More than two power modules can of course be used for additional options in multiway conversion.

[00037]   **Figure 3CC** shows an embodiment of the present inventions as a three phase Power Line Conditioner, in which role it can act as an Active Filter and/or supply or absorb reactive power to control the power factor on the utility lines.

[00038]   **Figure 3DD** shows a sample schematic of a microgrid embodiment.

[00039]   **Figure 3EE** shows another sample embodiment of a microgrid.

[00040]   **Figure 4** shows a schematic view for a second level III charging mode, according to an exemplary embodiment.

[00041]   **Figure 5** shows a schematic view for a level I/II charging mode, according to an exemplary embodiment.

[00042]   **Figure 6** shows a schematic view for a first bidirectional multi-port power conversion system for plug-in hybrid electric vehicles, according to an exemplary embodiment.

[00043]   **Figure 7** shows a schematic view for a second bidirectional multi-port power conversion system for plug-in hybrid electric vehicles, according to an exemplary embodiment.

[00044]   **Figure 8** shows a schematic view for a multiple multi-port application for electric vehicle charging with micro-grid, according to an exemplary embodiment.

DETAILED DESCRIPTION OF SAMPLE EMBODIMENTS

[00045]   The numerous innovative teachings of the present application will be described with particular reference to presently preferred embodiments (by way of example, and not of limitation).   The present application describes several inventions, and none of the statements below should be taken as limiting the claims generally.

[00046]   Some exemplary parameters will be given to illustrate the relations between these and other parameters. However it will be understood by a person of ordinary skill in the art that these values are merely illustrative, and will be modified by scaling of further device generations, and will be further modified to adapt to different materials or architectures if used.

[00047]   Definitions:

[00048]   Anchoring – Using a switch to fix the voltage of one end of the link of a line voltage. Any change in link voltage will occur on the other end of the link.

[00049]   Direct Anchoring – Leaving one switch of line pair closed after a charge transfer is complete to anchor the voltage of one end of the link to the line voltage.

[00050]   Indirect Anchoring – Anchoring that occurs at the start of a charge transfer one the change in link voltage cause one switch to conduct and anchor that end of the link to the line voltage.

[00051]   Dominant Phase – The phase of the three phase port that has the largest amount of charge to be transfer to the link.

[00052]   FPGA – Field programmable gate array.

[00053]   GFDI – Ground fault detection and interruption.

[00054]   Islanding – When part of a power system consisting of one or more power sources and loads that is, for some period of time, is separated from the rest of the system.

[00055]   Link – Inductor and capacitor pair that transfer energy between input and output line pairs.

[00056]   Line pair – Two lines of a port that can transfer energy to or from the link.

[00057]   Line pair switches – The bidirectional switches that connect a line pair to the link. The switches are composed of two IGBT in series with parallel diodes.

[00058]   Microgrid – A small power grid to deliver power from a converter to local loads. The converter is the only power source of the microgrid.

[00059]   MPPT - Maximum Power Point Tracking, algorithm to maximize the amount of power from a photovoltaic array

[00060]   Referring initially to **Figure 3H**, illustrated is a schematic of a sample three phase converter **100** that illustrates the operation of a power-packet-switching converter. The converter **100** is connected to a first and second power ports **122** and **123** each of which can source or sink power, and each with a line for each phase of the port. Converter **100** can transfer electric power between said ports while accommodating a wide range of voltages, current levels, power factors, and frequencies between the ports.

[00061]   The first port can be for example, a 460 VAC three phase utility connection, while said second port can be a three phase induction motor which is to be operated at variable frequency and voltage so as to achieve variable speed operation of said motor. The present inventions can

also accommodate additional ports on the same inductor, as can be desired to accommodate power transfer to and from other power sources and/or sinks, as shown in Figures 3W and 3X.

[00062]   Referring to Figure 3H, converter **100** is comprised of a first set of electronic switches S_{1u}, S_{2u}, S_{3u}, S_{4u}, S_{5u}, and S_{6u} that are connected between a first line **113** of a link inductor **120** and each phase, **124** through **129**, of the input port, and a second set of electronic switches S_{1l}, S_{2l}, S_{3l}, S_{4l}, S_{5l}, and S_{6l} that are similarly connected between a second line **114** of link inductor **120** and each phase of the output port. A link capacitor **121** is connected in parallel with the link inductor, forming the link reactance. Each of these switches is capable of conducting current and blocking current in both directions, as seen in e.g. Figure 3G. Many other such bi-directional switch combinations are also possible.

[00063]   The converter **100** also has input and output capacitor filters **130** and **131,** respectively, which smooth the current pulses produced by switching current into and out of inductor **120.** Optionally, a line reactor **132** can be added to the input to isolate the voltage ripple on input capacitor filter **131** from the utility and other equipment that can be attached to the utility lines. Similarly, another line reactor, not shown, can be used on the output if required by the application.

[00064]   For illustration purposes, assume that power is to be transferred in a full cycle of the inductor/capacitor from the first to the second port, as is illustrated in **Figure 3S**. Also assume that, at the instant the power cycle begins, phases A_i and B_i have the highest line to line voltage of the first (input) port, link inductor **120** has no current, and link capacitor **121** is charged to the same voltage as exists between phase A_i and B_i. The controller FPGA **1500**, shown in **Figure 3T**, now turns on switches S_{1u} and

S_{2l}, whereupon current begins to flow from phases A_i and B_i into link inductor **120,** shown as Mode 1 of **Figure 3I.**

[00065]   Figure 3S shows the inductor current and voltage during the power cycle of Figures 3I-3R, with the Conduction Mode sequence **1300** corresponding to the Conduction Modes of Figures 3I-3R. The voltage on the link reactance remains almost constant during each mode interval, varying only by the small amount the phase voltage changes during that interval. After an appropriate current level has been reached, as determined by controller **1500** to achieve the desired level of power transfer and current distribution among the input phases, switch S_{2l} is turned off.

[00066]   Current now circulates, as shown in **Figure 3J**, between link inductor **120** and link capacitor **121**, which is included in the circuit to slow the rate of voltage change, which in turn greatly reduces the energy dissipated in each switch as it turns off.   In very high frequency embodiments of the present inventions, the capacitor **121** can consist solely of the parasitic capacitance of the inductor and/or other circuit elements. (Note that a similar process is shown in **Figure 3O.**)

[00067]   To continue with the cycle, as shown as Mode 2 in Figure 3K and Figure 3S, switch S_{3l} is next enabled, along with the previously enabled switch S_{1u}. As soon as the link reactance voltage drops to just less than the voltage across phases A_i and C_i, which are assumed for this example to be at a lower line-to-line voltage than phases A_i and B_i, switches S_{1u} and S_{3l} become forward biased and start to further increase the current flow into the link inductor, and the current into link capacitor temporarily stops.

[00068]   The two "on" switches, S_{1u} and S_{3l}, are turned off when the desired peak link inductor current is reached, said peak link inductor

current determining the maximum energy per cycle that can be transferred to the output. The link inductor and link capacitor then again exchange current, as shown if Figure 3J, with the result that the voltage on the link reactance changes sign, as shown in graph **1301,** between modes 2 and 3 of Figure 3S. Now as shown in **Figure 3L,** output switches S_{5u} and S_{6l} are enabled, and start conducting inductor current into the motor phases A_o and B_o, which are assumed in this example to have the lowest line-to-line voltages at the present instance on the motor.

[00069]   After a portion of the inductor's energy has been transferred to the load, as determined by the controller, switch S_{5u} is turned off, and S_{4u} is enabled, causing current to flow again into the link capacitor. This increases the link inductor voltage until it becomes slightly greater than the line-to-line voltage of phases A_o and C_o, which are assumed in this example to have the highest line-to-line voltages on the motor. As shown in **Figure 3M**, most of the remaining link inductor energy is then transferred to this phase pair (into the motor), bringing the link inductor current down to a low level.

[00070]   Switches S_{4u} and S_{6l} are then turned off, causing the link inductor current again to be shunted into the link capacitor, raising the link reactance voltage to the slightly higher input line-to-line voltage on phases A_i and B_i. Any excess link inductor energy is returned to the input. The link inductor current then reverses, and the above described link reactance current/voltage half-cycle repeats, but with switches that are compeimentary to the first half-cycle, as is shown in Figures 3N-3R, and in Conduction Mode sequence **1300**, and graphs **1301** and **1302. Figure 3O** shows the link reactance current exchange during the inductor's negative current half-cycle, between conduction modes.

[00071]   Note that TWO power cycles occur during each link reactance cycle: with reference to Figures 3I-3R, power is pumped IN during modes 1 and 2, extracted OUT during modes 3 and 4, IN again during modes 5 and 6 (corresponding to e.g. **Figure 3P**), and OUT again during modes 7 (as in e.g. **Figure 3Q**) and 8. The use of multi-leg drive produces eight modes rather than four, but even if polyphase input and/or output is not used, the presence of TWO successive in and out cycles during one cycle of the inductor current is notable.

[00072]   As shown in Figures 3I-3S, Conduction Mode sequence **1300,** and in graphs **1301** and **1302,** the link reactance continues to alternate between being connected to appropriate phase pairs and not connected at all, with current and power transfer occurring while connected, and voltage ramping between phases while disconnected (as occurs between the closely spaced dashed vertical lines of which **1303** in Figure 3S is one example.

[00073]   In general, when the controller 1500 deems it necessary, each switch is enabled, as is known in the art, by raising the voltage of the gate **204** on switch **200** above the corresponding terminal **205,** as an example. Furthermore, each switch is enabled (in a preferred two gate version of the switch) while the portion of the switch that is being enabled is zero or reverse biased, such that the switch does not start conduction until the changing link reactance voltage causes the switch to become forward biased. Single gate AC switches can be used, as with a one-way switch embedded in a four diode bridge rectifier, but achieving zero-voltage turn on is difficult, and conduction losses are higher.

[00074]   In **Figure 3T**, current through the inductor is sensed by sensor **1510**, and the FPGA **1500** integrates current flows to determine the current flowing in each phase (line) of the input and output ports. Phase

voltage sensing circuits **1511** and **1512** allow the FPGA 1500 to control which switches to enable next, and when.

[00075]   Figures 3I-3R shows current being drawn and delivered to both pairs of input and output phases, resulting in 4 modes for each direction of link inductor current during a power cycle, for a total of 8 conduction modes since there are two power cycles per link reactance cycle in the preferred embodiment.   This distinction is not dependent on the topology, as a three phase converter can be operated in either 2 modes or 4 conduction modes per power cycle, but the preferred method of operation is with 4 conduction modes per power cycle, as that minimizes input and output harmonics.

[00076]   For single phase AC or DC, it is preferred to have only two conduction modes per power cycle, or four modes per link reactance cycle, as there is only one input and output pair in that case.   For mixed situations, as in the embodiment of **Figure 3X** which converts between DC or single phase AC and three phase AC, there can be 1 conduction mode for the DC interface, and 2 for the three phase AC, for 3 conduction modes per power cycle, or 6 modes per link reactance cycle.   In any case, however, the two conduction modes per power half-cycle for three phase operation together give a similar power transfer effect as the singe conduction mode for single phase AC or DC.

[00077]   Another sample embodiment of the present inventions is shown in **Figure 3U**, which shows a single phase AC or DC to single phase AC or DC converter.   Either or both input and output can be AC or DC, with no restrictions on the relative voltages.   If a port is DC and can only have power flow either into or out of said port, the switches applied to said port

can be uni-directional. An example of this is shown with the photovoltaic array of Figure 3W, which can only source power.

[00078]   **Figure 3V** shows a sample implementation of a Flyback Converter. The circuit of Figure 3U has been modified, in that the link inductor is replaced with a transformer **2200** that has a magnetizing inductance that functions as the link inductor. Any embodiment of the present inventions can use such a transformer, which can be useful to provide full electrical isolation between ports, and/or to provide voltage and current translation between ports, as is advantageous, for example, when a first port is a low voltage DC battery bank, and a second port is 120 volts AC, or when the converter is used as an active transformer.

[00079]   In the embodiments of the present inventions shown in Figures 3W and 3X, the number of ports attached to the link reactance is more than two, simply by using more switches to connect in additional ports to the inductor. As applied in the solar power system of **Figure 3W**, this allows a single converter to direct power flow as needed between the ports, regardless of their polarity or magnitude.

[00080]   Thus, in one sample embodiment, the solar photovoltaic array can be at full power, e.g. 400 volts output, and delivering 50% of its power to the battery bank at e.g. 320 volts, and 50% to the house AC at e.g. 230 VAC. Prior art requires at least two converters to handle this situation, such as a DC-DC converter to transfer power from the solar PV array to the batteries, and a separate DC-AC converter (inverter) to transfer power from the battery bank to the house, with consequential higher cost and electrical losses. The switches shown attached to the photovoltaic power source need be only one-way since the source is DC and power can only flow out of the source, not in and out as with the battery.

[00081]   In the sample power converter of **Figure 3X**, as can be used for a hybrid electric vehicle, a first port is the vehicle's battery bank, a second port is a variable voltage, variable speed generator run by the vehicle's engine, and a third port is a motor for driving the wheels of the vehicle. A fourth port, not shown, can be external single phase 230 VAC to charge the battery. Using this single converter, power can be exchanged in any direction among the various ports. For example, the motor/generator can be at full output power, with 50% of its power going to the battery, and 50% going to the wheel motor. Then the driver can depress the accelerator, at which time all of the generator power can be instantly applied to the wheel motor. Conversely, if the vehicle is braking, the full wheel motor power can be injected into the battery bank, with all of these modes using a single converter.

[00082]   **Figures 3Y** and **3Z** show half-bridge converter embodiments of the present inventions for single phase/DC and three phase AC applications, respectively. The half-bridge embodiment requires only 50% as many switches, but results in 50% of the power transfer capability, and gives a ripple current in the input and output filters which is about double that of the full bridge implementation for a given power level.

[00083]   **Figure 3AA** shows a sample embodiment as a single phase to three phase synchronous motor drive, as can be used for driving a household air-conditioner compressor at variable speed, with unity power factor and low harmonics input. Delivered power is pulsating at twice the input power frequency.

[00084]   **Figure 3BB** shows a sample embodiment with dual, parallel power modules, with each module constructed as per the converter of Figure 3H, excluding the I/O filtering. This arrangement can be

advantageously used whenever the converter drive requirements exceed that obtainable from a singe power module and/or when redundancy is desired for reliability reasons and/or to reduce I/O filter size, so as to reduce costs, losses, and to increase available bandwidth.

[00085]   The power modules are best operated in a manner similar to multi-phase DC power supplies such that the link reactance frequencies are identical and the current pulses drawn and supplied to the input/output filters from each module are uniformly spaced in time. This provides for a more uniform current draw and supply, which can greatly reduce the per unit filtering requirement for the converter. For example, going from one to two power modules, operated with a phase difference of 90 degrees referenced to each of the modules inductor/capacitor, produces a similar RMS current in the I/O filter capacitors, while doubling the ripple frequency on those capacitors. This allows the same I/O filter capacitors to be used, but for twice the total power, so the per unit I/O filter capacitance is reduced by a factor of 2. More importantly, since the ripple voltage is reduced by a factor of 2, and the frequency doubled, the input line reactance requirement is reduced by 4, allowing the total line reactor mass to drop by 2, thereby reducing per unit line reactance requirement by a factor of 4.

[00086]   **Figure 3CC** shows a sample embodiment as a three phase Power Line Conditioner, in which role it can act as an Active Filter and/or supply or absorb reactive power to control the power factor on the utility lines. If a battery, with series inductor to smooth current flow, is placed in parallel with the output capacitor **2901**, the converter can then operate as an Uninterruptible Power Supply (UPS).

[00087]   **Figure 3A** shows an example of a circuit implementing this architecture. In this example, one port is used for connection to the AC

grid (or other three-phase power connection). The other is connected to a motor, to provide a variable-frequency drive.

[00088]   In Figure 3A, an LC link reactance is connected to two DC ports having two lines each, and to a three-phase AC port. Each line connects to a pair of bidirectional switches, such that one bidirectional switch connects the respective line to a rail at one side of the link reactance and the other bidirectional switch connects the line to a rail at the other side of the link reactance.

