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Dong et al.

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(45) **Date of Patent: Jul. 16, 2019**

(54) **BATTERY INTEGRATED ISOLATED POWER CONVERTER AND SYSTEMS FOR ELECTRIC VEHICLE PROPULSION**

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(22) Filed: **Dec. 30, 2015**

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(51) **Int. Cl.**

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H02M 7/797	(2006.01)
H02M 5/458	(2006.01)
H02M 7/483	(2007.01)

(Continued)

(52) **U.S. Cl.**

CPC ***B64D 27/24*** (2013.01); ***H02M 5/458*** (2013.01); ***H02M 7/483*** (2013.01); ***H02M 7/797*** (2013.01); *B60Y 2200/51* (2013.01); *B60Y 2200/92* (2013.01); *B64D 2027/026* (2013.01); *B64D 2221/00* (2013.01); *H02M 2001/0077* (2013.01); *H02M 2007/4835* (2013.01); *Y10S 903/903* (2013.01)

(58) **Field of Classification Search**

CPC Y10T 307/707; H02M 2001/0077

See application file for complete search history.

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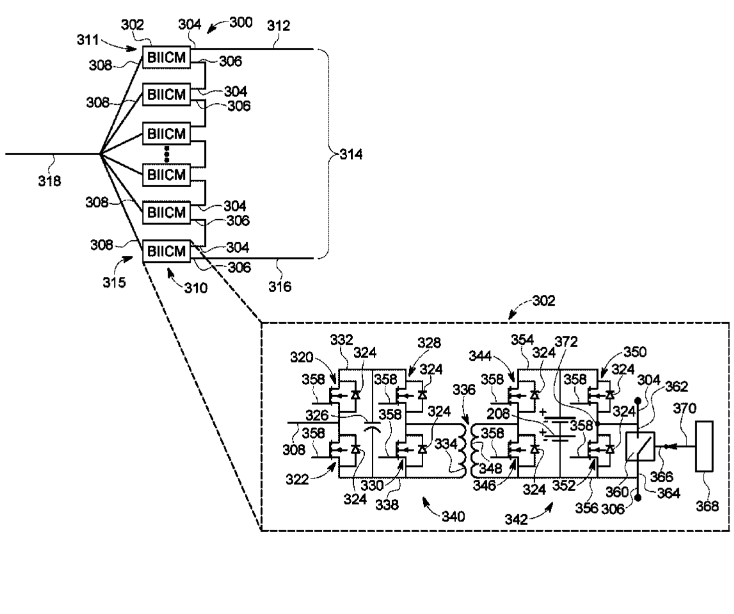
(57) **ABSTRACT**

An electric propulsion system includes at least one generator. The electric propulsion system also includes at least one drive engine coupled to the at least one generator. The electric propulsion system further includes at least one electrical device. The electric propulsion system also includes at least one battery integrated isolated power converter (BIIC), where the at least one generator and at least one of the at least one BIIC and the at least one electrical device are coupled, and where the at least one BIIC and the at least one electrical device are coupled.

13 Claims, 14 Drawing Sheets



(51) **Int. Cl.**
B64D 27/02 (2006.01)
H02M 1/00 (2006.01)

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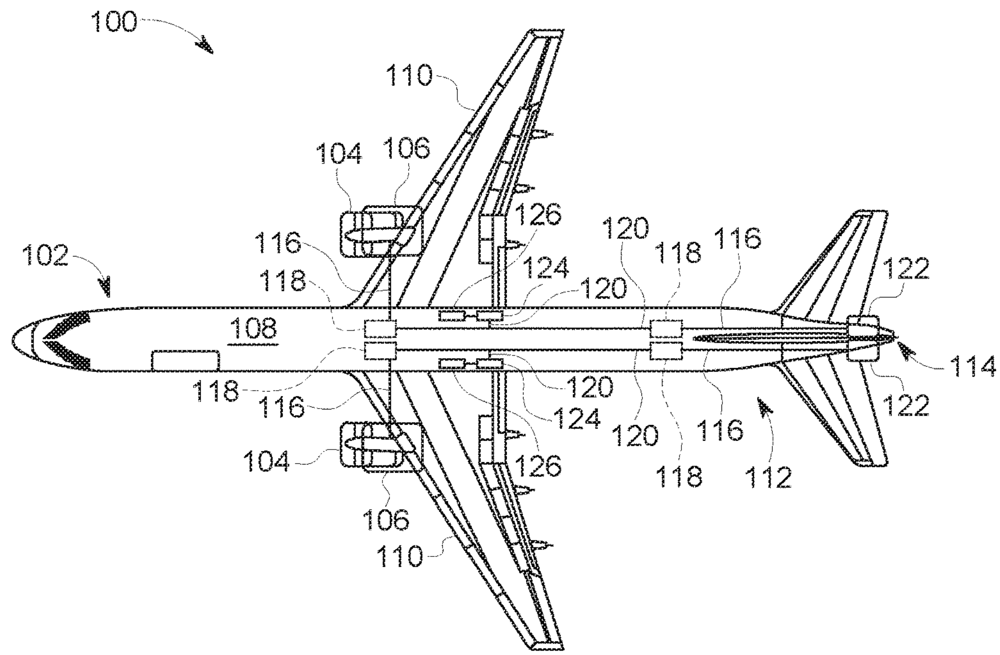