[00089]   In one sample embodiment, voltage and current across a link reactance can be seen in, e.g., **Figure 3B**. Link voltage waveform **1301** and link current waveform **1302** correspond to an arbitrary set of inputs and outputs. After a conduction interval begins and the relevant switches are activated, voltage 1301 on the link reactance remains almost constant during each mode interval, e.g. during each of modes 1-8. After an appropriate current level has been reached for the present conduction mode, as determined by the controller, the appropriate switches are turned off. This can correspond to, e.g., conduction gap **1303**. The appropriate current level can be, e.g., one that can achieve the desired level of power transfer and current distribution among the input phases.

[00090]   Current can now circulate between the link inductor and the link capacitor, which is included in the circuit to slow the rate of voltage change. This in turn greatly reduces the energy dissipated in each switch as it turns off. After the link voltage reaches appropriate levels for the next set of lines, the appropriate switches are enabled, and energy transfer between the port and the link continues with the next line pair.

[00091]   A power converter according to some embodiments of this architecture can be controlled by, e.g., a Modbus serial interface, which

can read and write to a set of registers in a field programmable gate array (FPGA). These registers can define, e.g., whether a port is presently an input, an output, or disabled. Power levels and operation modes can also be determined by these registers.

[00092]   In some embodiments, a DC port preferably has one line pair, where each line pair is e.g. a pair of lines that can transfer energy to or from the link reactance through semiconductor switches. A three-phase AC port will always have three lines, and will often have a fourth (neutral), but only two are preferably used for any given power cycle (of the inductor).

[00093]   Given three lines, there are three possible two-line combinations. For example, given lines A, B, and C, the line pairs will be A-B, B-C, and A-C.

[00094]   Register values for each port can be used to determine the amount of charge, and then the amount of energy, to be transferred to or from each port during each conduction period. An interface then controls each port's switches appropriately to transfer the required charge between the link and the enabled ports.

[00095]   A separate set of working registers can be used in some embodiments to control converter operations. Any value requiring a ramped rate of change can apply the rate of change to the working registers.

[00096]   The mode set for a port during a given power cycle can determine what factor will drive the port's power level. This can be, for example, power, current, conductance, or net power. In "net power" mode, the port's power level can be set by, e.g., the sum of other port's power settings. The mode of at least one port will most preferably be set to net power in order to source or sink the power set by the other ports. If two ports are set as net power, the two ports will share the available power.

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[00097]   A main control state machine and its associated processes can control the transfer of power and charge between ports, as seen in **Figure 3C**. The state machine can be controlled in turn by the contents of registers. The state machine transfers the amount of energy set by the interface from designated input ports to the link reactance, and then transfers the appropriate amount of energy from the link to designated output ports.

[00098]   The **Reset/Initialize** state occurs upon a power reset, when converter firmware will perform self-tests to verify that the converter is functioning correctly and then prepare to start the converter. If no faults are found, the state machine proceeds to the Wait_Restart state.

[00099]   The **Wait_Restart** state can be used to delay the start of the converter upon power up or the restart of the converter when certain faults occur. If a fault occurs, a bleed resistor is preferably engaged. Certain faults, once cleared, will preferably have a delay before restarting normal converter operation. The next state will be Startup.

[000100]   When the **Startup** state begins, there is no energy in the link. This state will put enough energy into the link to resonate the link to the operational voltage levels, which are preferably greater than the highest voltage of any input line pair.

[000101]   When starting from an AC port, the firmware will wait until a zero voltage crossing occurs on a line pair of the AC port. The firmware will then wait until the voltage increases to about 40 volts, then turn on the switches of the line pair for a short duration. This will put energy into the link and start the link resonating. The peak resonant voltage must be greater than the AC line pair for the next cycle. After the first energy transfer, more small energy transfers can be made to the link as the link voltage passes through the line pair voltage, increasing the link's

resonant voltage until the link's peak voltage is equal to or greater than the first input line pair voltage. At this point, a normal power cycle is ready to start and the state will change to Power Cycle Start upon detection of a zero current crossing in the link.

[000102]   In the **Power Cycle Start** state, the amount of charge and energy that will be transferred to or from the link and each port is determined at the start of a power cycle. This state begins on a link zero current crossing detection, so the link current will be zero at the start of the state. The link voltage will preferably be equal or greater than the highest input voltage.

[000103]   The input and output line pairs that are not disabled is preferably sorted by their differential voltages from the highest voltage to the lowest voltage, where outputs are defined as having a negative voltage with respect to the start of the current power cycle. If the power factor of the AC port is not unity, one of the two line pairs of the AC port will switch between input and output for a portion of a 60 Hz waveform.

[000104]   If a DC port's mode is set to have constant current or constant power, the constant current or power levels are converted to equivalent conductance values and used to adjust the relevant port's settings appropriately. If the port's mode is set to net power, the port will transfer the sum of all the energy of all other ports not in net power mode.

[000105]   MPPT (Maximum Power Point Tracking) mode preferably constantly adjusts the charge put into the Link from a photovoltaic array to maximize transferred energy. There will typically be a maximum current draw after which voltage begins to decrease, where the particular maximal current depends on the photovoltaic array's output characteristics. This maximal current corresponds to maximum power,

beyond which point energy transfer will decline. To determine this maximal point, energy transfer can be monitored while conductance is adjusted until a local maximum is found. There can be some variations in the amount of energy delivered, but this will tend to maximize energy transfer.

[000106]   The charge Q to be transferred to the link can be found as, e.g., the product of conductance G, voltage V, and link power cycle period T (i.e. $Q=G*V*T$). The energy E to be transferred is then simply the product of the voltage times the charge ($E=V*Q=G*V^2*T$).

[000107]   Since other port operation modes prescribe the energy to be transferred to or from the link, at least one port is most preferably in "net power" mode. This assures that at least one port is most preferably thus dependent on the energy in the link, rather than prescribing the same, so that the amount of energy put into the link equals the amount of energy taken out of the link.

[000108]   The amount of energy that is put into the link by other modes is summed together to determine the energy transfer to or from ports operating in net power mode. A small amount of energy can in some cases be subtracted from this sum if extra energy is to be added to the link this cycle. If multiple ports are operating in net power mode, the available energy is preferably split between the two ports according to, e.g., the Modbus registers. The amount of charge to be transferred is preferably determined by the relationship charge = energy / voltage.

[000109]   For an AC port, the phase angle between the voltage and current on the AC port can be varied, based on e.g. power factor settings. An AC port can also source reactive current for AC port filter capacitors to prevent the filter capacitors from causing a phase shift.

[000110]   Three-phase charge calculations for a three-phase AC port can, in some embodiments, proceed as follows. Zero crossing of the AC voltage waveform for a first phase is detected when the voltage changes from a negative to positive. This can be defined as zero degrees, and a phase angle timer is reset by this zero crossing. The phase angle timer is preferably scaled by the measured period of the AC voltage to derive the instantaneous phase angle between the voltage of this first phase and the zero crossing. The instantaneous phase angle can then be used to read the appropriate sinusoidal scalar from a sinusoidal table for the first phase. The instantaneous phase angle can then be adjusted appropriately to determine the sinusoidal scalars for the second and third phases.

[000111]   The instantaneous phase angle of the first phase can be decremented by e.g. 90° to read a reactive sinusoidal scalar for the first phase, and then adjusted again to determine reactive sinusoidal scalars for the other two phases.

[000112]   The required RMS line current of the port can then be determined, but can differ dependent on, e.g., whether the port is in net power mode is controlled by conductance. In conductance mode, RMS line current can be found by, e.g., multiplying the conductance for the AC port by its RMS voltage.

[000113]   In net power mode, RMS line current can be found e.g. as follows. The energy transferred to the link by all ports not in net power mode is first summed to determine the net power energy available. The small amount of energy defined by the link energy management algorithm can be subtracted from the available energy if relevant. The net energy available is multiplied by the percentage of total power to be allocated to the

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present port, which is 100% if only one port is in net power mode: Power= Σ Energy* port %.

[000114]   Line RMS current can then be found by dividing the energy for the AC port by the RMS voltage of the port, the link power cycle period, and square root of 3: line current$_{rms}$ = Power / (time$_{link\ cycle}$ * voltage$_{rms}$ * $\sqrt{3}$).

[000115]   The instantaneous in-phase current can then be calculated, and will again differ based on the operational mode of the port. In a conductance mode, the three line-to-line instantaneous voltages can be multiplied by the port conductance to determine the instantaneous current of each phase.

[000116]   In net power mode, the sinusoidal scalar for each phase can be multiplied by the RMS line current to determine the instantaneous current of each phase. Alternately, voltages from an analog/digital converter can be used to find the instantaneous currents directly: Instantaneous Current = energy*$V_{a/d}$/(3*period*$Vrms^2$). The charge can then be found as Q = energy * $V_{a/d}$/(3*Vr_{ms}^2).

[000117]   RMS line reactive current can then be found e.g. from power factor as follows:

Power Factor = Power / (Power+reactive power)

reactive power = (Power/power factor) – Power

reactive power$_{line\ to\ line}$ = Power/(3*power factor)–Power/3

rms reactive current$_{line}$= reactive power$_{line\ to\ line}$/ rms voltage$_{line\ to\ line}$.

[000118]   Filter capacitive current can then be calculated from the filter capacitance values, line to line voltage, and frequency. Capacitive compensation current can then be added to the RMS line reactive current to determine the total RMS line reactive current. Total RMS reactive current

can then be multiplied by the reactive sinusoidal scalar to derive the instantaneous reactive current for each phase.

[000119]   The instantaneous current and the instantaneous current for each phase can then be added together and multiplied by the period of the link power cycle to determine the amount of charge to be transferred for each phase.

[000120]   The energy to transfer to or from the link can be found by multiplying the charge value of each phase by the instantaneous voltage and summing the energy of the three phases together.

[000121]   The phase with the largest charge will be dominant phase for this cycle, and the two line pairs for the AC port will be between the dominant phase and each of the other two phases. The amount of charge to be transferred for each line pair is preferably the amount of charge calculated for the non-dominant line of the pair. The next state will be the Charge Transfer state.

[000122]   In the **Charge Transfer** state, a first line pair is selected and the respective switches turned on. Even though the switches are on, no conduction will occur until the voltage of the link drops below that of an input line pair, or rises above the voltage of an output line pair where appropriate. If one end of the link inductor reaches the voltage of one line of the line pair, that end of the link inductor is indirectly anchored to the respective line. The link inductor will subsequently not change in voltage until the respective switch is turned off.

[000123]   The voltage of the line pair is then compared to the integrated link voltage. It is generally assumed that current will begin to flow through the switches once the integrated link voltage reaches the

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voltage of the line pair, minus a switch voltage drop. This switch voltage drop is assumed to be on the order of e.g. 8 V for a pair of switches.

[000124]   The amount of charge flowing into or out of the link is monitored. The charge can be found as $Q = \sum I \Delta t$, or the sum of the current times the time interval.

[000125]   The link current is typically approximately zero at the start of a power cycle. The link current increases through the end of the last input, then decreases until reaching zero at the beginning of the next power cycle. The link current can be found as $I = \sum(V_{instantaneous}\Delta t/L)$, or the sum of the instantaneous voltage times the time interval divided by the inductance.

[000126]   When the transferred charge is determined to have met the calculated amount for the given line pair, the state machine can progress to the next state. The next state can be Common Mode Management, or can be Idle. If the next state is Idle, all switches are turned off. In some sample embodiments, the state machine will only progress to the Common Mode Management state after the final output line pair.

[000127]   The **Common Mode Management** state controls the common mode voltage of the link, as well as the energy left in the link following the prior state. To control the common mode voltage, one of the switches for the prior line pair is turned off, while the other switch is controlled by the Common Mode Management state. By having one switch on, the adjacent end of the link can be anchored at the respective line voltage. The voltage at the opposite end of the link can then increase until the current through the inductor drops to zero. The remaining switch can then be turned off. When a zero crossing is detected in the link current, the state machine will progress to the Idle state.

[000128]   Two types of anchoring can be used in Common Mode Management. Direct anchoring occurs when one switch of a line pair is closed (turned on), which fixes the voltage of the nearest end of the link to the respective line voltage. While this switch is turned on, any change to the link's differential voltage will occur on the other end of the link, which will in turn change the link's common mode voltage.

[000129]   Indirect anchoring occurs when both of a line pair's switches are turned on prior to a charge transfer. When the voltage of one end of the link is one switch-voltage-drop below the corresponding line voltage, the respective end of the link is anchored to that voltage. The voltage of the other end of the link will continue to change until the voltage across the link is equal to two switch-voltage-drops below the line pair voltage. At this point, charge transfer between the link and the line pair begins.

[000130]   The Common Mode Management state also controls the energy left in the link after output charge transfer is completed, or after ramp-up. After the last output charge transfer, enough energy will most preferably remain in the link to have completed the last output charge transfer, and to cause the link voltages first to span, and then to decrease to just below, the voltages of the first input line pair. This can permit zero-voltage switching of the input switches. Zero-voltage switching, in turn, can reduce switching losses and switch overstressing. The voltages across the switches when conduction begins can preferably be e.g. 4 V, but is most preferably no more than 20 V. If insufficient energy remains in the link to permit zero-voltage switching, a small amount of power can be transferred from one or more ports in net power mode to the link during the subsequent power cycle.

[000131]   **Figure 3D** shows a sample embodiment in which the voltages of the last output span the voltages of the first input. It can be seen that the link-energy requirements have been met, though small amounts of energy can occasionally be needed to account for link losses.

[000132]   **Figure 3E** shows another sample embodiment in which the voltages of the last output are spanned by the voltages of the first input. Enough energy must be maintained in the link to resonate the link voltages to above the voltages of the first input. Additional energy can sometimes be needed to account for small link losses, but the link-energy requirements can be met fairly easily.

[000133]   **Figure 3F** shows a third sample embodiment, in which the voltages of the last output neither span nor are spanned by the voltages of the first input. Since the last output voltages do not span the first input voltages, the link voltage will need to be increased. Enough energy in the link needs to be maintained in the link to resonate the link voltages above the voltages of the first input pair before the link current crosses zero. This can in some sample embodiments require small amounts of additional energy to fulfill this requirement.

[000134]   In each of the sample embodiments of Figures 3D-3F, the common mode voltage of the link will preferably be forced toward the common mode voltage of the first input. The switch of the last output furthest in voltage from the common mode voltage will preferably be turned off first. The link will thus first anchor to the end with a voltage closest to that desired while the other end changes. The other switch is preferably turned off either once the common mode voltage of the first input is turned off or else a zero-crossing is detected in the link current.

[000135]   The **Idle State** most preferably ensures that all link switches remain for a period of time immediately after a switch is turned off. As switches do not turn off instantaneously, this can be used to minimize cross-conduction between lines, which can occur when one switch is turned on before another has time to completely turn off. In some sample embodiments in which the switches comprise e.g. IGBTs, the time between nominal and actual turn-off of the switches can be significant. After the requisite time has elapsed, the state machine can advance to the next state. If the prior state was the last line pair, the next state is preferably the Power Cycle Start state, and is otherwise preferably the Charge Transfer state.

[000136]   In one sample embodiment, the bidirectional switches can comprise, e.g., two series IGBTs and two parallel diodes, as in **Figure 3G**. In an embodiment like that of Figure 3G, a bidirectional switch can have two control signals, each controlling one direction of current flow. Other bidirectional switches are also possible.

[000137]   Switch control signals are most preferably monitored to prevent combinations of switches being turned which can lead to catastrophic failures of the converter. Only switches corresponding to a single line pair will preferably be enabled at a time. As relatively few possible switch combinations will prevent catastrophic failure, monitoring can look for the few permissible combinations to allow instead of looking for the many combinations to forbid.

[000138]   Switch control signals can preferably also be monitored to avoid turning new switches on too quickly after another switch has been turned off. The switches take a finite time to turn off, and turning on another switch too quickly can cause damaging cross-conduction.

[000139]   Voltage across each switch is also preferably monitored before it is turned on to avoid damaging overvoltage.

[000140]   Zero-crossings in the link current are preferably detected e.g. using a toroid installed on a link cable. Instead of directly measuring link current, it can be calculated by integrating the voltage across the link and scaling the result. This calculated current can preferably be reset every time a zero-crossing is detected, to prevent long-term accumulation of error. Zero-crossings, when detected, can also be used to set the link polarity flag, as the voltage across the link reverses when the direction of current flow changes.

[000141]   In some sample embodiments, power converter voltages can be measured with high-speed serial analog-to-digital (A/D) converters. In one sample embodiment, these converters can have e.g. a 3 MSPS (mega-samples per second) conversion rate. In one sample embodiment, the converters can take e.g. 14 clocks to start a conversion and clock in the serial data, leading to e.g. a data latency of $0.3\mu s$. One sample embodiment can use e.g. 22 such A/D converters.

[000142]   Islanding occurs when a converter continues to output power when the AC power grid goes down. This can be extremely dangerous, especially for line crews attempting to fix the AC power grid. Islanding conditions are most preferably detected and used to trigger a shutdown of the converter's AC output.

[000143]   Preferably ground fault detection is used on the DC inputs. When DC contactors are closed, the voltage drop between the common connection of a port's connectors and the DC port's ground connection will preferably be measured. If this voltage is over a certain

limit, either too much ground current is present or else the port's ground fuse is blown. Both of these situations will generate a fault.

[000144]   A fault will preferably be generated if toroids on input cables detect surges.

[000145]   Each DC port will preferably have a pair of contactors connecting positive and negative power sources to an input ground connection. Configuration information is preferably read from the registers and used to open or close the contactors as needed. Before contactors are closed, DC filter capacitors are preferably pre-charged to the voltage on the line side of the contactors in order to prevent high-current surges across the contacts of the contactors.

[000146]   An LCD or other type of screen is preferably provided as an interface to a power converter.

[000147]   The temperature of a heat sink is preferably monitored and used to direct fans. Tachometers on the fans can preferably be monitored, and the information used to shut down fan control lines if a fan fails. As these temperature sensors can occasionally give incorrect information, in some sample embodiments e.g. two preceding readings can be compared against the current temperature reading, and e.g. the median value can be chosen as the current valid temperature.

[000148]   In some sample embodiments, a processor can be used to control a power converter. This can be e.g. a NIOS processor which is instantiated in the field-programmable gate array.

[000149]   In some sample embodiments, an interface to e.g. a 1GB flash RAM can be used. In one sample embodiment, a flash RAM can have e.g. a 16-bit-wide bus and e.g. a 25-bit address bus. In some sample

embodiments, an active serial memory interface can permit reading from, writing to, or erasing data from a serial configuration flash memory.

[000150]   In some sample embodiments, a field-programmable gate array can be connected to e.g. a 1MB serial nvSRAM with real time clock.

[000151]   In some sample embodiments, dual row headers on a pc board can be used e.g. for testing and debugging purposes.

[000152]   In some sample embodiments, LEDs or other indicators can be present on a control board. These indicators can be used e.g. for diagnostic purposes.

[000153]   To minimize risks of condensation or other types of moisture damaging electronics, a power converter can preferably be kept in a sealed compartment. Some air flow is often necessary, however, due to e.g. temperature changes over time. Any air flowing into or out of the converter most preferably passes through one or more dehumidifiers. If left alone, the dehumidifiers eventually saturate and become useless or worse. Instead, heating elements can preferably be included with dehumidifiers to drive out accumulated moisture. When air flows into the otherwise-sealed compartment, dehumidifiers can remove moisture. When air flows out of the compartment, the heating elements can activate, so that ejected moisture is carried away with the outflowing air instead of continuing into the converter.

[000154]   **Figures 3DD** and **3EE** show two sample embodiments of bi-directional multi-port power conversion systems. In this sample embodiment, first input port **102** can include a power generator **202** connected to wind turbines **204**, second input port **104** can include DC port for energy storage, and output port **108** can include an AC power grid.

[000155]   According to one sample embodiment, generator **202** connected to wind turbines **204** can produce asynchronous AC, this

asynchronous AC from generator **202** can be transformed to synchronous AC by power conversion module **106**, and subsequently stored in second input port **104**.

[000156] All scientific and technical terms used in the present disclosure have meanings commonly used in the art, unless otherwise specified. The definitions provided herein are to facilitate understanding of certain terms used frequently and are not meant to limit the scope of the present disclosure.

[000157] **Figure 1** shows a bidirectional 3-port power conversion system **200**, in accordance with the present application. 3-port power conversion system **200** can be used to convert energy from first input portal **202** and second input portal **204**, passing through a power converter **206** to output portal **208** while adjusting a wide range of voltages, current levels, power factors, and frequencies between portals. According to an exemplary embodiment, first input portal **202** can include a DC generator, such as buffer battery **102**. Second input portal **204** can include a second DC port such as level III charger **112**. Output portal **208** can be a three-phase AC port enhanced with an active neutral **210** to support micro-grid functionality. Furthermore, output portal **208** can include a low power AC such as AC power grid **108**.

[000158] Power converter **206** can include different bidirectional switches **212** connected between first input portal **202**, second input portal **204**, and link **214** to output portal **208**. Each bidirectional switches **212** is capable of conducting and blocking current in two directions, and can be composed of bidirectional internal gate bipolar transistors (IGBTs) or other bidirectional switches. Most combinations of bidirectional switches contain two independently controlled gates, with each gate controlling current flow

in one direction. Generally, in the embodiments described, when switches are enabled, only the gate that controls current in the desired direction is enabled.

[000159]   Link **214** can include link inductor **216** and link capacitor **218**, connected in parallel with link inductor **216**, forming a resonant circuit that can allow for soft switching and flexibility of adjusting link **214** voltage to meet individual needs of first input portal **202**, second input portal **204**, and output portal **208**. Additionally, link **214** can provide isolation between first input portal **202**, second input portal **204**, and output portal **208**, eliminating the need for a transformer, as well as improving speed of response and reducing acoustic noise in case of frequency being outside audible range.

[000160]   Furthermore, filter capacitors **220** can be placed between input phases and also between output phases, in order to closely approximate first input portal **202**, second input portal **204**, and output portal **208**, and to attenuate current pulses produced by the bidirectional switches **212** and link inductor **216**. An input line reactor can be needed in some applications to isolate the voltage ripple on the input and output filter capacitors **220**.

[000161]   **Figure 2** shows a schematic view for a first level III charging mode **100**, according to the state of the art. First level III charging mode **100** can include buffer battery **102**, DC-AC converter **104**, first AC-DC converter **106**, AC power grid **108**, second AC-DC converter **110**, level III charger **112**, and electric vehicle **114**.

[000162]   According to first level III charging mode **100**, an internal battery from an electric vehicle or plug-in hybrid electric vehicle such as electric vehicle **114** can require between 40 and 60 kilowatts in order to be charged. However, a low power AC such as AC power grid **108** often

provides no more than e.g. 10kw of power. Buffer battery **102** can be needed in order to supply the additional energy. Furthermore, in order to supply energy to level III charger **112**, energy from buffer battery **102** must be transferred to a DC-AC converter **104**, and subsequently to a first AC-DC converter **106**. In addition to this process, second AC-DC converter **110** can be used in order to convert low power AC from AC power grid **108** into DC for level III charger **112**.

[000163]   **Figure 4** shows a schematic view for a second level III charging mode **300**, according to the present application. Second level III charging mode **300** can include buffer battery **102**, AC power grid **108**, power converter **206**, level III charger **112**, and electric vehicle **114**. Where buffer battery **102** can correspond to first input portal **202**, level III charger **112** can correspond to second input portal **204**, and AC power grid **108** can correspond to output portal **208** (explained in **Figure 1**).

[000164]   According to second level III charging mode **300**, an internal battery from an electric vehicle or plug-in hybrid electric vehicle such as electric vehicle **114** can require between 40 and 60 kilowatts in order to be charged. However, a low power AC source, such as AC power grid **108,** often provides no more than 10kw of power. Buffer battery **102** can be needed in order to supply the additional energy. Furthermore, in order to supply energy to level III charger **112**, energy from buffer battery **102** can be transferred to power converter **206**. Similarly, power converter **206** can be used in order to convert low power AC from AC power grid **108** into DC for level III charger **112**. Buffer battery **102** can be charged with low power AC from AC power grid **108** during the night, in order to take advantage of low cost night-time power rates, and also to avoid peak demand charges.

[000165]   Level III charging mode **300** with power converter **206** can avoid multiple power conversion stages, decreasing power generation consumption costs and increasing efficiency for level III charger **112**. Furthermore, power converter **206** from second level III charging mode **300** can permit vehicle to grid (V2G) applications, since only a single DC-AC conversion can be needed.

[000166]   **Figure 5** shows a schematic view for a level I/II charging mode **400**, according to an exemplary embodiment. Level I/II charging mode **400** can include buffer battery **102**, AC power grid **108**, power converter **206**, level I/II charger **402**, and electric vehicle **114**. Where buffer battery **102** can correspond to first input portal **202**, level I/II charger **402** can correspond to second input portal **204**, and AC power grid **108** can correspond to output portal **208** (explained in **Figure 1**). Level I/II charger **402** can refer to a level I charger or a level II charger.

[000167]   According to level I/II charging mode **400**, an internal battery from an electric vehicle or plug-in hybrid electric vehicle (such as electric vehicle **114)** can require between 7 and 25 kilowatts in order to be charged. In this embodiment, buffer battery **102** is often unnecessary, since a low power AC such as AC power grid **108** can often provide sufficient power for level I/II charger **402**.

[000168]   **Figure 6** shows a first bidirectional multi-port power conversion system for plug-in hybrid electric vehicles **500**, which can include an input charging **502**, batteries **504**, engine motor **506**, drive motor **508** with regenerative charging, and power converter **206**.

[000169]   Input charging **502** can include an AC power grid, e.g. a 120/240 V single-phase input. This can include capacitors, one or more AC voltage source, and bidirectional switches **212**. Batteries **504** can include one

or more lithium-ion batteries with a positive and a negative conductive line, capacitors, and bidirectional switches **212**. Engine motor **506** can include an internal combustion engine with a three-phase AC, capacitors, and bidirectional switches **212**. Drive motor **508** with regenerative charging can also include three-phase AC, capacitors, and bidirectional switches **212**.

[000170]   **Figure 7** shows a second bidirectional multi-port power conversion system for plug-in hybrid electric vehicles **600**, which can include an input charging **502**, super-capacitor port **602**, batteries **504**, engine motor **506**, drive motor **508**, and power converter **206**. Second bidirectional multi-port power conversion system for plug-in hybrid electric vehicles **600** can function with capabilities of high power on-board bidirectional 480VAC > 50kW charger.

[000171]   Input charging **502** can include e.g. a 120/240 V single-phase input, capacitors, an AC voltage source, and bidirectional switches **212**. Super-capacitor port **602** can be used as short-term storage, which can include a battery source, one or more capacitors, and bidirectional switches **212**.

[000172]   Batteries **504** can include one or more Lithium-ion batteries with a positive and a negative conductive line, capacitors, and bidirectional switches **212**. Engine motor **506** can include an internal combustion engine with three-phase AC, capacitors, and bidirectional switches **212**. Drive motor **508** with regenerative charging can also include three-phase AC, capacitors, and bidirectional switches **212**.

[000173]   **Figure 8** shows a schematic view for a multiple multi-port application for electric vehicle charging with micro-grid **700**, according to an exemplary embodiment. Multiple multi-port application for electric vehicle charging with micro-grid **700** can include first electric vehicle **702**,

second electric vehicle **704**, crossbar switch **706**, one or more power converter **206**, DC storage **708**, DC generator **710**, AC panel **712**, critical loads **714**, AC disconnect **716**, and AC grid **718**. Where DC generator **710** can include a photovoltaic array, DC storage **708** can include one or more batteries.

[000174]   According to an exemplary embodiment, AC panel **712** can be connected to AC grid **718** by AC disconnect **716**. During grid faults from AC grid **718**, AC disconnect **716** can be switched to open position, and therefore, DC storage **708** and DC generator **710** can provide power for critical loads **714**. Furthermore, AC grid **718**, DC storage **708**, and DC generator **710** can provide power for first electric vehicle **702** and second electric vehicle **704** when required.

[000175]   According to some but not necessarily all embodiments, there is provided: A car charging station in which battery buffering includes at least approximately as much energy as is required to charge one car rapidly. This is particularly advantageous when a photovoltaic array is connected through a power converter to charge the battery, and also to provide a lower rate of charge directly to the vehicle charge connections. Advantageously, a mains power connection can also be made through yet another port of the same multiport power converter.

[000176]   According to some but not necessarily all embodiments, there is provided: A vehicle charging station, comprising: at least one standard vehicle electrical connection; at least one battery; at least one power input connection; and a power-packet-switching multiport power converter having a first port thereof connected to said vehicle electrical connections, a second port thereof connected to said battery, and a third port thereof connected to said power input connection; wherein the maximum power available from said power input connection is less than half the maximum power output which can be accepted at said vehicle charging connections.

[000177]   According to some but not necessarily all embodiments, there is provided: A vehicle charging station, comprising: at least one standard vehicle electrical connection; at least one battery; at least one photovoltaic power input connection; and a power-packet-switching multiport power converter having a first port thereof connected to said vehicle electrical connections, a second port thereof connected to said battery, a third port thereof connected to said power input connection, and a fourth port thereof connected to a power grid.

[000178]   According to some but not necessarily all embodiments, there is provided: A vehicle charging station, comprising: a plurality of standard vehicle electrical connections; at least one battery; at least one power mains connection; and a power-packet-switching multiport power converter having at least one first port thereof connected to said vehicle electrical connections, a second port thereof connected to said battery, and a third port thereof connected to said power input connection; whereby less transient loading is imposed on the power mains connection when multiple vehicles connect in quick succession to said plurality of standard vehicle electrical connections.

[000179]   According to some but not necessarily all embodiments, there is provided: A system for charging an electric vehicle, comprising: a bidirectional multiport power converter, comprising: a plurality of input/output portals, each comprising one or more ports; an energy transfer reactance comprising an inductor and a capacitor in parallel; wherein each said port of each said input/output portal is connected in parallel to each end of said energy transfer reactance by a bidirectional switching device; wherein, at various times, said energy transfer reactance can be connected to two said ports, to transfer energy therebetween; and wherein, at various times, said energy transfer reactance can be disconnected from said input/output portals; an electric vehicle charger connected to one said input/output portal of said bidirectional multiport power converter, which connects to an electric vehicle to charge a battery in said electric vehicle; an AC power grid connected to one said input/output portal of said bidirectional multiport power converter; a backup/buffer battery connected to one said input/output portal of said bidirectional multiport power converter; wherein said backup/buffer battery supplies additional power to charge said electric

vehicle when said electric vehicle charger demands more power than said AC power grid supplies.

MODIFICATIONS AND VARIATIONS

[000180]   As will be recognized by those skilled in the art, the innovative concepts described in the present application can be modified and varied over a tremendous range of applications, and accordingly the scope of patented subject matter is not limited by any of the specific exemplary teachings given. It is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims.

[000181]   In some alternate embodiments, the teachings of the present application can be applied to Level I and/or Level II charging.

[000182]   In some alternate embodiments similar to the sample embodiment of Figure 8, power can be drawn from one or more electric vehicles to power critical loads in the event of a grid fault. This can be particularly advantageous when the innovative teachings of the present application are used with plug-in hybrid electric vehicles.

[000183]   In some sample embodiments, the battery and/or supercapacitor buffering most preferably holds at least enough power needed to quickly charge a single vehicle of the expected type or types. In some embodiments, the battery and/or supercapacitor buffering holds more than e.g. 60-200% of the power needed to quickly charge a single vehicle of the expected type or types.

[000184]   The power conversion principles described herein can be used in virtually any power conversion circuit.

[000185]   None of the description in the present application should be read as implying that any particular element, step, or function is an essential element which must be included in the claim scope: THE SCOPE

OF PATENTED SUBJECT MATTER IS DEFINED ONLY BY THE ALLOWED CLAIMS. Moreover, none of these claims are intended to invoke paragraph six of 35 USC section 112 unless the exact words "means for" are followed by a participle.