FIG. 1
PRIOR ART

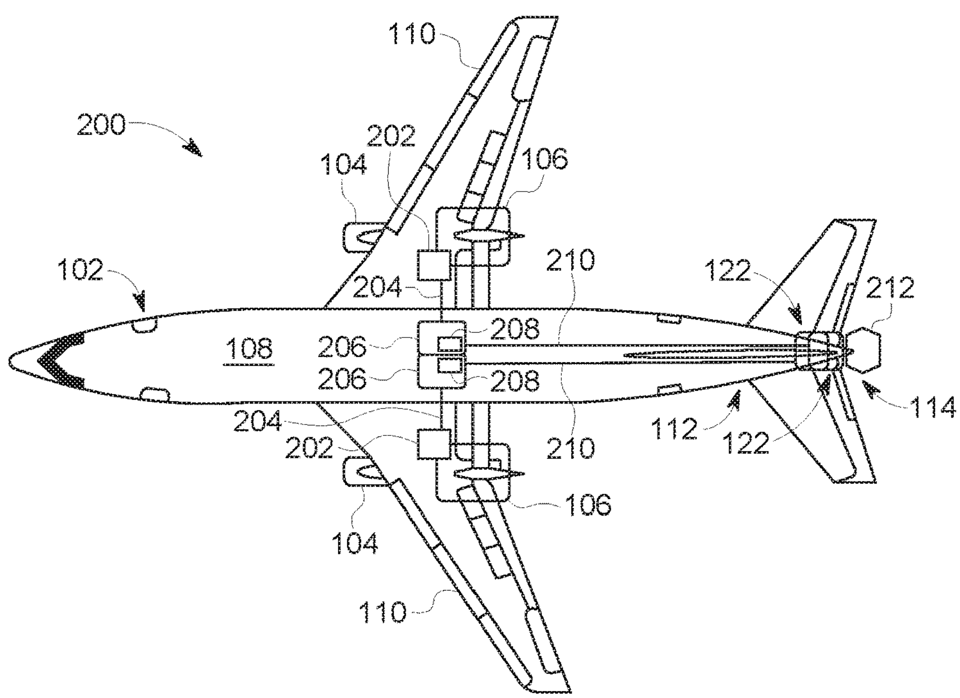


FIG. 2

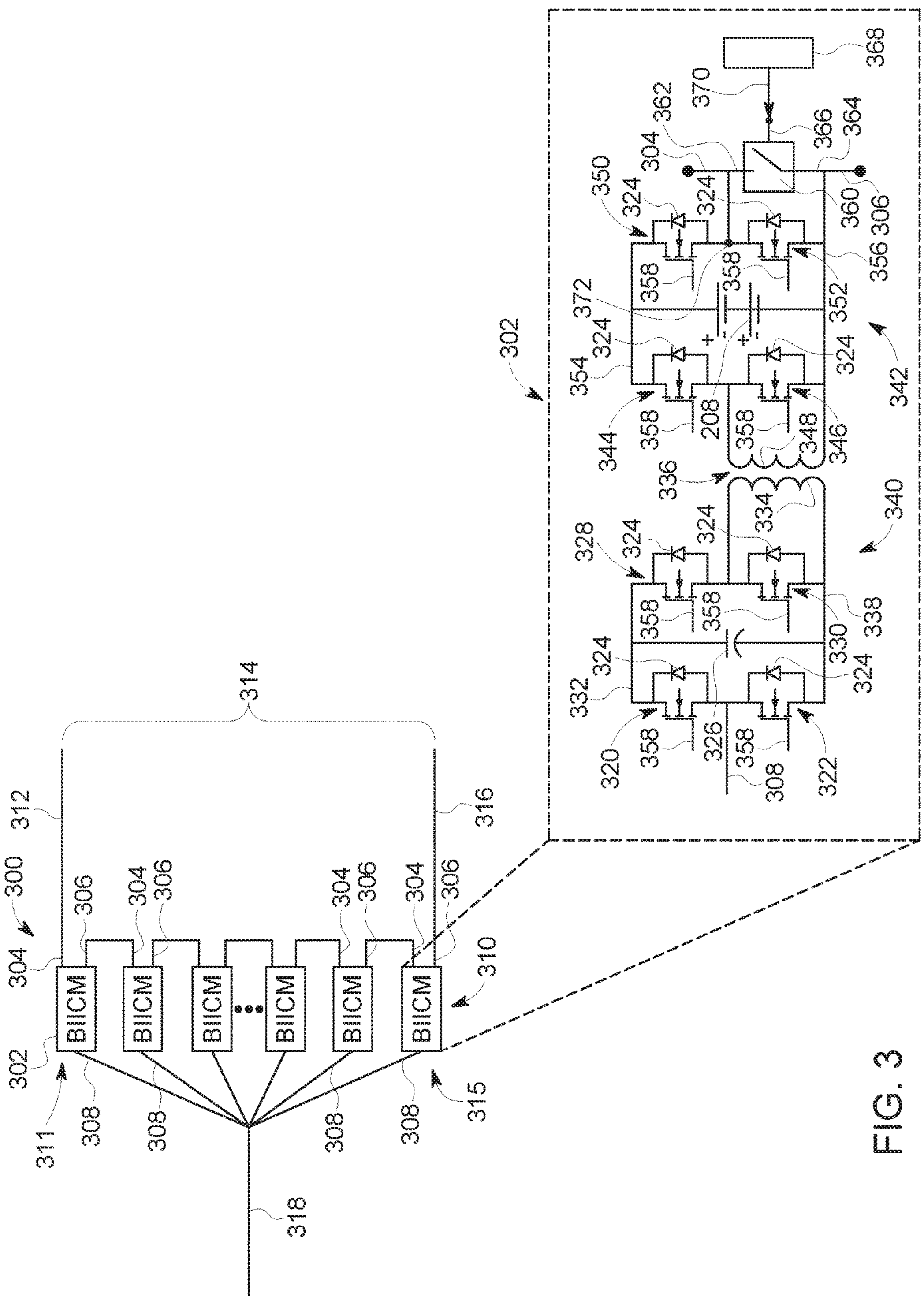
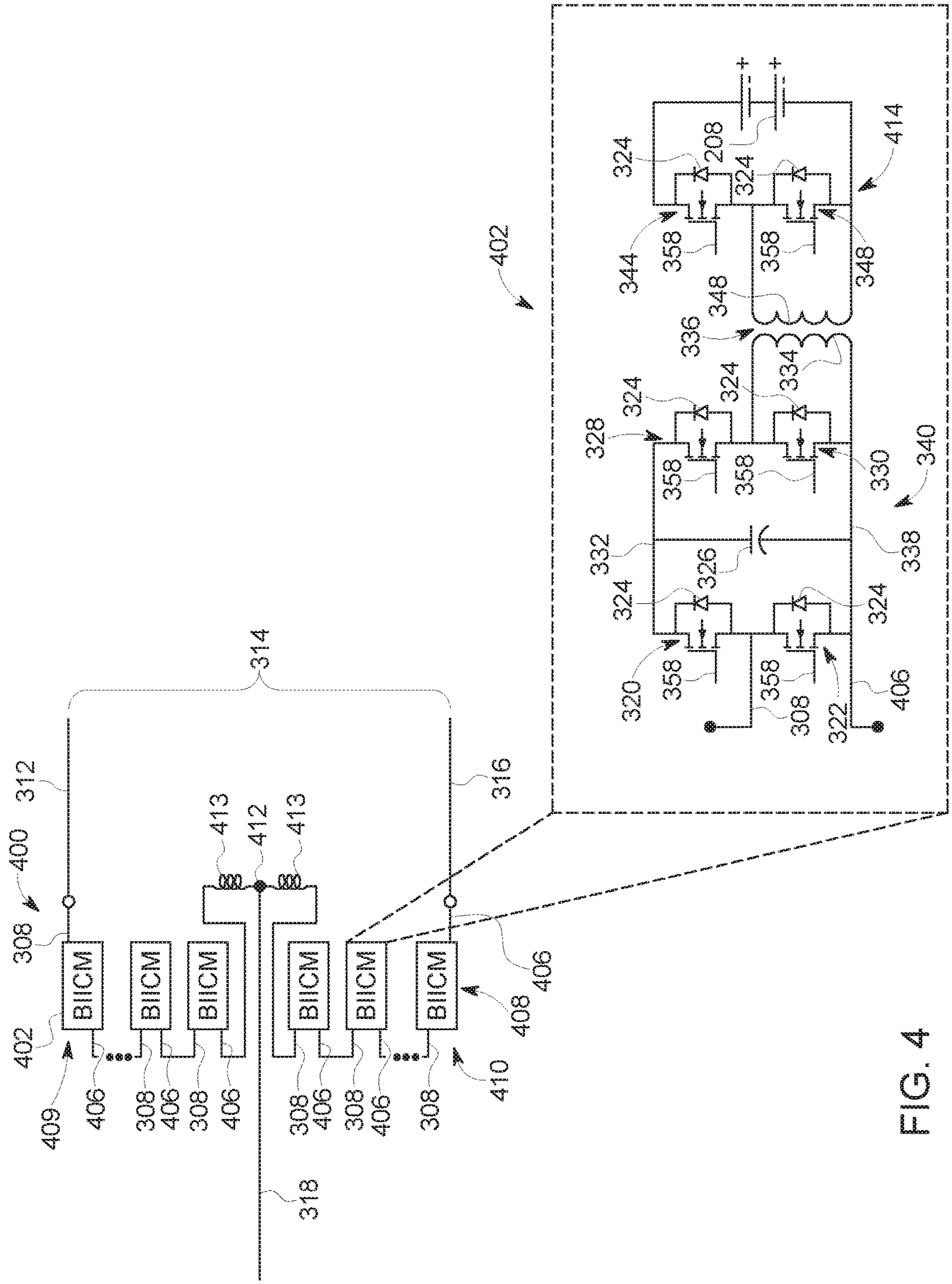


FIG. 3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402
409
410
408
BIICM
BIICM
BIICM
BIICM
BIICM
BIICM
308
406
312
314
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318
412
413
413
402
320
322
328
330
332
326
338
340
336
334
348
344
348
358
324
208
414