[000186] Additional general background, which helps to show variations and implementations, as well as some features which can be implemented synergistically with the inventions claimed below, may be found in the following US patent applications. All of these applications have at least some common ownership, copendency, and inventorship with the present application, and all of them, as well as any material directly or indirectly incorporated within them, are hereby incorporated by reference: US 8,406,265, US 8,400,800, US 8,395,910, US 8,391,033, US 8,345,452, US 8,300,426, US 8,295,069, US 7,778,045, US 7,599,196, US 2012-0279567 A1, US 2012-0268975 A1, US 2012-0274138 A1, US 2013-0038129 A1, US 2012-0051100 A1, 14/182,243, 14/182,236, PCT/US14/16740, 14/182,245, 14/182,246, 14/183,403, 14/182,249, 14/182,250, 14/182,251, 14/182,256, 14/182,268, 14/183,259, 14/182,265, 14/183,415, 14/182,280, 14/183,422, 14/182,252, 14/183,245, 14/183,274, 14/183,289, 14/183,309, 14/183,335, 14/183,371, 14/182,270, 14/182,277, 14/207,039; US Provisionals 61/765,098, 61/765,099, 61/765,100, 61/765,102, 61/765,104, 61/765,107, 61/765,110, 61/765,112, 61/765,114, 61/765,116, 61/765,118, 61/765,119, 61/765,122, 61/765,123, 61/765,126, 61/765,129, 61/765,131, 61/765,132, 61/765,137, 61/765,139, 61/765,144, 61/765,146 all filed February 15, 2013; 61/778,648, 61/778,661, 61/778,680, 61/784,001 all filed March 13, 2013; 61/814,993 filed April 23, 2013; 61/817,012, 61/817,019, 61/817,092 filed April 29, 2013; 61/838,578 filed June 24, 2013; 61/841,618, 61/841,621, 61/841,624 all filed July 1, 2013;

61/914,491 and 61/914,538 filed December 11, 2013; 61/924,884 filed January 8, 2014; 61/925,311 filed January 9, 2014; 61/928,133 filed January 16, 2014; 61/928,644 filed January 17, 2014; 61/929,731 and 61/929,874 filed January 21, 2014; 61/931,785 filed January 27, 2014; 61/932,422 filed January 28, 2014; and 61/933,442 filed January 30, 2014; and all priority applications of any of the above thereof, each and every one of which is hereby incorporated by reference.

[000187]   The claims as filed are intended to be as comprehensive as possible, and NO subject matter is intentionally relinquished, dedicated, or abandoned.

CLAIMS

What is claimed is:

1. A vehicle charging station, comprising:

    at least one standard vehicle electrical connection;

    at least one battery;

    at least one power input connection; and

    a power-packet-switching multiport power converter having a first port thereof connected to said vehicle electrical connections, a second port thereof connected to said battery, and a third port thereof connected to said power input connection;

    wherein the maximum power available from said power input connection is less than half the maximum power output which can be accepted at said vehicle charging connections.

2. The vehicle charging station of Claim 1, wherein said battery holds at least 60% of the maximum power output which can be accepted at said vehicle charging connections.

3. The vehicle charging station of Claim 1, wherein said battery holds at least 100% of the maximum power output which can be accepted at said vehicle charging connections.

4. The vehicle charging station of Claim 1, wherein said battery holds at least 200% of the maximum power output which can be accepted at said vehicle charging connections.

5. The vehicle charging station of Claim 1, wherein said power converter can direct power from said battery to said power input connection.

6. The vehicle charging station of Claim 1, wherein said power converter can direct power between two or more said ports.

7. A vehicle charging station, comprising:

at least one standard vehicle electrical connection;

at least one battery;

at least one photovoltaic power input connection; and

a power-packet-switching multiport power converter having a first port thereof connected to said vehicle electrical connections, a second port thereof connected to said battery, a third port thereof connected to said power input connection, and a fourth port thereof connected to a power grid.

8. The vehicle charging station of Claim 7, wherein said battery holds more than 60% of the maximum power output which can be accepted at said vehicle electrical connections.

9. The vehicle charging station of Claim 7, wherein said battery holds more than 100% of the maximum power output which can be accepted at said vehicle electrical connections.

10. The vehicle charging station of Claim 7, wherein said battery holds more than 200% of the maximum power output which can be accepted at said vehicle electrical connections.

11. The vehicle charging station of Claim 7, wherein said power converter can direct power from said battery to said power input connection.

12. The vehicle charging station of Claim 7, wherein said power converter can direct power between two or more said ports.

13. A vehicle charging station, comprising:

a plurality of standard vehicle electrical connections;

at least one battery;

at least one power mains connection; and

a power-packet-switching multiport power converter having at least one first port thereof connected to said vehicle electrical connections, a second port thereof connected to said battery, and a third port thereof connected to said power input connection;

whereby less transient loading is imposed on the power mains connection when multiple vehicles connect in quick succession to said plurality of standard vehicle electrical connections.

14. The vehicle charging station of Claim 13, further comprising a plurality of said first ports.

15. The vehicle charging station of Claim 13, wherein at least two said standard vehicle electrical connections are connected to one said first port by a crossbar switch.

16. The vehicle charging station of Claim 13, wherein said battery holds more than 60% of the maximum power output which can be accepted at said vehicle electrical connections.

17. The vehicle charging station of Claim 13, wherein said battery holds more than 100% of the maximum power output which can be accepted at said vehicle electrical connections.

18. The vehicle charging station of Claim 13, wherein said battery holds more than 200% of the maximum power output which can be accepted at said vehicle electrical connections.

19. The vehicle charging station of Claim 13, wherein said power converter can direct power from said battery to said power input connection.

20. The vehicle charging station of Claim 13, wherein said power converter can direct power between two or more said ports.

21. A system for charging an electric vehicle, comprising:

    a bidirectional multiport power converter, comprising:

        a plurality of input/output portals, each comprising one or more ports;

        an energy transfer reactance comprising an inductor and a capacitor in parallel; wherein each said port of each said input/output portal is connected in parallel to each end of said energy transfer reactance by a bidirectional switching device;

        wherein, at various times, said energy transfer reactance can be connected to two said ports, to transfer energy therebetween; and wherein, at various times, said energy transfer reactance can be disconnected from said input/output portals;

    an electric vehicle charger connected to one said input/output portal of said bidirectional multiport power converter, which connects to an electric vehicle to charge a battery in said electric vehicle;

    an AC power grid connected to one said input/output portal of said bidirectional multiport power converter;

    a backup/buffer battery connected to one said input/output portal of said bidirectional multiport power converter; wherein said backup/buffer battery supplies additional power to charge said electric vehicle when said electric vehicle charger demands more power than said AC power grid supplies.

FIG. 1

100

102

Battery

104

DC-AC
Converter

106

AC-DC
Converter

110

Level III
Charger

112

108

AC Power
Grid

AC-DC
Converter

114

Prior Art

FIG. 2

Fig. 3A

Fig. 3B

Fig. 3C

Fig. 3D

Fig. 3E

Legend:
- Link +
- Link -
- Output End
- End Direct Anchoring
- Zero Current
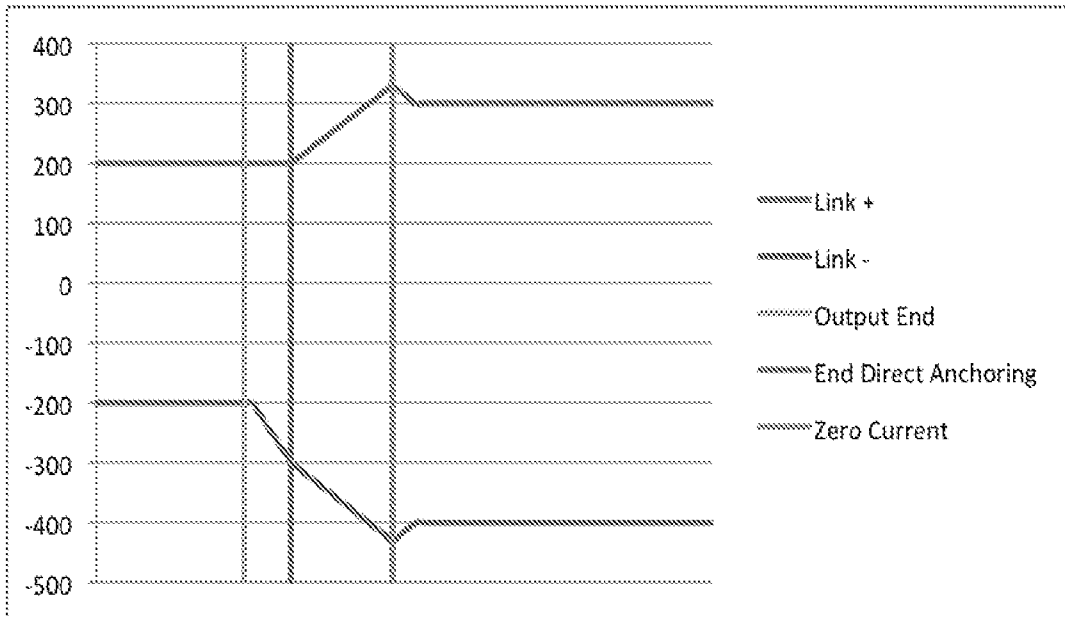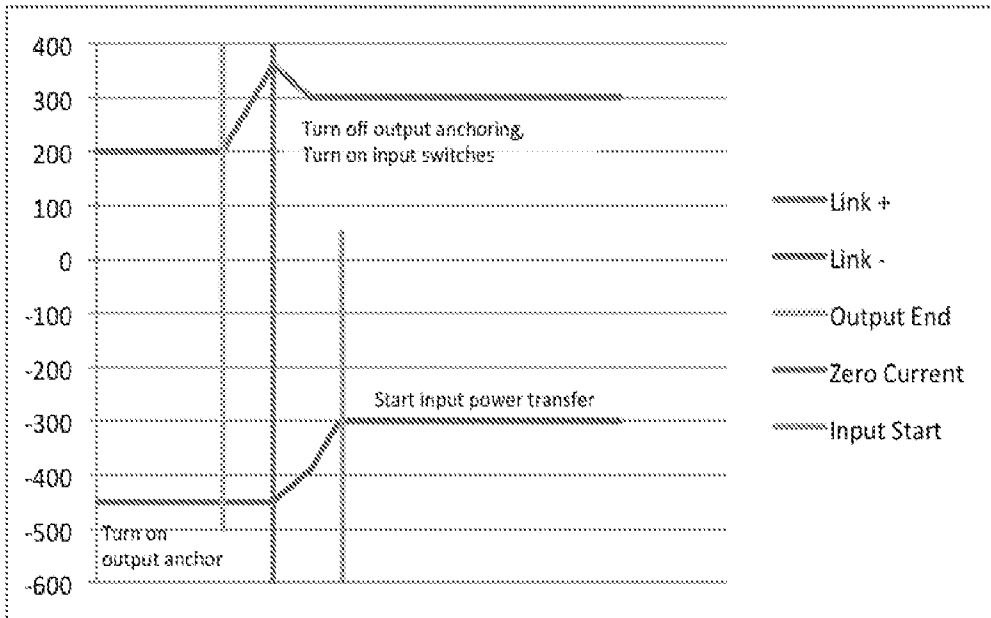
Fig. 3F
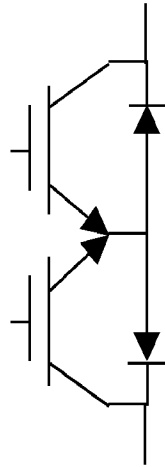
Fig. 3G
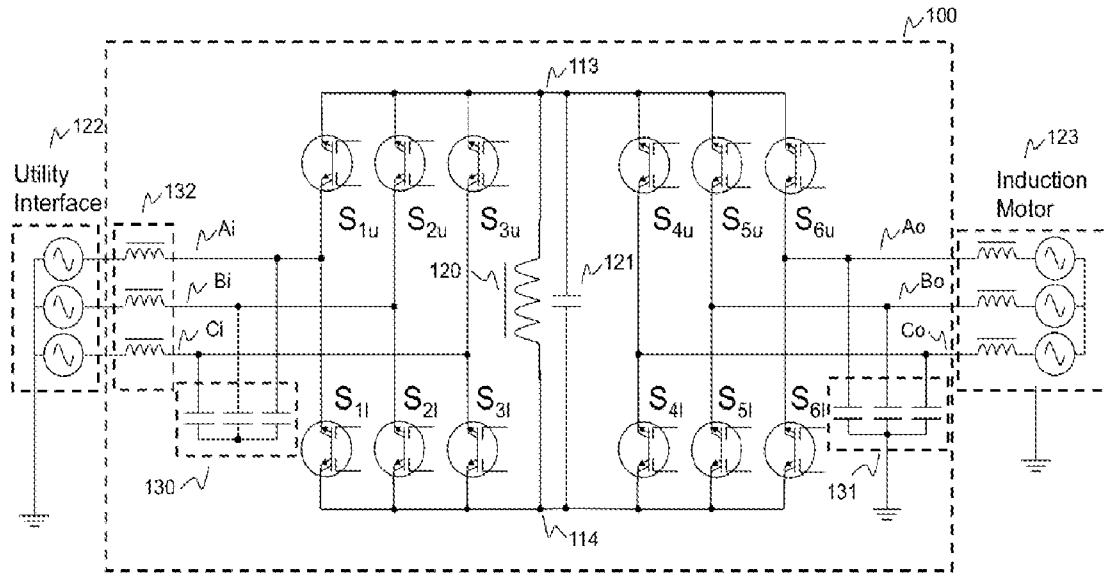
Fig. 3H

Three Phase Power Converter

Inductor Charging -- max input line-line volts
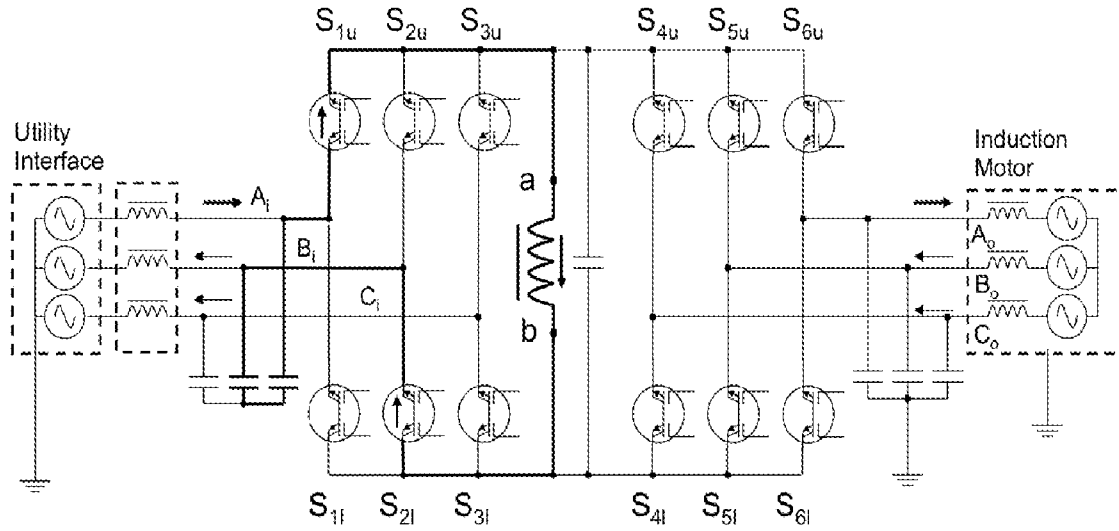
$V_{a-b} > 0$

Current Switching -- Mode 1 of 8

Fig. 3I

Three Phase Power Converter

Inductor/Capacitor Voltage Ramping between Modes
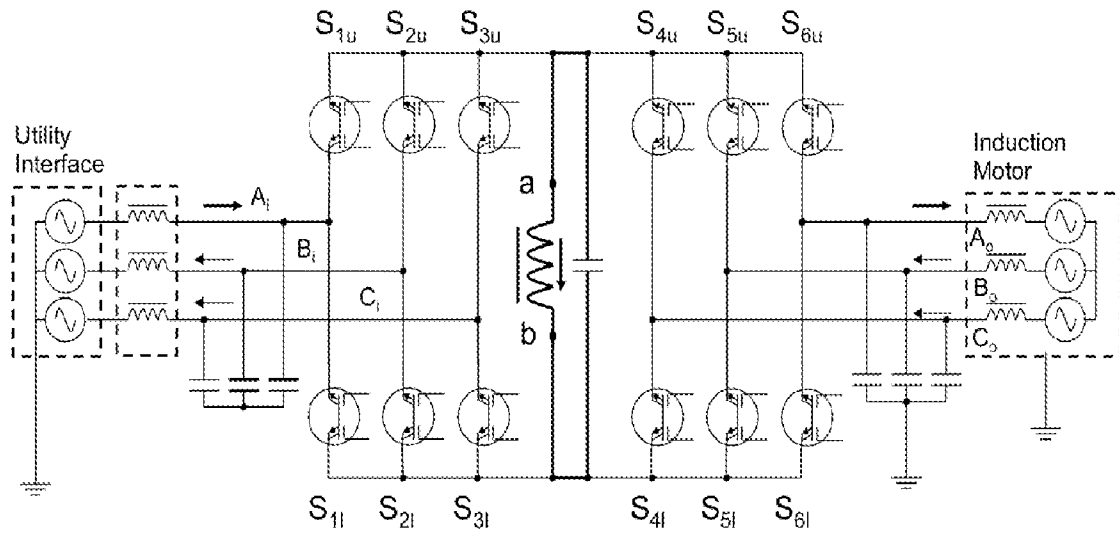
Voltage Ramping – Between each of Modes 1 - 5

Fig. 3J

Three Phase Power Converter

Inductor Charging – min input line-line volts

$$V_{a-b} > 0$$
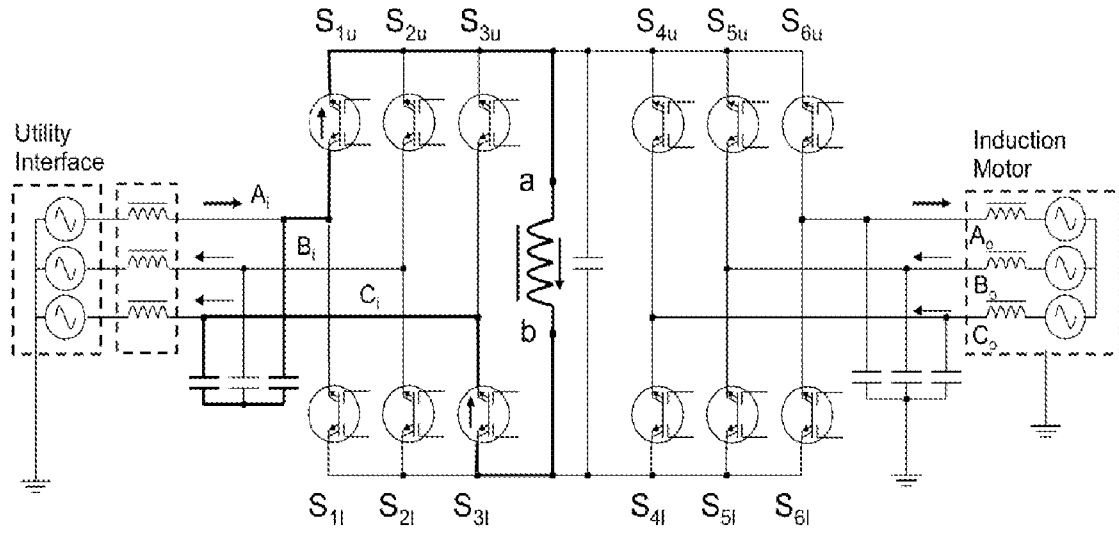
Current Switching – Mode 2 of 8

Fig. 3K

Three Phase Power Converter

Inductor Dis-charging – min output line-line volts

$$V_{a-b} < 0$$
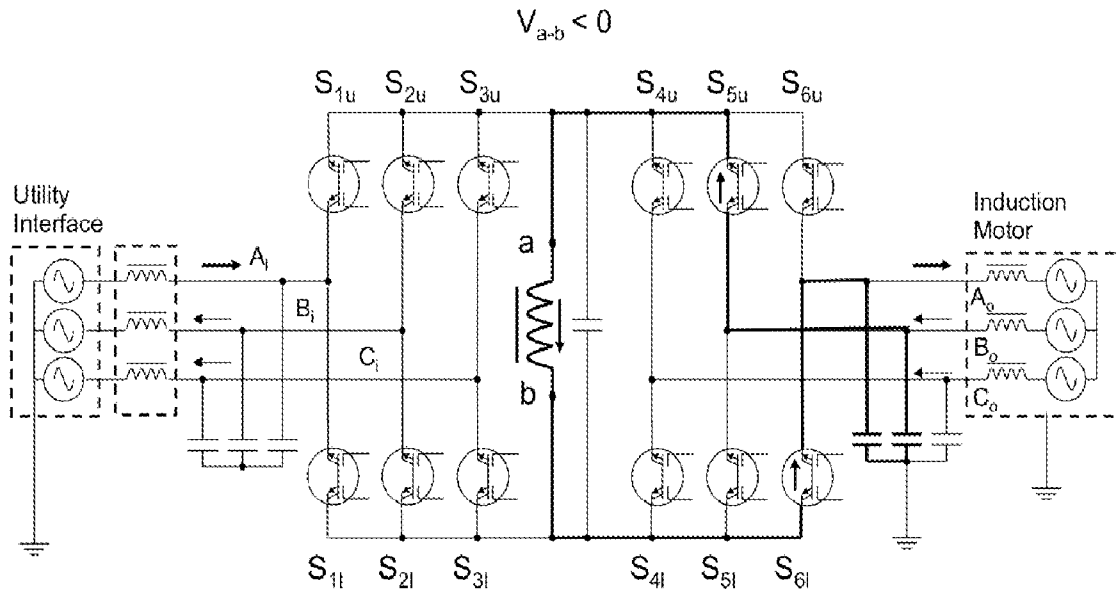
Current Switching – Mode 3 of 8

Fig. 3L

Three Phase Power Converter

Inductor Dis-charging – max output line-line volts

$$V_{a-b} < 0$$
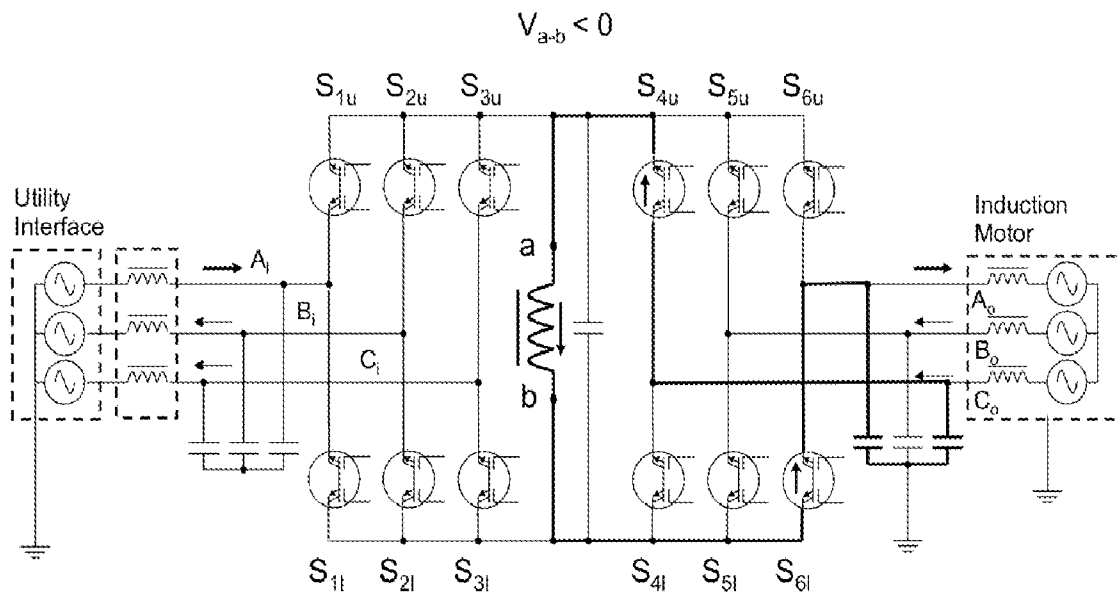
Current Switching – Mode 4 of 8

Fig. 3M

Three Phase Power Converter

Inductor Charging – max input line-line, reverse inductor current

$$V_{a\text{-}b} < 0$$
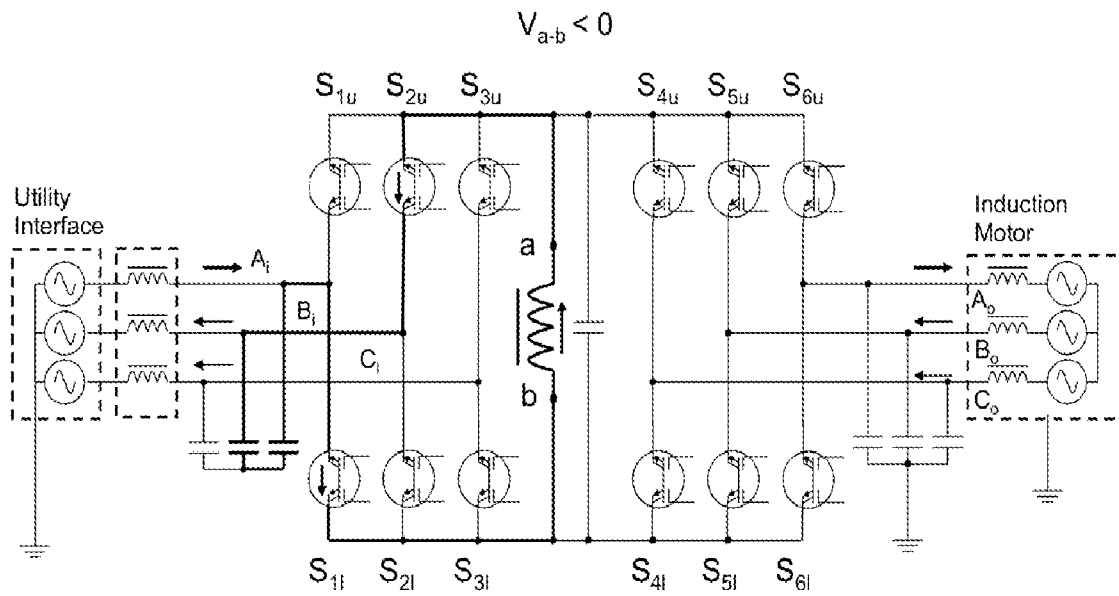
Current Switching – Mode 5 of 8

Fig. 3N

Three Phase Power Converter

Inductor/Capacitor Voltage Ramping between Modes
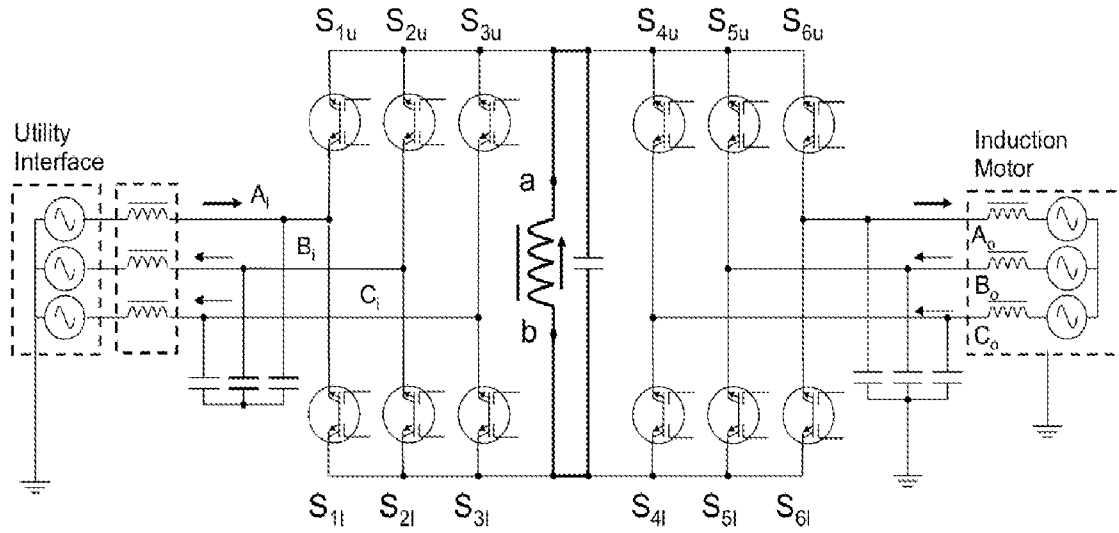
Capacitor Ramping – Between each of Modes 5 - 1

Fig. 3O

Three Phase Power Converter

Inductor Charging – min input line-line, reverse inductor current
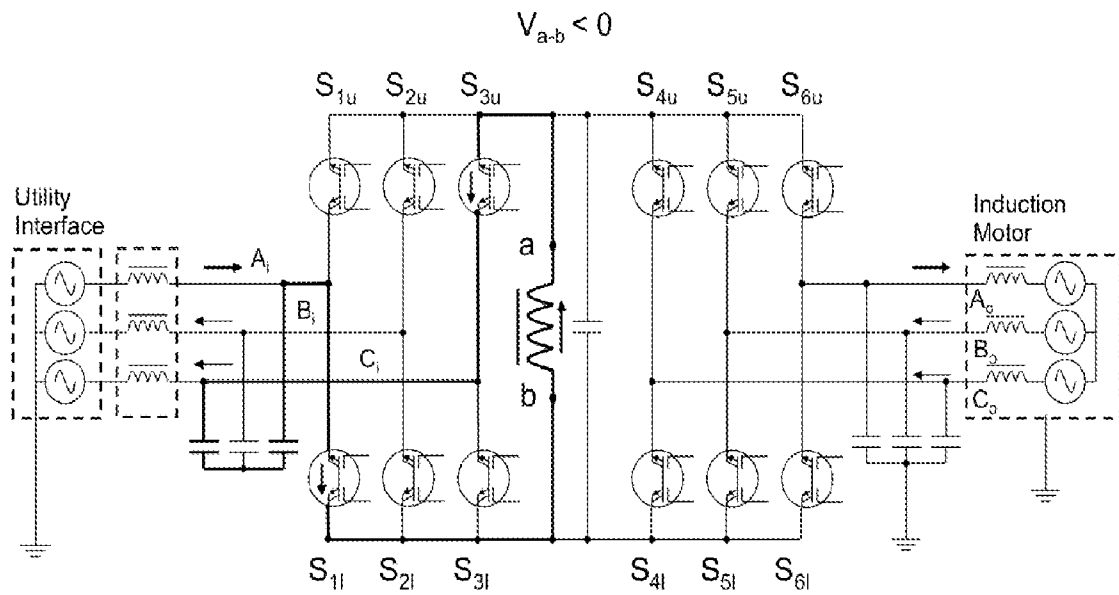
$$V_{a-b} < 0$$

Current Switching – Mode 6 of 8

Fig. 3P

Three Phase Power Converter

Inductor Dis-charging – min output line-line, reverse inductor current
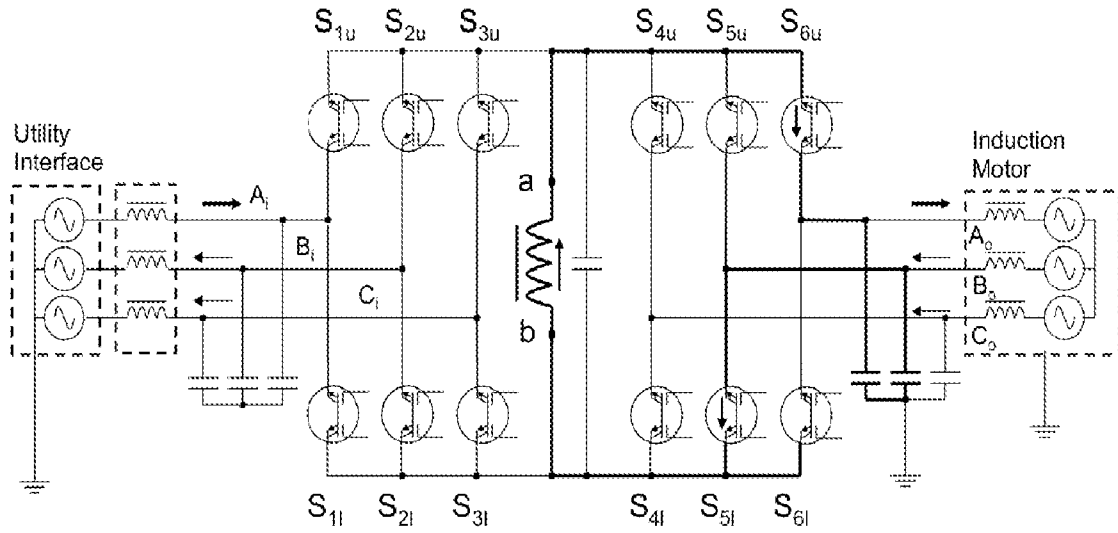
$$V_{a-b} > 0$$