FIG. 4

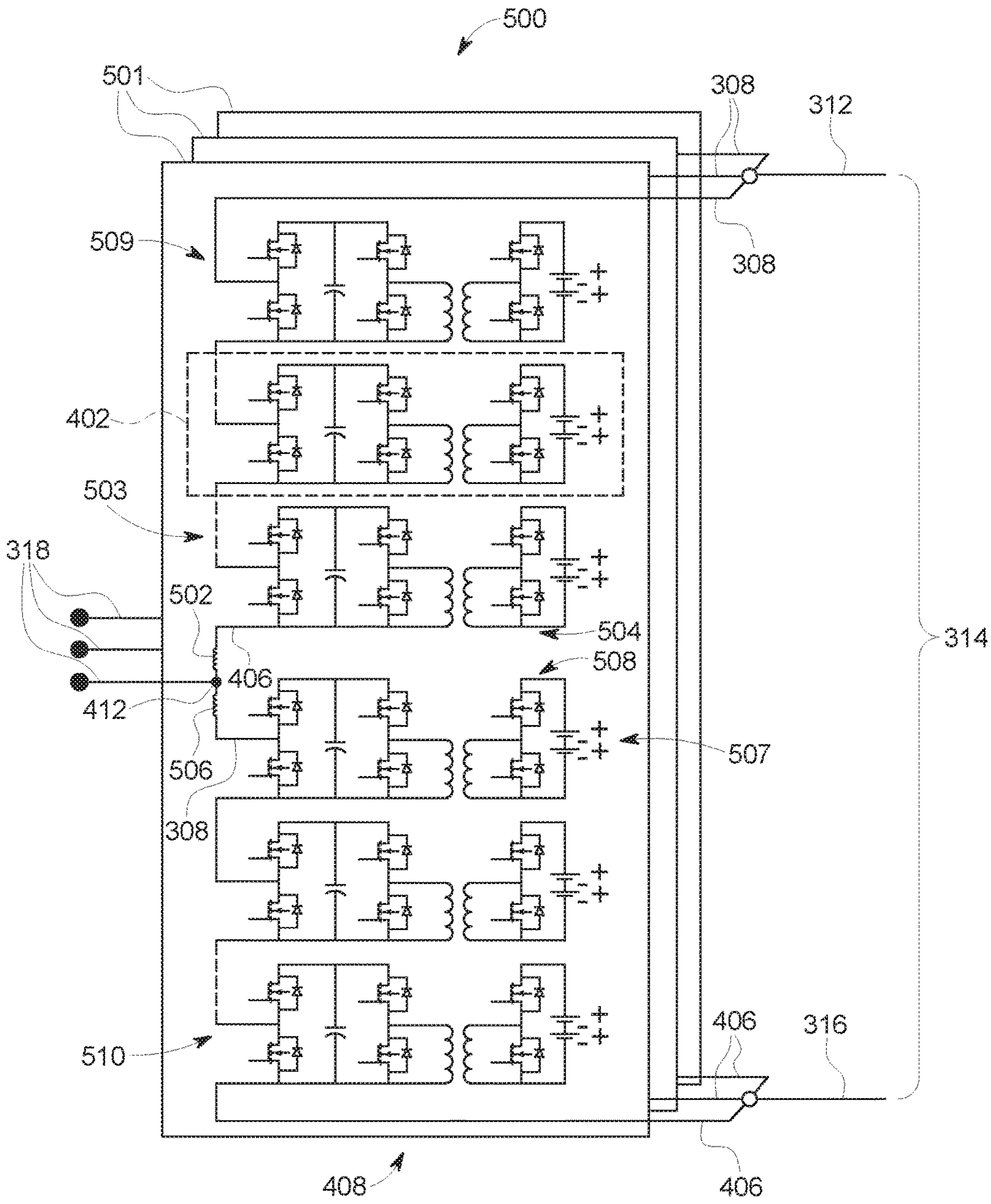
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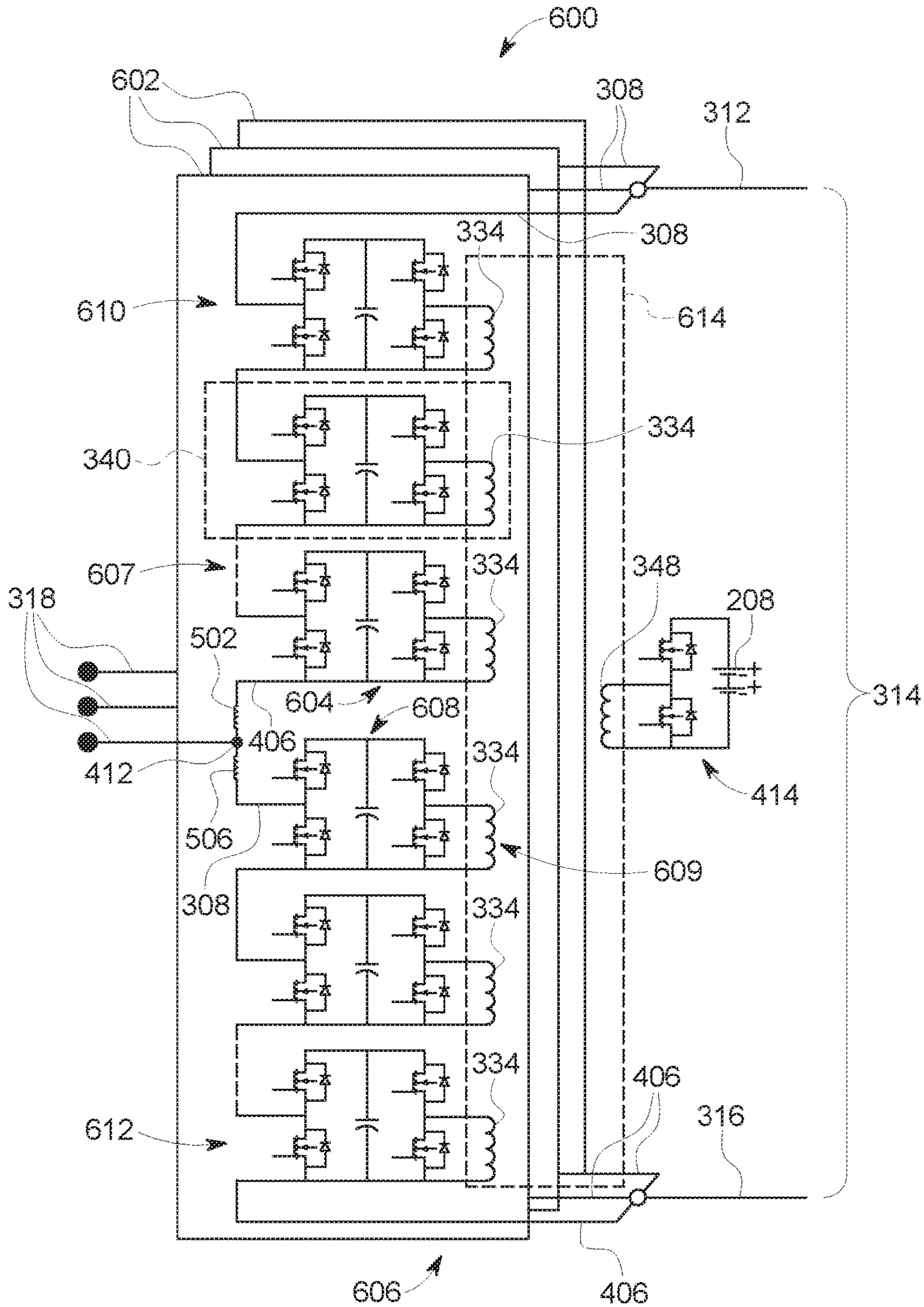
FIG. 5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612
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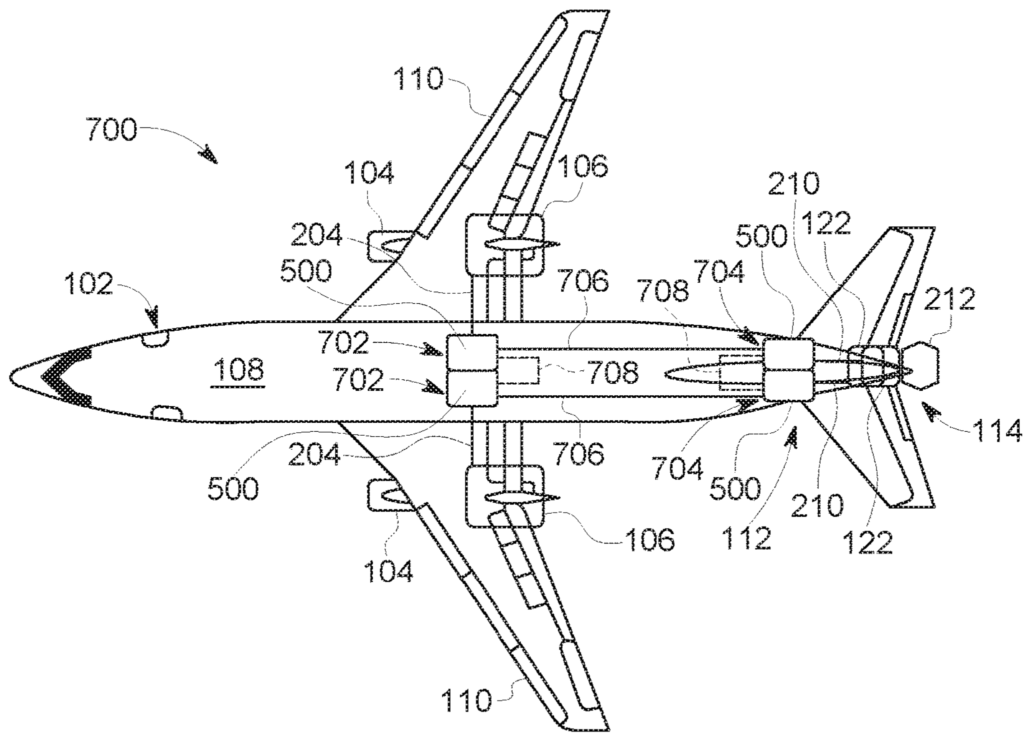
FIG. 6



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106
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702
706
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112
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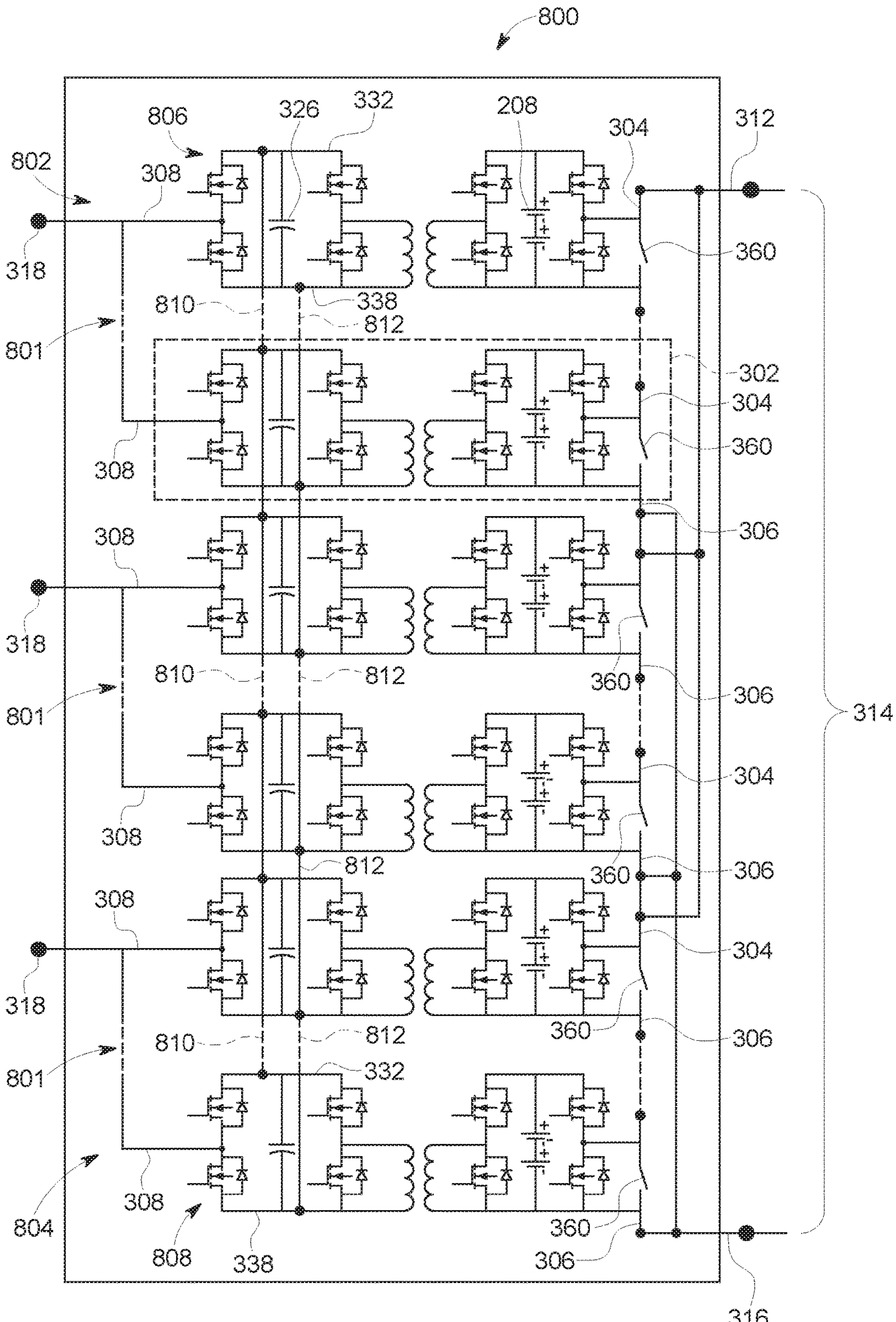
106
104
110