Current Switching – Mode 7 of 8

Fig. 3Q

Three Phase Power Converter

Inductor Dis-charging – min output line-line, reverse inductor current

$V_{a\text{-}b} > 0$
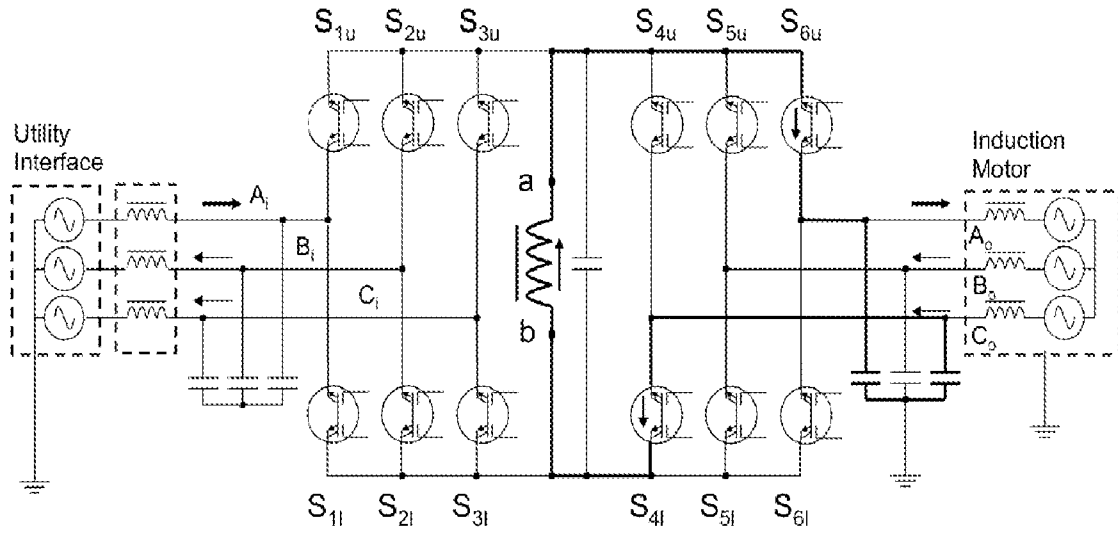
Current Switching – Mode 8 of 8