FIG. 7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360
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314
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304
308
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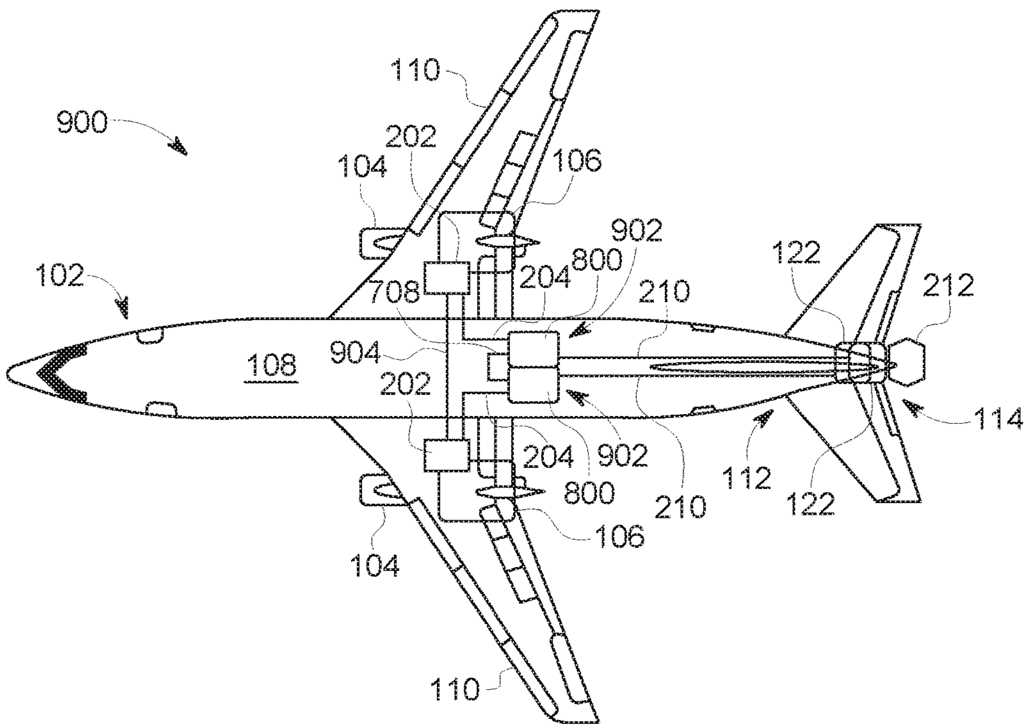
FIG. 8



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106
902
800
102
204
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202
902
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112
114
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106
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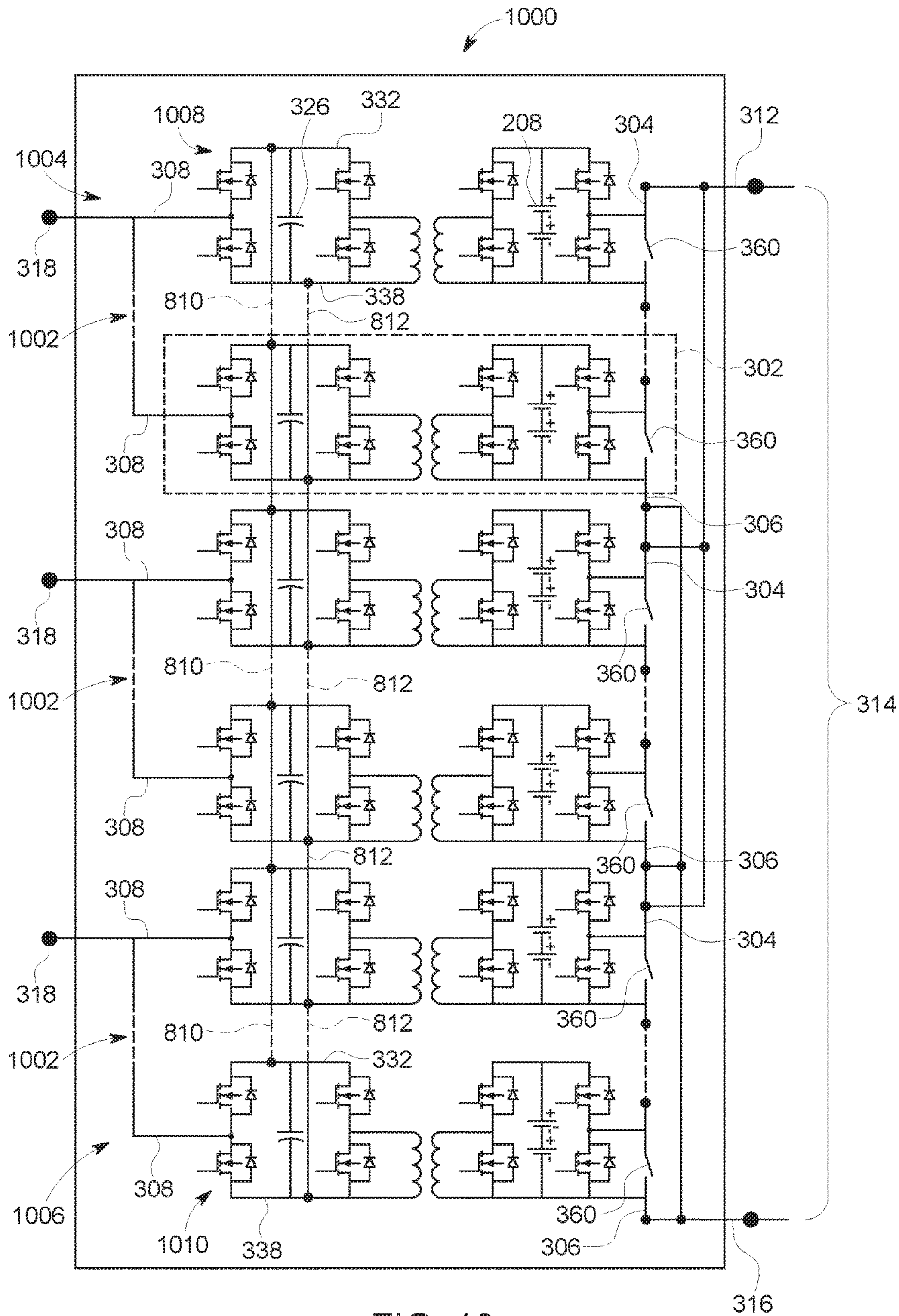
110

FIG. 9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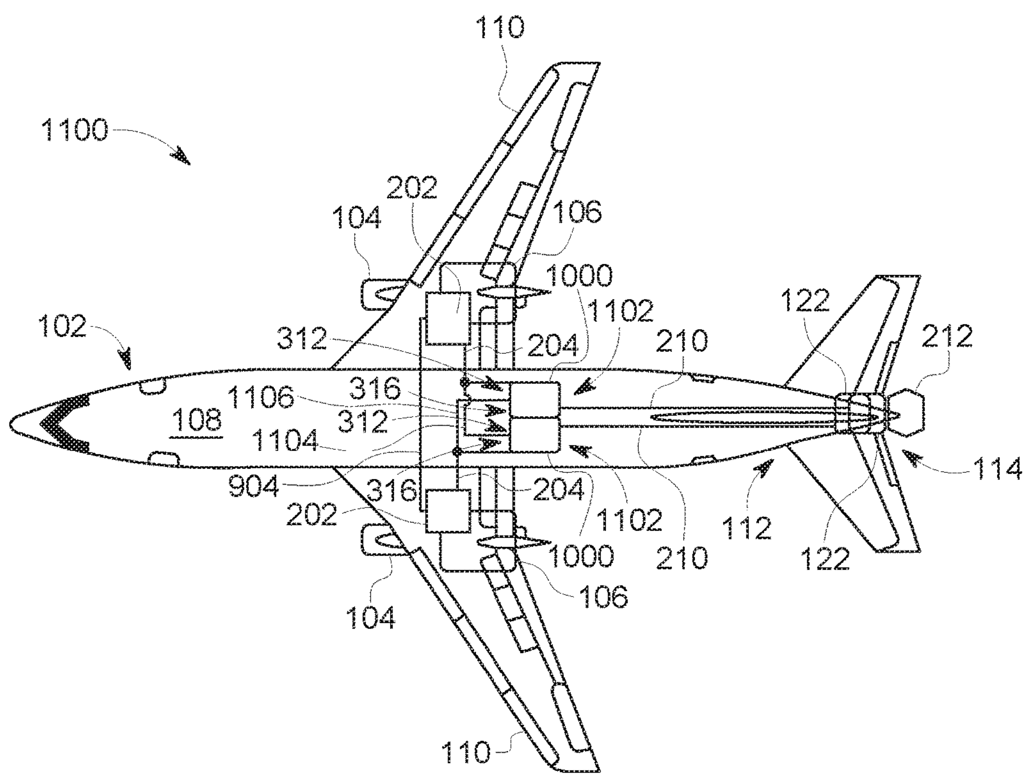
1006
1010
316

FIG. 10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212
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204
202
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114
1000
210
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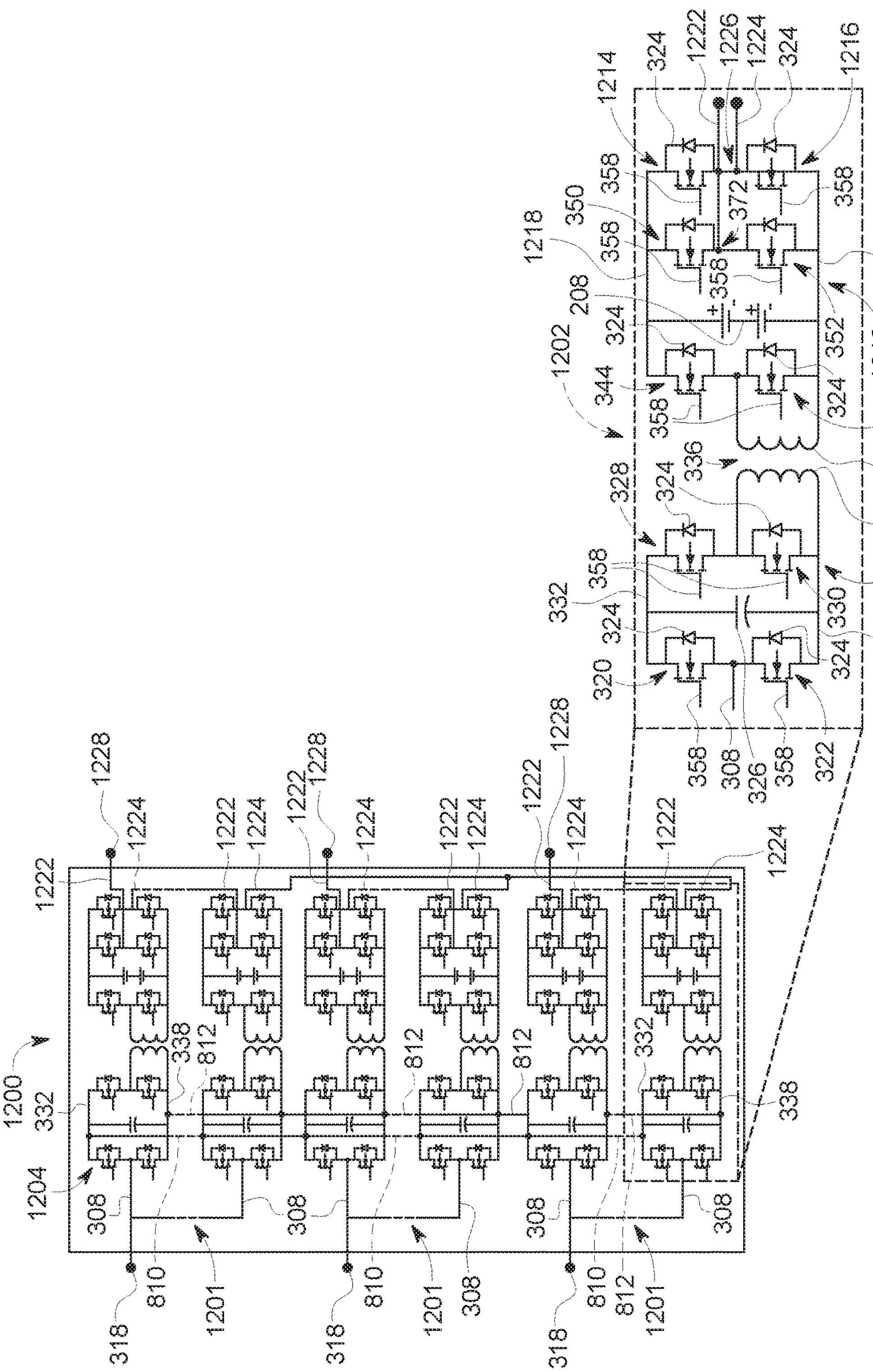
106
104
110

FIG. 11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338
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350
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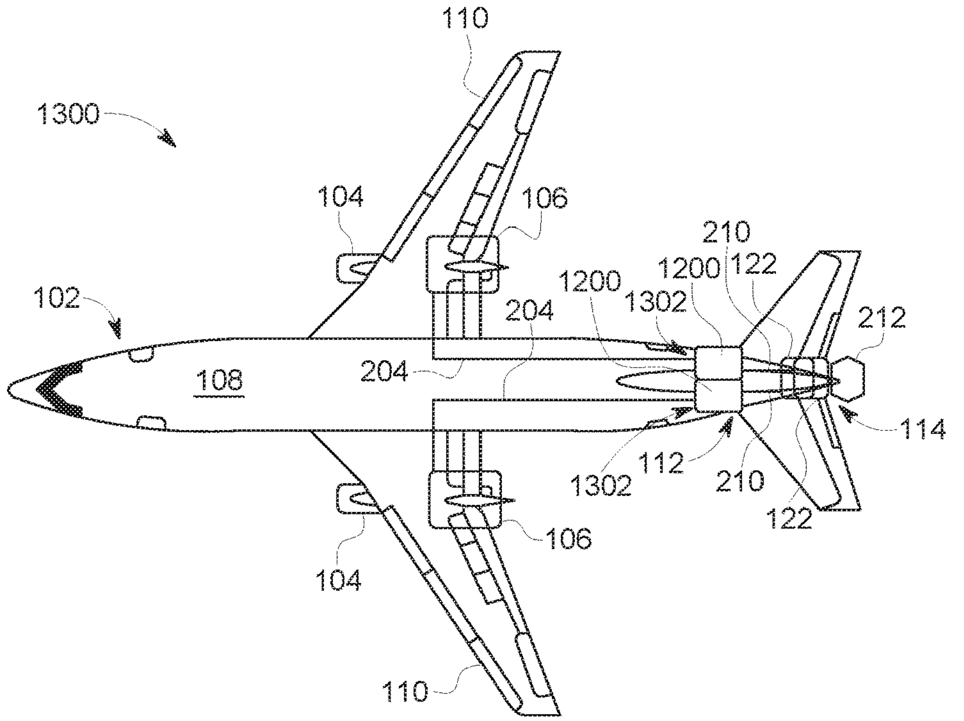
372
810
812

FIG. 12



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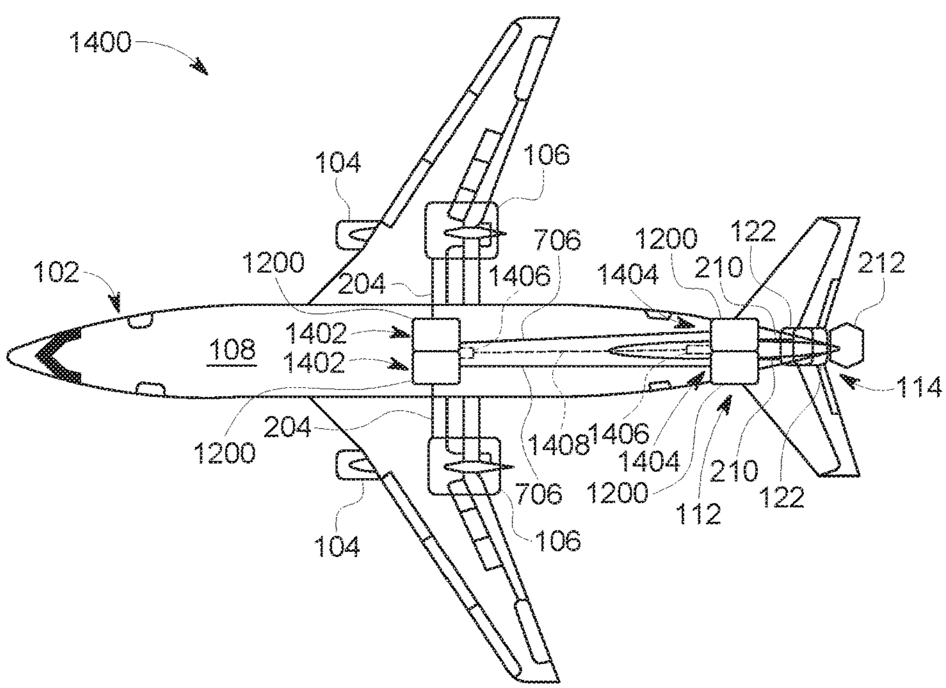
106
102
108
204
1200
1302
210
122
212
114
112