Fig. 3R

Fig. 3S

Fig. 3T

1st Portal

2nd Portal
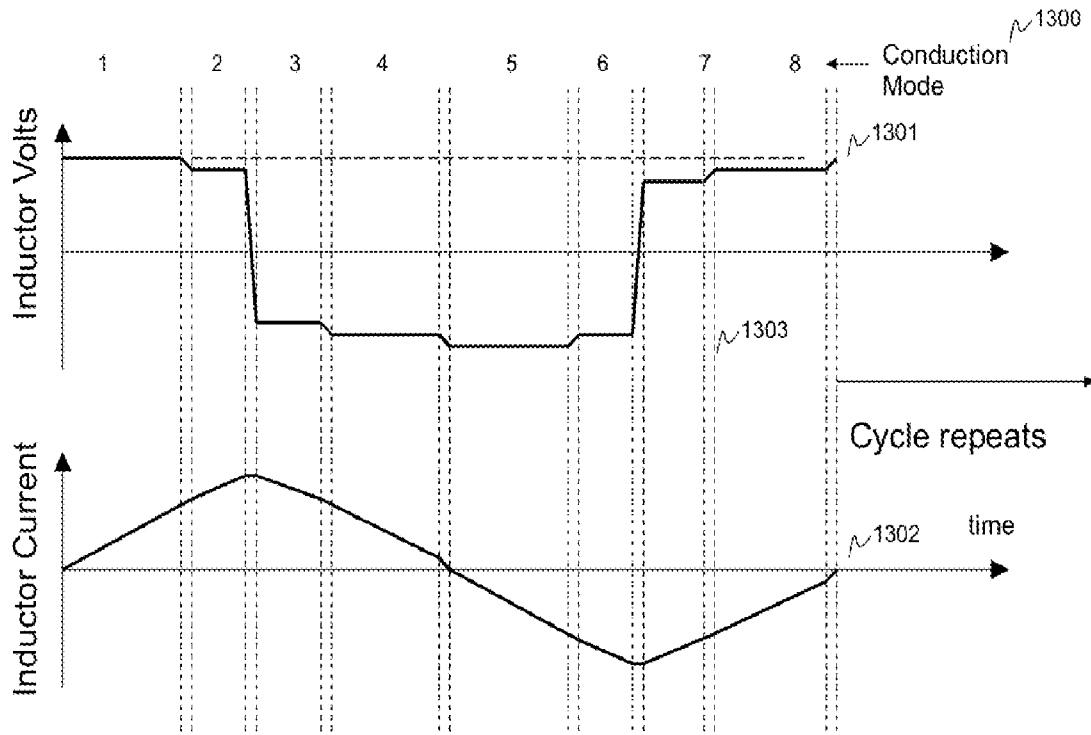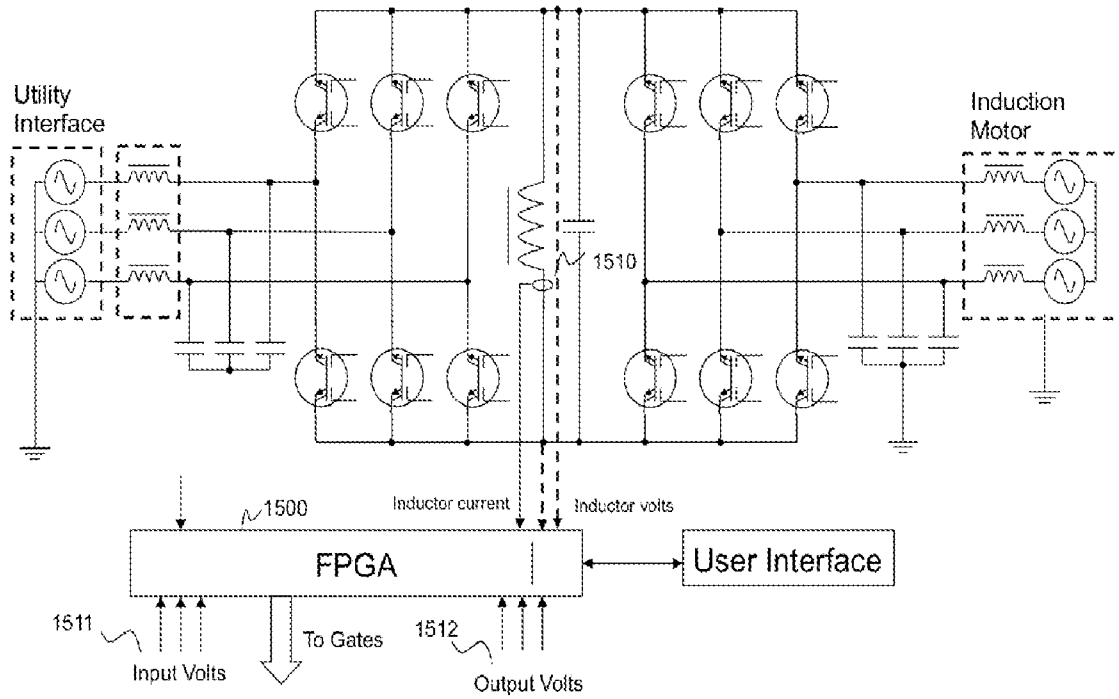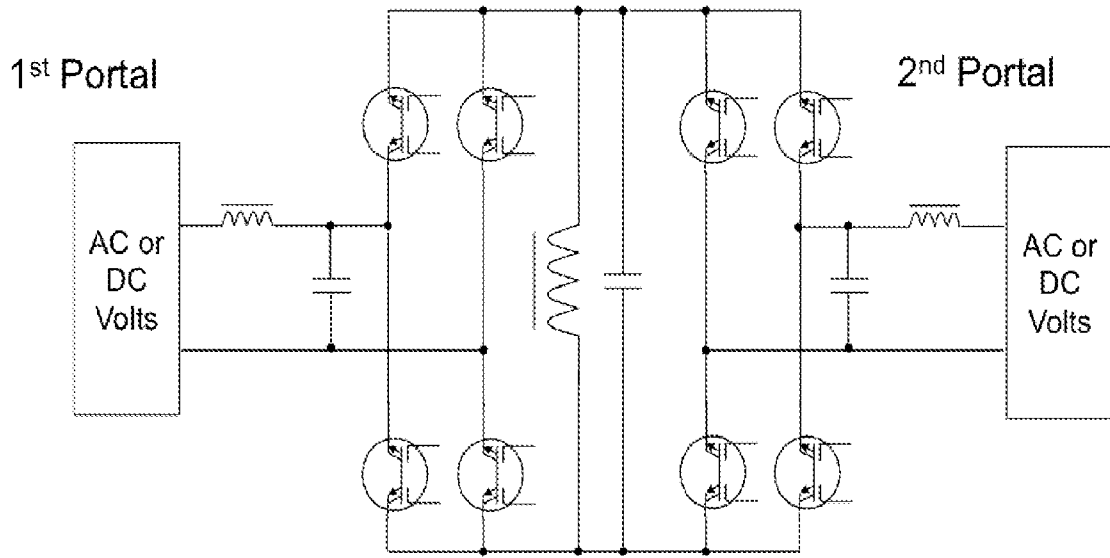
Fig. 3U
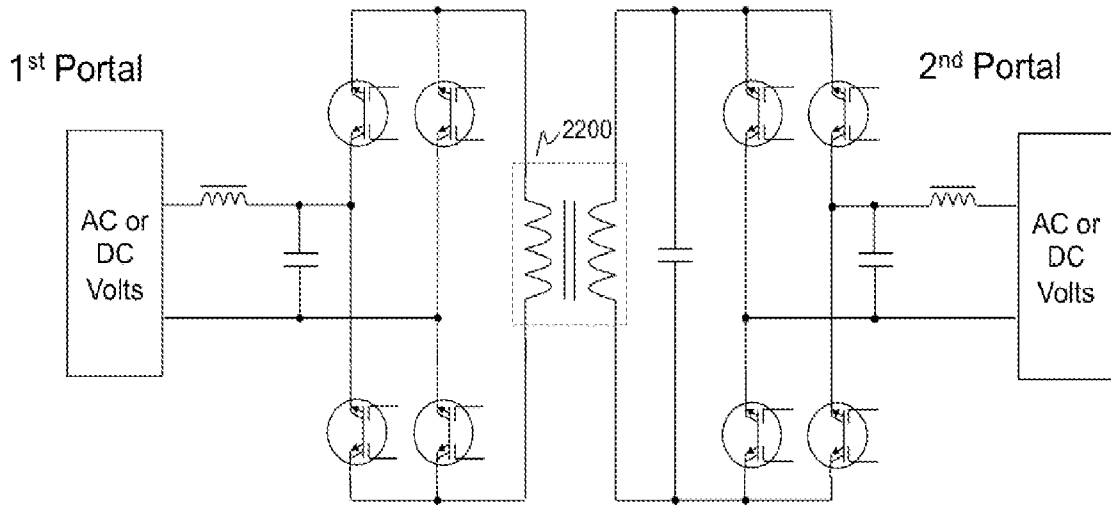
Fig. 3V
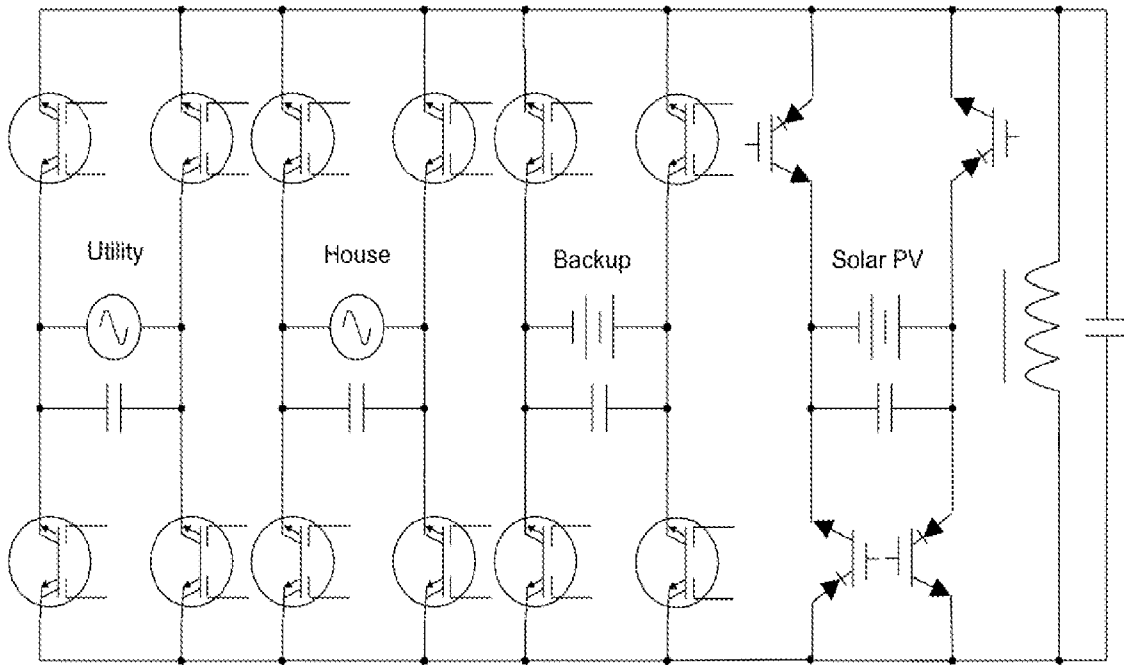
Fig. 3W
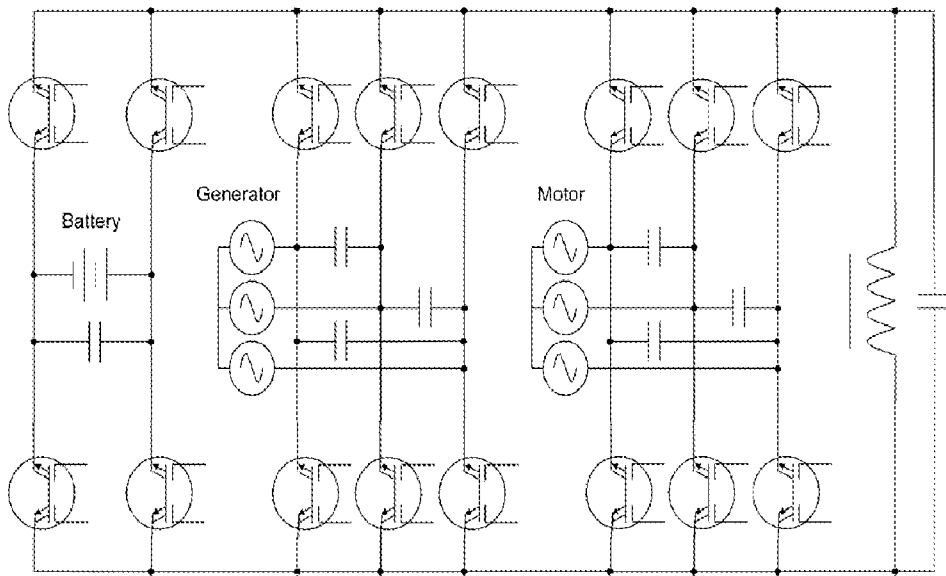
Fig. 3X
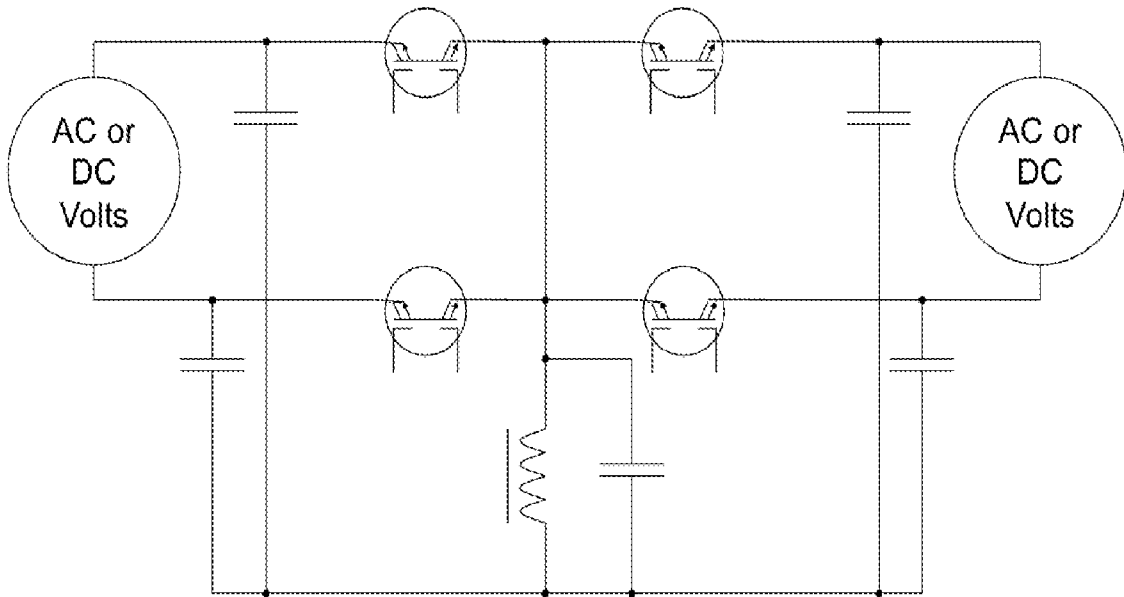
Fig. 3Y
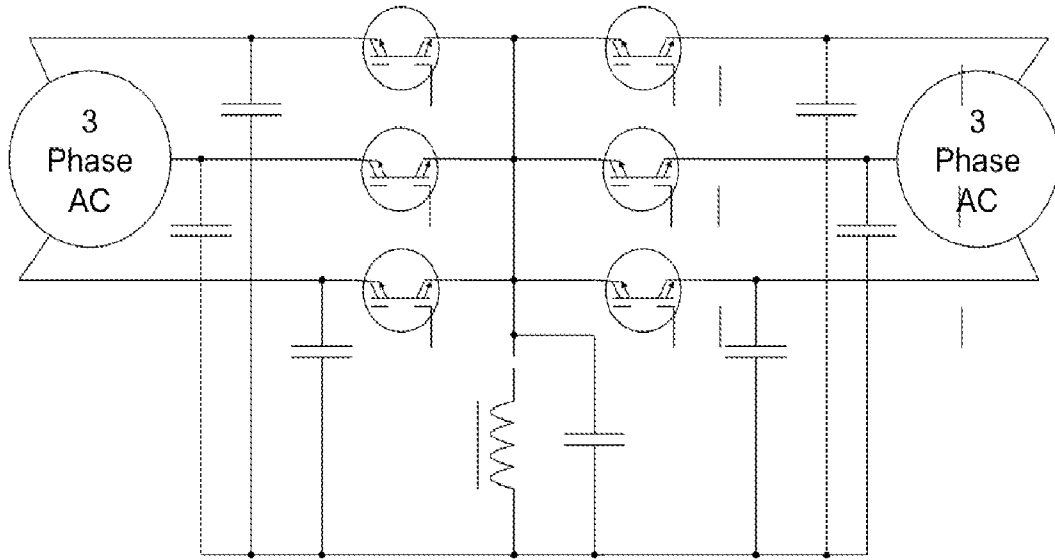
Fig. 3Z
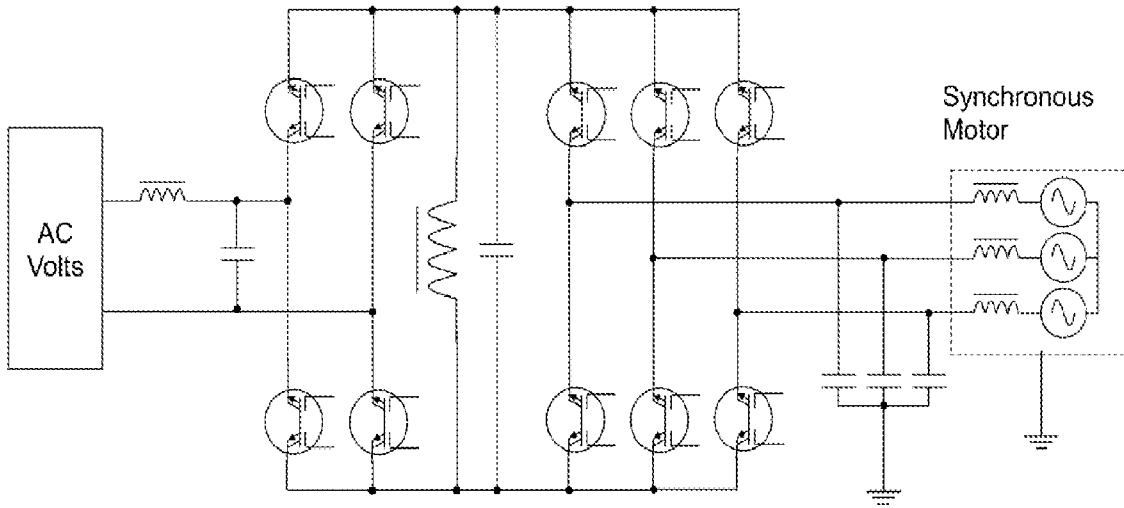
Fig. 3AA
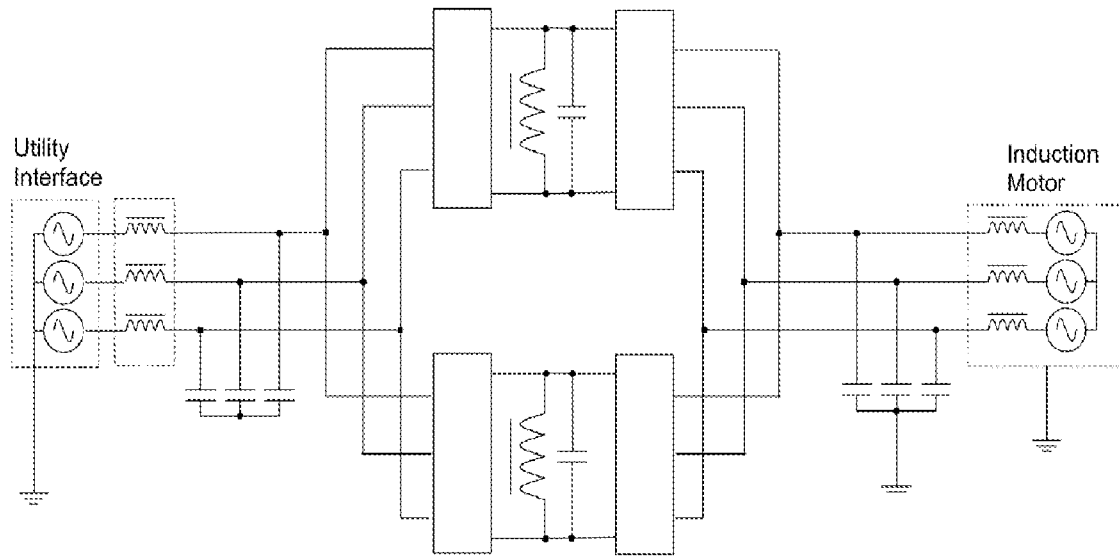
Fig. 3BB
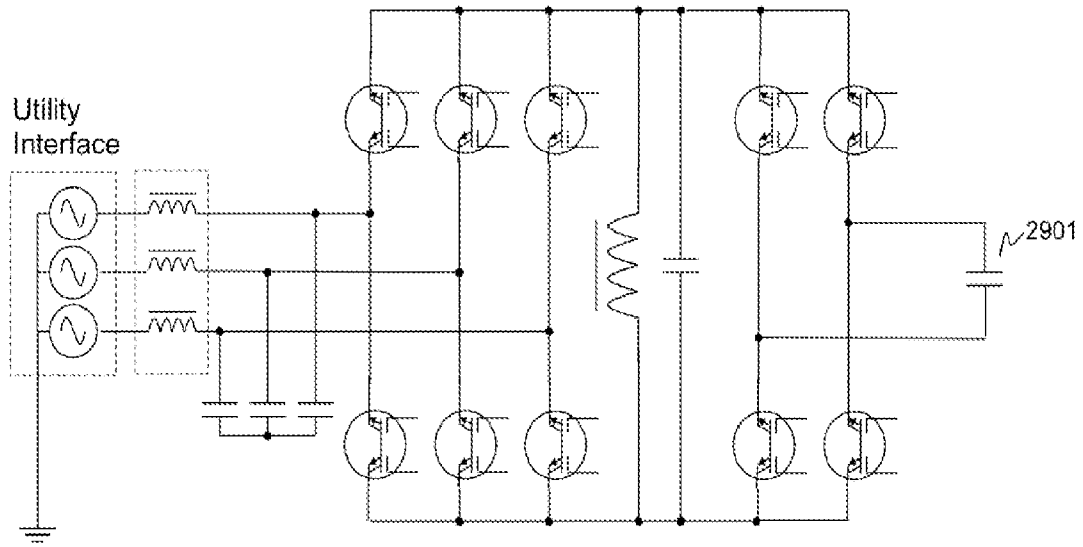
Fig. 3CC
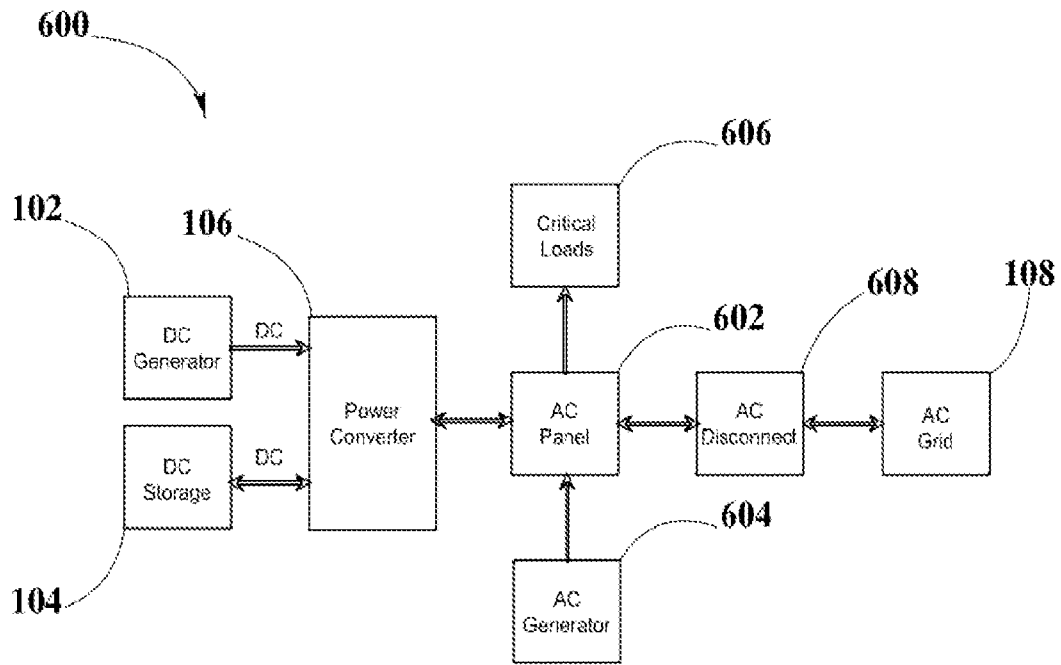
Fig. 3DD
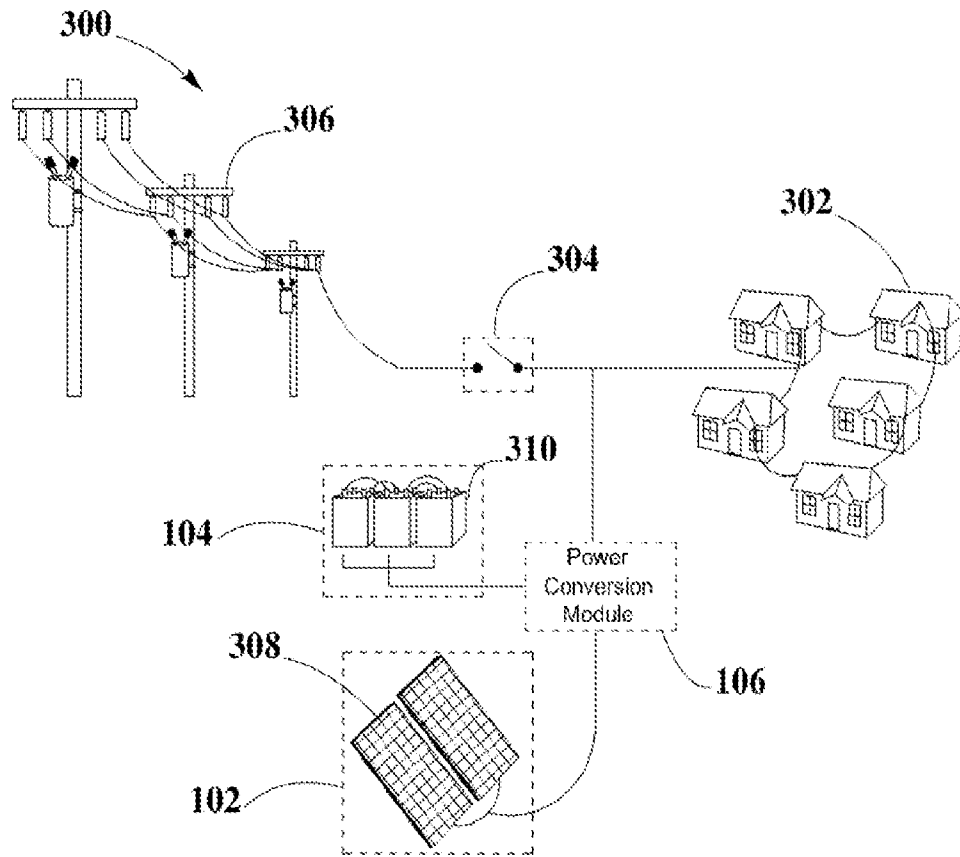
Fig. 3EE
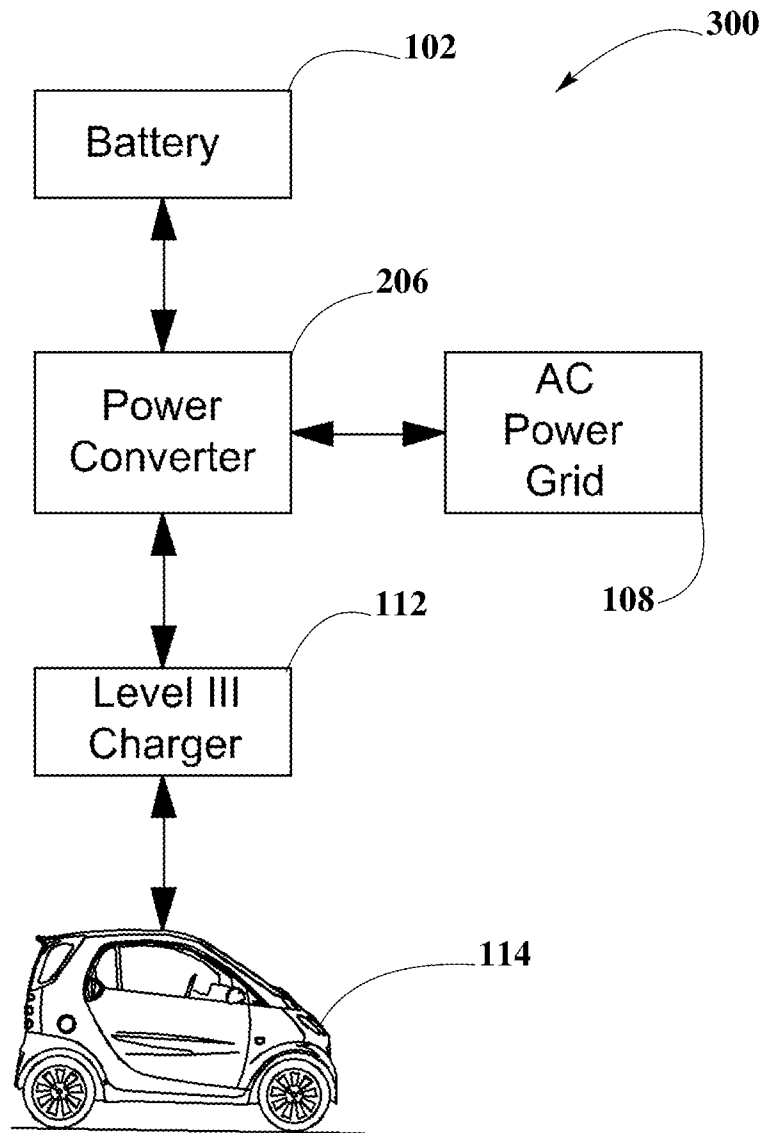
FIG. 4
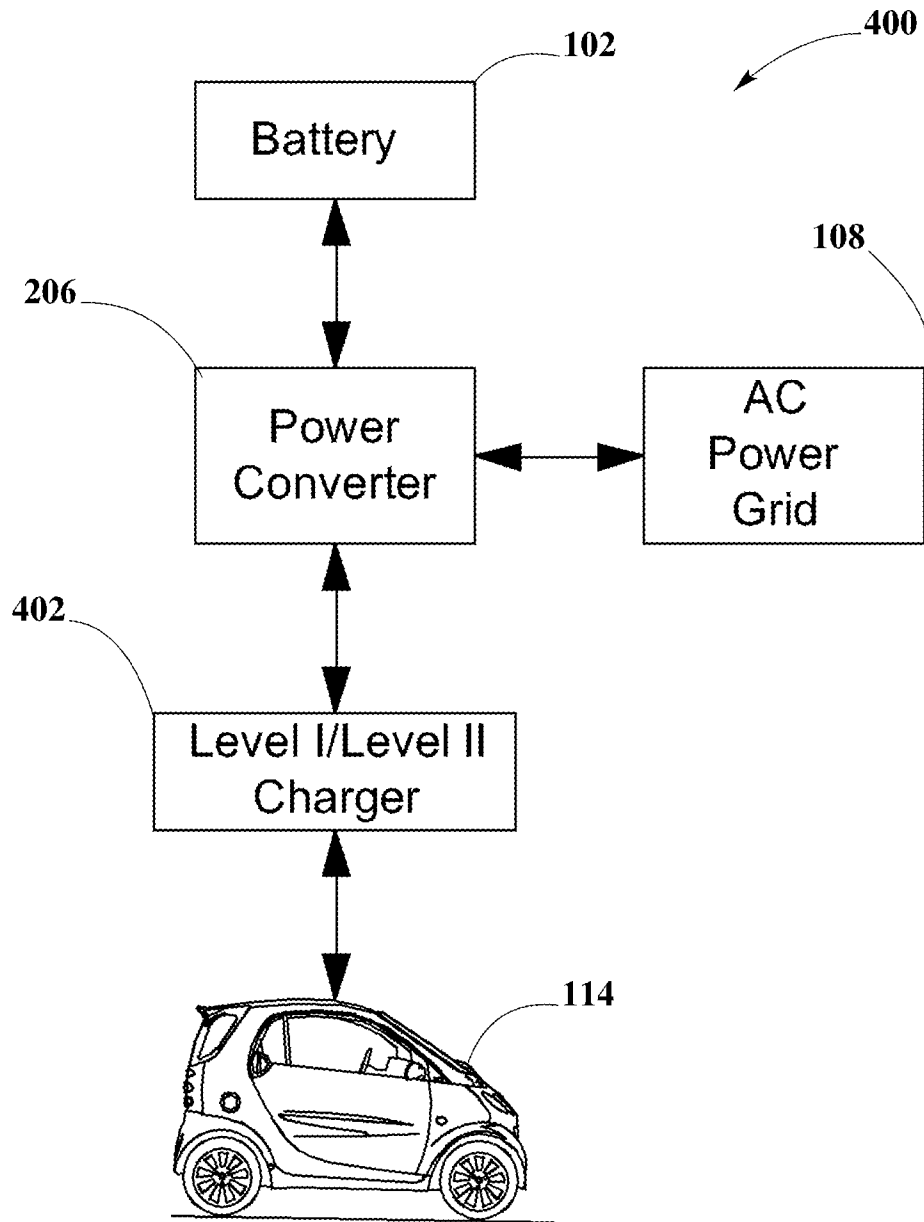
FIG. 5
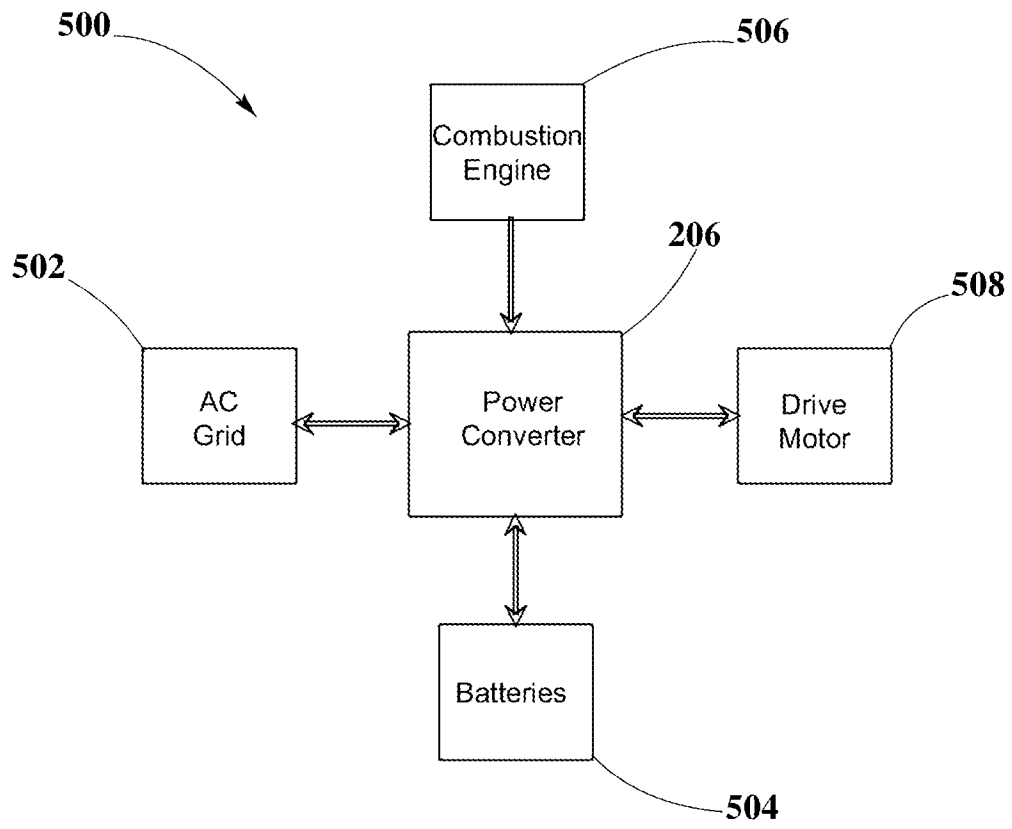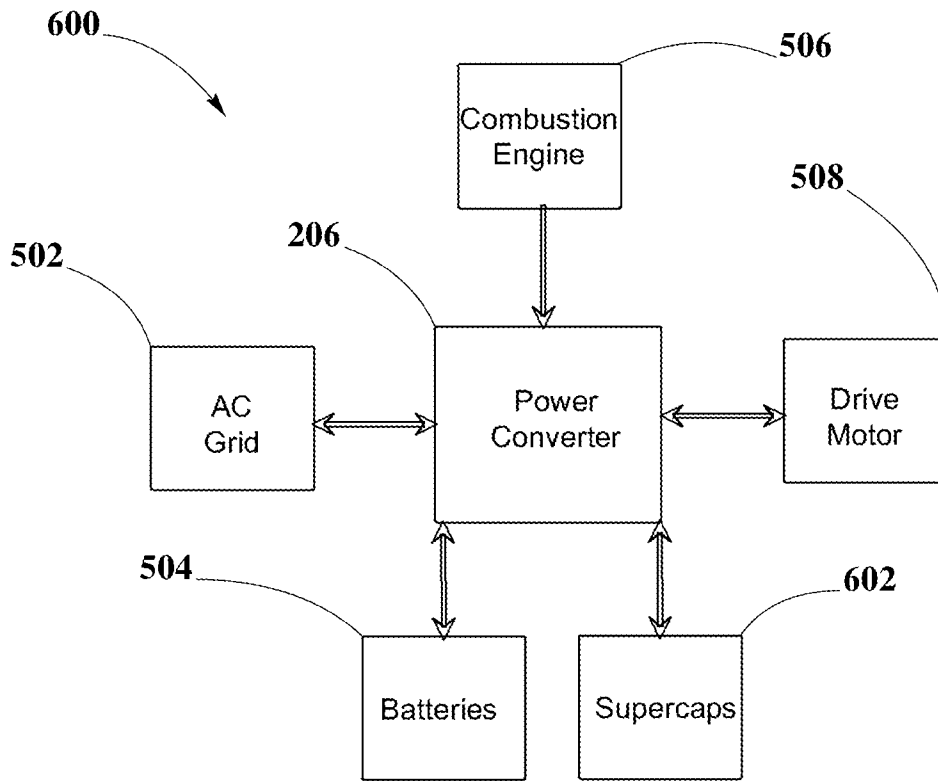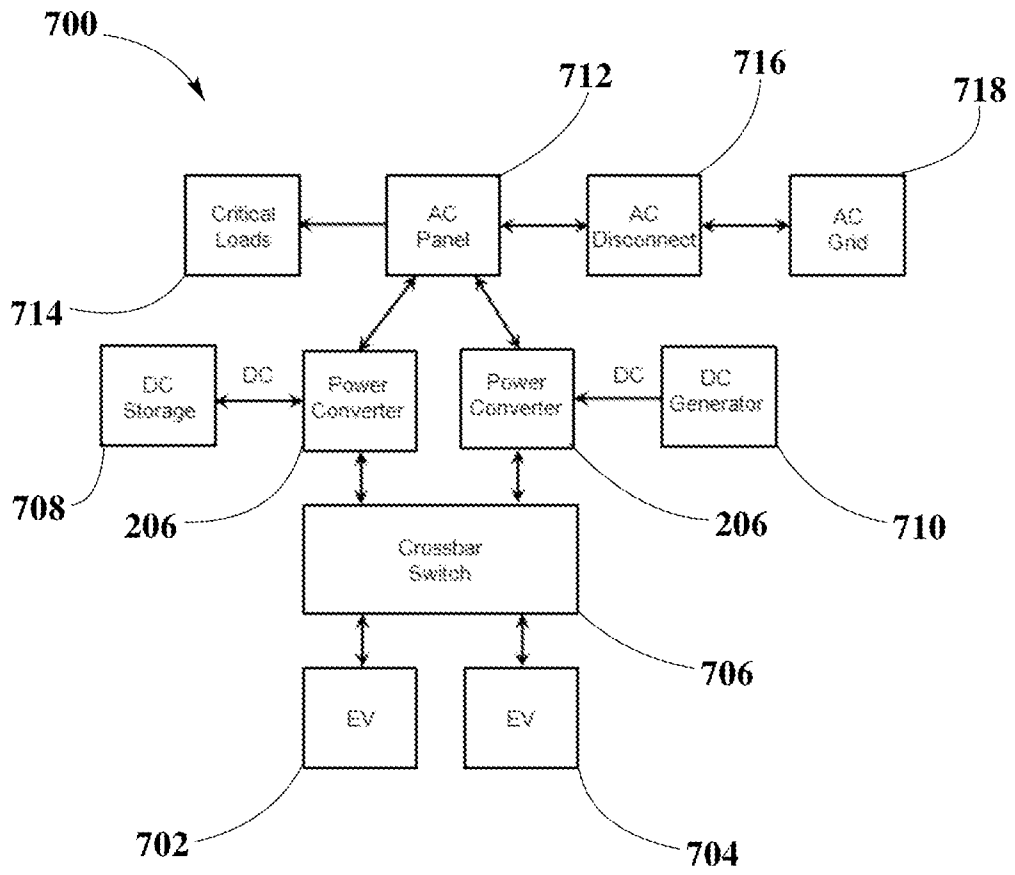
500