FIG. 13



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1200
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1402
1406
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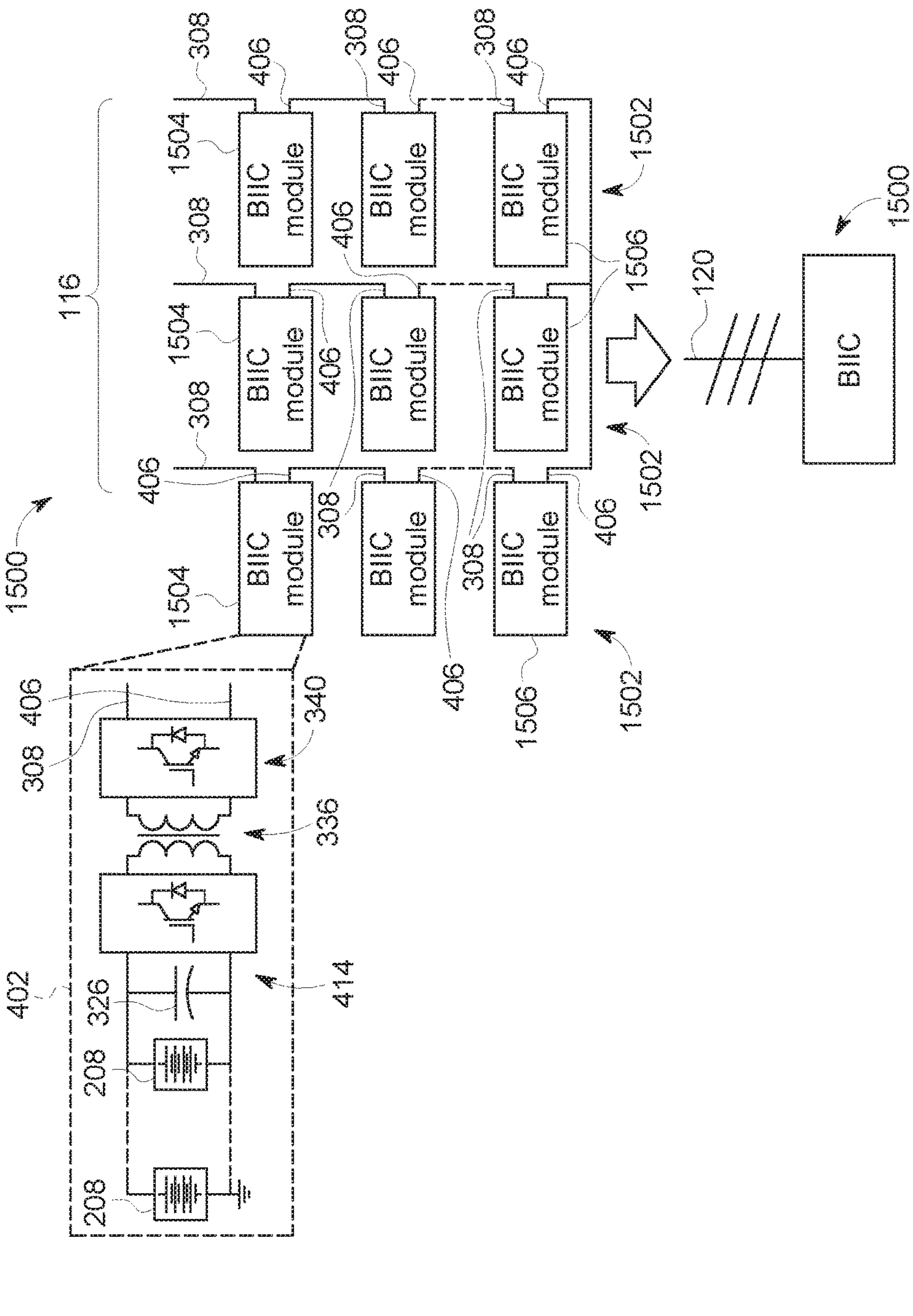
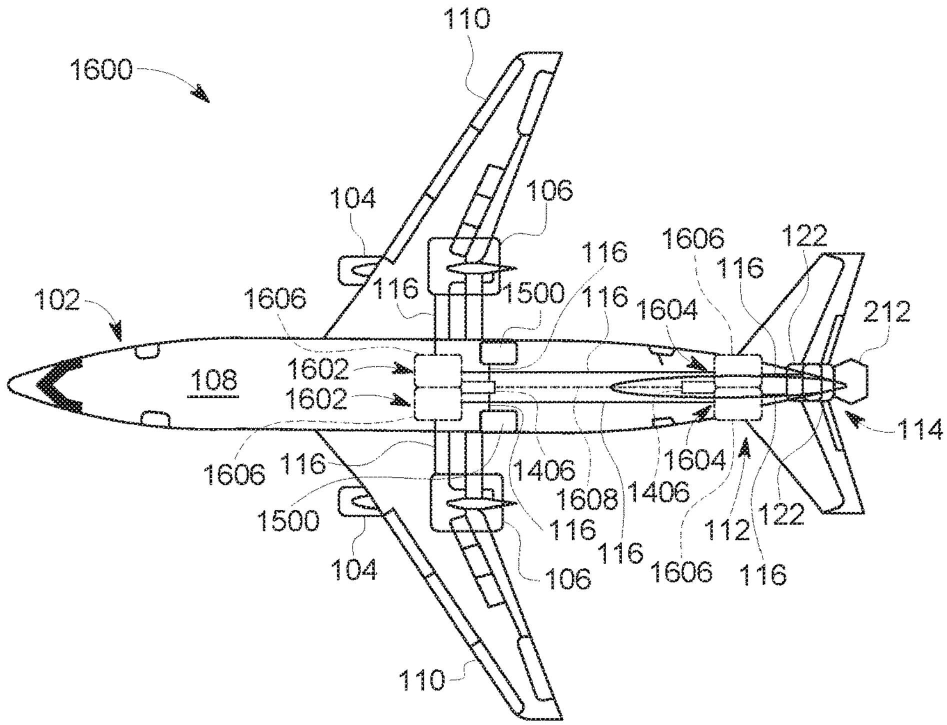
114
1408
112

FIG. 14



BIIC module
BIIC
116
1500
1502
1504
1506
120
308
406
402
326
208
414
336
340

FIG. 15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1604
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212
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1602
1602
1606
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1604
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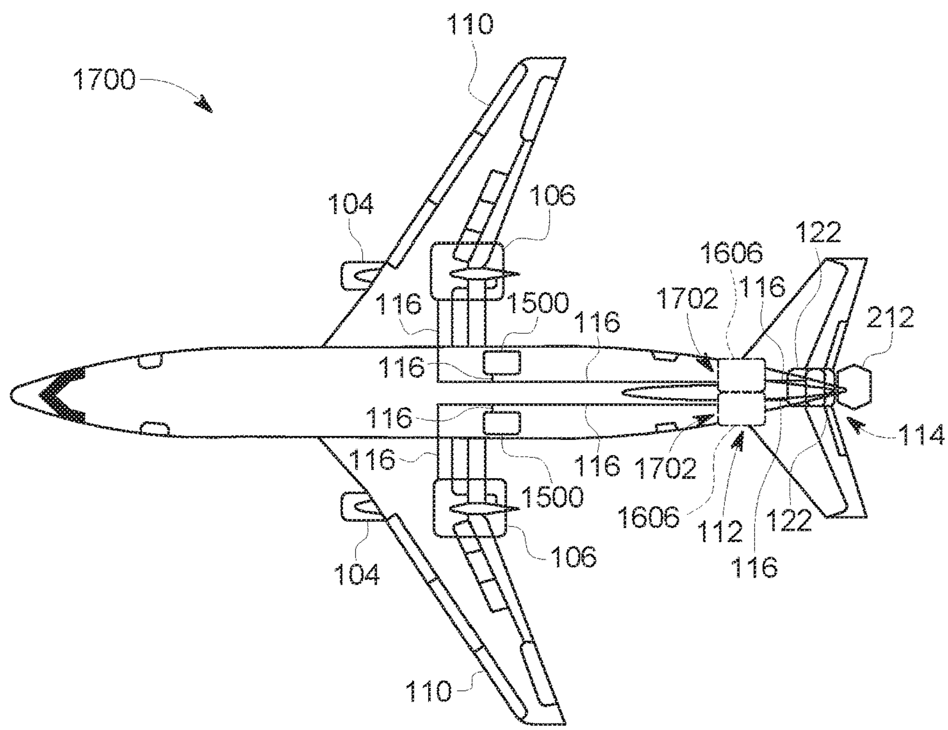
1406
1500
116
116
112
122
104
106
1606
116
110
114

FIG. 16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1702
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1606
112
122
116
104
106
110
114

FIG. 17

BATTERY INTEGRATED ISOLATED POWER CONVERTER AND SYSTEMS FOR ELECTRIC VEHICLE PROPULSION

BACKGROUND

The field of the disclosure relates generally to power converters, and, more specifically, to battery integrated isolated power converters for hybrid-electric or all-electric vehicle propulsion systems.

In large vehicles such as aircraft, it is beneficial for hybrid-electric or all-electric propulsion, power converter, and energy storage systems to maximize the specific power, i.e., kilowatts per kilogram (kW/kg) of these components of the power system. To improve performance of propulsion systems, the specific power values of known power converters for hybrid-electric or all-electric vehicle propulsion must be increased. Moreover, known power converters for hybrid-electric or all-electric vehicle propulsion systems need to reliably supply power to critical propulsion equipment at all times, without being impacted whatsoever by power needs of, or electrical faults in accessory systems. In such known power converters for hybrid-electric or all-electric vehicle propulsion systems, interrupting power to the least number of electrical load components as possible is problematic and often results in diminished performance of the main propulsion system due to faults in individual non-propulsion accessory equipment.

At least some known power converters for hybrid-electric or all-electric vehicle propulsion systems utilize modular multi-level converter (MMC) architecture. Controllers for MMCs in such known power converters for hybrid-electric or all-electric vehicle propulsion systems must not only switch the MMC submodules, including those with insulated-gate bipolar transistors (IGBTs) or MOSFETs, they must also implement complex control algorithms with sophisticated high speed computing and communications to continually balance the voltages of each submodule capacitor.

The MMCs of such known power converters for hybrid-electric or all-electric vehicle propulsion systems utilize large energy storage capacitors on each MMC valve submodule as independently controllable two-level converters and voltage sources for AC or DC electrical loads. Also, in such known power converters for hybrid-electric or all-electric vehicle propulsion systems, isolation of power system components such as batteries require large line frequency transformers for enhanced safety and reduction of common mode interference. Many of these known power converters for hybrid-electric or all-electric vehicle propulsion systems utilize heavy and bulky passive components, e.g., capacitors and inductors, amounting to more than half of their weight.

BRIEF DESCRIPTION

In one aspect, an electric propulsion system for a vehicle is provided. The electric propulsion system includes at least one generator. The electric propulsion system also includes at least one drive engine coupled to the at least one generator. The electric propulsion system further includes at least one electrical device. The electric propulsion system also includes at least one battery integrated isolated power converter (BIIC), where the at least one generator and at least one of the at least one BIIC and the at least one electrical device are coupled, and where the at least one BIIC and the at least one electrical device are coupled.

In another aspect, a BIIC is provided. BIIC includes at least one BIIC module (BIICM) string. BIICM string includes a plurality of BIICMs coupled to each other. Each BIICM of the plurality of BIICMs includes a first BIICM circuit including a first plurality of switching devices coupled together. Each BIICM of the plurality of BIICMs also includes a second BIICM circuit including a second plurality of switching devices coupled together. Each BIICM of the plurality of BIICMs further includes a BIICM high-frequency transformer coupled to and between the first BIICM circuit and the second BIICM circuit, where the first BIICM circuit and the second BIICM circuit are physically isolated and inductively coupled through the BIICM high-frequency transformer.

DRAWINGS

These and other features, aspects, and advantages of the present disclosure will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. **1** is a generalized schematic view of a prior art electric vehicle propulsion system superimposed on a plan view of an aircraft;

FIG. **2** is a schematic view of an exemplary embodiment of an electric vehicle propulsion system superimposed on a plan view of an aircraft;

FIG. **3** is a schematic diagram of an exemplary bi-directional AC-to-DC battery integrated isolated power converter (BIIC) that may be used in the electric vehicle propulsion system shown in FIG. **2**;

FIG. **4** is a schematic diagram of an alternative bi-directional AC-to-DC BIIC that may be used in the electric vehicle propulsion system shown in FIG. **2**;

FIG. **5** is a schematic diagram of an alternative bi-directional AC-to-DC BIIC configured for 3-phase AC power conversion;

FIG. **6** is a schematic diagram of another alternative bi-directional AC-to-DC BIIC configured for 3-phase AC power conversion;

FIG. **7** is a schematic view of an alternative embodiment of an electric vehicle propulsion system superimposed on a plan view of an aircraft;

FIG. **8** is a schematic diagram of another alternative bi-directional AC-to-DC BIIC configured for 3-phase AC power conversion;

FIG. **9** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system superimposed on a plan view of an aircraft;

FIG. **10** is a schematic diagram of yet another alternative bi-directional AC-to-DC BIIC configured for 3-phase AC power conversion;

FIG. **11** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system superimposed on a plan view of an aircraft;

FIG. **12** is a schematic diagram of an exemplary AC-to-AC BIIC configured for 3-phase AC power conversion;

FIG. **13** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system superimposed on a plan view of an aircraft;

FIG. **14** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system superimposed on a plan view of an aircraft;

FIG. **15** is a schematic diagram of an exemplary shunt type BIIC configured for bidirectional DC-to-AC power conversion;

FIG. **16** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system superimposed on a plan view of an aircraft; and

FIG. **17** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system superimposed on a plan view of an aircraft.

Unless otherwise indicated, the drawings provided herein are meant to illustrate features of embodiments of this disclosure. These features are believed to be applicable in a wide variety of systems comprising one or more embodiments of this disclosure. As such, the drawings are not meant to include all conventional features known by those of ordinary skill in the art to be required for the practice of the embodiments disclosed herein.

DETAILED DESCRIPTION

In the following specification and the claims, reference will be made to a number of terms, which shall be defined to have the following meanings.

The singular forms "a", "an", and "the" include plural references unless the context clearly dictates otherwise.

"Optional" or "optionally" means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where the event occurs and instances where it does not.

Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as "about", "approximately", and "substantially", are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Here and throughout the specification and claims, range limitations may be combined and/or interchanged, and such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise.

The battery integrated isolated power converters (BIICs) described herein are suited to increasing the specific power, i.e., kilowatt/kilogram (kW/kg), of electric vehicle propulsion systems by reducing the number and weight of passive components and cables. Specifically, the BIICs described herein do not require a large number of passive filtering capacitors because the rates of change of voltage with time, i.e., dv/dt, of individual battery integrated power converter modules (BIICMs) are small relative to known power converters in known electric vehicle propulsion systems. Further, specifically, tight control of dv/dt in individual BIICMs results in low levels of harmonic distortion and electromagnetic interference (EMI) relative to known power converters for electric vehicle propulsion systems. Further, such BIICs are more modular, sealable, reliable, as well as easier to maintain and manufacture relative to known power converters for electric vehicle propulsion systems. Furthermore, a wide variety of energy storage devices are adaptable to use with the BIICs described herein, which facilitates incorporation of more advanced energy storage devices into electric vehicle propulsion systems without replacement of power converter components. Moreover, the BIICs described herein provide effective physical and galvanic isolation of energy storage devices, including, without limitation, direct current (DC) batteries, from other components of the BIICs and the overall power system, thus enhancing safety and reliability in electric vehicle propulsion systems. As such, the BIICs described herein utilize energy storage devices to not only provide energy for electric vehicle propulsion, but also to act as voltage sources to enable multi-level power converter operations without additional film capacitors, and at the same time reduce the requirements of using filtering component elements relative to known power converters for electric vehicle propulsion systems.

FIG. **1** is a generalized schematic view of a prior art electric vehicle propulsion system **100** superimposed on a plan view of an aircraft. Prior art electric vehicle propulsion system **100** for a vehicle **102** includes at least one drive engine **104**, including an internal combustion engine, coupled to vehicle **102**. At least one generator **106** is coupled to at least one drive engine **104** and to vehicle **102**. At least one drive engine **104** functions as a prime mover for at least one generator **106** to provide torque to turn the rotor of at least one generator **106** to induce an alternating current (AC) in a stator of at least one generator **106**. In the case where vehicle **102** is an aircraft, aircraft further includes a fuselage **108**, at least one wing **110**, and an aft portion **112**, including, without limitation, a tail **114**.

In some embodiments of prior art electric vehicle propulsion systems **100**, AC current is transmitted on at least one AC line **116** from at least one generator **106** to at least one bi-directional AC/DC power converter **118**, which converts AC power from generator **106** to DC power. Bi-directional AC/DC power converter **118** includes conventional AC/DC power convertors, i.e., not BIICs as described herein. DC power from bi-directional AC/DC power converter **118** is carried to at least one additional bi-directional AC/DC power converter **118** on at least one transmission line **120** of a DC type. For additional bi-directional AC/DC power converter **118**, at least one electrical device **122** is supplied with AC power on at least one additional AC line **116**. By way of additional transmission line **120** of a DC type, at least one bi-directional DC/DC power converter **124** is coupled to and between DC type transmission line **120** and at least one battery bank **126**. Electrical energy stored in battery bank **126** is made available to power electrical device **122** when needed, as where full capacity operation of generator **106** is unavailable or undesirable. Likewise, where full capacity operation of generator **106** supplies power in excess of that required by electrical device **122**, battery bank **126** is charged, if needed. In the case where vehicle **102** is an aircraft, electrical device **122** includes at least one fan motor used for vehicle propulsion including, without limitation, during taxiing on a runway.

FIG. **2** is a schematic view of an exemplary embodiment of an electric vehicle propulsion system **200** superimposed on a plan view of an aircraft. In the exemplary embodiment, vehicle **102** is an aircraft, as shown as described above with reference to FIG. **1**. Also, in the exemplary embodiment, at least one generator rectifier **202** is coupled to vehicle **102** and to generator **106**. Generator rectifier **202** includes rectifiers known in the art including, without limitation, half-wave rectifiers, full-wave rectifiers, bridge rectifiers, rectifiers with at least one diode, and rectifiers without at least one diode. Generator rectifier **202** is configured to rectify an AC power output of generator **106** and to transmit a DC power on at least one generator cable **204** to at least one battery integrated isolated power converter (BIIC) **206** located in fuselage **108** proximate wing **110**. Further, in the exemplary embodiment, generator cable **204** is a DC cable.