506

Combustion
Engine

206

502

508

AC
Grid

Power
Converter

Drive
Motor

Batteries

504

FIG. 6

FIG. 7

FIG. 8

A. CLASSIFICATION OF SUBJECT MATTER

B60L 11/18(2006.01)i, H02J 7/02(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B60L 11/18; H01M 10/46; H02J 7/00; H02M 3/155; H02J 7/14; H02J 7/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: electric vehicle, charging, multiport power converter, bidirectional, maximum power, backup/buffer battery

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2012-0280655 A1 (DANIEL SCHNEIDER et al.) 08 November 2012 See abstract, paragraph [0025], claim 1 and figures 1-2.	1-21
Y	US 2008-0309301 A1 (TAKAE SHIMADA et al.) 18 December 2008 See abstract, paragraphs [0203]-[0204], claim 1 and figures 1-22, 44.	1-21
A	US 2011-0115425 A1 (MATS OLSSON) 19 May 2011 See claims 1-17 and figures 1-5.	1-21
A	US 2008-0067974 A1 (JIANHUA ZHANG et al.) 20 March 2008 See abstract, claim 1 and figures 1-9.	1-21
A	US 2004-0169489 A1 (RAYMOND HOBBS) 02 September 2004 See abstract, claims 1-14 and figures 1-3.	1-21

☐ Further documents are listed in the continuation of Box C.   ☒ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	
"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 August 2014 (25.08.2014)	**25 August 2014 (25.08.2014)**

Name and mailing address of the ISA/KR	Authorized officer
International Application Division Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701, Republic of Korea	PARK, Hye Lyun
Facsimile No. +82-42-472-7140	Telephone No. +82-42-481-3463

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2012-0280655 A1	08/11/2012	CN 102712262 A DE 102009046422 A1 EP 2496436 A2 WO 2011-054849 A2 WO 2011-054849 A3	03/10/2012 12/05/2011 12/09/2012 12/05/2011 19/07/2012
US 2008-0309301 A1	18/12/2008	JP 2007-288876 A JP 4768498 B2 TW I390831 B US 7812575 B2	01/11/2007 07/09/2011 21/03/2013 12/10/2010
US 2011-0115425 A1	19/05/2011	CN 102762409 A EP 2499017 A2 WO 2011-060269 A2 WO 2011-060269 A3	31/10/2012 19/09/2012 19/05/2011 02/08/2012
US 2008-0067974 A1	20/03/2008	CN 101150259 A CN 101150259 B US 7768229 B2 WO 2008-040225 A1	26/03/2008 12/05/2010 03/08/2010 10/04/2008
US 2004-0169489 A1	02/09/2004	CA 2556791 A1 CA 2556791 C EP 1770845 A2 EP 1770845 A3 US 2006-0028178 A1 US 6963186 B2 US 7411371 B2	28/02/2007 22/09/2009 04/04/2007 06/04/2011 09/02/2006 08/11/2005 12/08/2008