Also, in the exemplary embodiment, BIIC **206** includes at least one energy storage device **208**, including, without limitation, a DC energy storage device such as at least one battery, collocated with BIIC **206**. Further, in the exemplary embodiment, BIIC **206** is configured to function as a DC-to-AC power converter which receives DC power from generator rectifier **202** and transmits AC power to electrical device **122** on at least one BIIC cable **210**. Further, in the exemplary embodiment, electrical device **122** includes at least one fan motor **212** used for vehicle propulsion during taxiing on a runway, i.e., where vehicle **102** is an aircraft. In an alternative embodiment, not shown, BIIC **206** is located in aft portion **112** of fuselage **108** proximate tail **114**. As such, it is possible to use longer lengths of DC type generator cable **204** for coupling generator rectifier **202** to BIIC **206** relative to electric vehicle propulsion system **200** shown and described with reference to FIG. **2**. Likewise, shorter lengths of AC type BIIC cable **210** are used for coupling BIIC **206** to electrical device **122** relative to the exemplary electric vehicle propulsion system **200**. Thus, use of shorter lengths of AC type BIIC cable **210** and longer lengths of DC type generator cable **204** facilitates decreasing the weight of electric vehicle propulsion system **200** relative to the exemplary embodiment shown and described with reference to FIG. **2**.

In operation of the exemplary embodiment, rectified DC power from generator rectifier **202**, either alone or in combination with DC power from energy storage device **208**, is converted by BIIC **206** to AC power transmitted to electrical device **122**. BIIC **206** diverts at least a portion of DC power from generator rectifier **202** to charge energy storage device **208** when energy storage device **208** does not adequately supply power to electrical device **122**. In that case, a larger portion of DC power from generator rectifier **202** is converted to AC power by BIIC **206** to supply AC power to electrical device **122** than when energy storage device **208** fully supplies AC power to electrical device **122**. When energy storage device **208** is fully supplying power to electrical device **122**, a mechanical load placed upon drive engine **104** by generator **106** is lower than when generator rectifier **202** is supplying DC power to one or both of electrical device **122** and energy storage device **208**, i.e., for charging. Moreover, in operation of the exemplary embodiment, inclusion of generator rectifier **202** facilitates coupling of DC cable, rather than larger and heavier AC cable, between generator **106** and BIIC **206**, thus increasing the specific power, i.e., kW/kg, of the exemplary electric vehicle propulsion system **200** relative to electric vehicle propulsion system **100** shown and described above with reference to FIG. **1**.

FIG. **3** is a schematic diagram of an exemplary bi-directional AC-to-DC BIIC **300** that may be used in the electric vehicle propulsion system **200** shown in FIG. **2**. In the exemplary embodiment, bi-directional AC-to-DC BIIC **300** includes at least one bi-directional AC-to-DC BIIC module (bi-directional AC-to-DC BIICM) **302** including a first DC terminal **304** and a second DC terminal **306**. Bi-directional AC-to-DC BIICM **302** also includes a first node **308** configured to receive and transmit a phase of AC power. Also, in the exemplary embodiment, a plurality of bi-directional AC-to-DC BIICMs **302** are arranged in at least one string **310**. First DC terminal **304** of a first bi-directional AC-to-DC BIICM **302** of string **310**, i.e., the topmost bi-directional AC-to-DC BIICM **302** (topmost BIICM **311**) in FIG. **3**, couples to a first DC line **312** of a DC link, including, without limitation, a high voltage DC link **314**. Second DC terminal **306** of a last bi-directional AC-to-DC BIICM **302** of string **310**, i.e., the bottommost bi-directional AC-to-DC BIICM **302** (bottommost BIICM **315**) in FIG. **3**, couples to a second DC line **316** of high voltage DC link **314**. Further, in the exemplary embodiment, first DC terminals **304** and second DC terminals **306** of each bi-directional AC-to-DC BIICMs **302** of string **310** other than the first BIICM **302** and second BIICM **302**, respectively, are serially coupled. Furthermore, in the exemplary embodiment, first node **308** of each bi-directional AC-to-DC BIICMs **302** of string **310** receives or transmits a phase of AC power on a first AC line **318**. First AC line **318** includes BIIC cable **210** as shown and described with reference to FIG. **2**. In other alternative embodiments shown and described below, first AC line **318** also includes AC type generator cable **204**.

Also, in the exemplary embodiment, bi-directional AC-to-DC BIICM **302** that may be used in bi-directional AC-to-DC BIIC **300** includes first node **308** coupled to and between a first switching device **320** and a second switching device **322**. First switching device **320** is serially coupled to second switching device **322**. First switching device **320** and all switching devices hereinafter described include, without limitation, such devices as integrated gate commutated thyristors, non-linear controllable resistors, varistors, and transistors such as insulated-gate bipolar transistors (IGBTs), metal-oxide semiconductor field-effect transistors (MOSFETs), injection enhanced gate transistors, junction gate field-effect transistors (JFETs), bipolar junction transistors (BJTs), and combinations thereof. First switching device **320** and second switching device **322** each include an antiparallel diode **324** coupled in parallel thereto. These devices can be made of silicon (Si) or wide bandgap materials such as SiC or GaN. Also, in the exemplary embodiment, all switching devices hereinafter described also have antiparallel diode **324** coupled in parallel thereto.

Also, in the exemplary embodiment, at least one capacitor **326** is coupled in parallel across both of first switching device **320** and second switching device **322**. Further, in the exemplary embodiment, a third switching device **328** and a fourth switching device **330** are serially coupled. Serially coupled third switching device **328** and fourth switching device **330** are coupled in parallel across both of first switching device **320** and second switching device **322**. A second node **332** includes connections to and between first switching device **320**, capacitor **326**, and third switching device **328**. A first winding **334** of a BIICM high-frequency transformer **336** is coupled in parallel to fourth switching device **330**. In an alternative embodiment, not shown, first winding **334** is coupled in parallel to third switching device **328**. BIICM high-frequency transformer **336** includes, without limitation, a high-frequency transformer configured to operate at frequencies from kilohertz (kHz) to megahertz (MHz) range. A third node **338** includes connections to and between second switching device **322**, capacitor **326**, fourth switching device **330**, and first winding **334**. Together, first node **308**, first switching device **320**, second switching device **322**, capacitor **326**, third switching device **328**, fourth switching device **330**, and first winding **334** form a first side **340**, i.e., a first BIICM circuit, of bi-directional AC-to-DC BIICM **302**.

Further, in the exemplary embodiment, bi-directional AC-to-DC BIICM **302** includes a second side **342**, i.e., a second BIICM circuit. Second side **342** includes a fifth switching device **344** serially coupled to a sixth switching device **346**. A second winding **348** of BIICM high-frequency transformer **336** is coupled in parallel to sixth switching device **346**. In an alternative embodiment, not shown, second winding **348** is coupled in parallel to fifth switching device **344**. At least one energy storage device **208** is coupled in parallel across both of fifth switching device **344** and sixth switching device **346**. Also, in the exemplary embodiment, second side **342** includes a seventh switching device **350** serially coupled to an eighth switching device **352**. Serially coupled seventh switching device **350** and eighth switching device **352** are coupled in parallel across both of fifth switching device **344** and sixth switching device **346**. A node **354** includes connections to and between fifth switching device **344**, energy storage device **208**, and seventh switching device **350**.

Furthermore, in the exemplary embodiment, second side **342** includes first DC terminal **304** coupled to and between seventh switching device **350** and eighth switching device **352**. Second side **342** also includes second DC terminal **306** coupled to a fourth node **356**. Fourth node **356** includes connections to and between second winding **348**, sixth switching device **346**, energy storage device **208**, eighth switching device **352**, and second DC terminal **306**. In an alternative embodiment, not shown, energy storage device **208** and capacitor **326** are swapped in bi-directional AC-to-DC BIICM **302**. Moreover, in the alternative embodiment, first side **340** and second side **342** are inductively coupled, i.e., galvanically coupled, through BIICM high-frequency transformer **336**.

Moreover, in the exemplary embodiment, first **320**, second **322**, third **328**, fourth **330**, fifth **344**, sixth **346**, seventh **350**, and eighth **352** switching devices include at least one switch control terminal **358** coupled to at least one switching controller, not shown in FIG. **3**. Switching controller is configured to transmit at least one switch control signal to at least one of first **320**, second **322**, third **328**, fourth **330**, fifth **344**, sixth **346**, seventh **350**, and eighth **352** switching devices to control its switching states. In an alternative embodiment, not shown, switching controller receives and transmits other control signals to and from other controllers located elsewhere within or outside bi-directional AC-to-DC BIIC **300**, also not shown in FIG. **3**.

Also, in the exemplary embodiment, bi-directional AC-to-DC BIICM **302** includes at least one bypass switch **360** including, without limitation, such devices as non-linear controllable resistors, varistors, and transistors such as IGBTs, MOSFETs, JFETs, BJTs, and relays. Bypass switch **360** includes a first bypass terminal **362** coupled to first DC terminal **304** and a second bypass terminal **364** coupled to second DC terminal **306**, i.e., fourth node **356**. Bypass switch **360** also includes at least a third bypass terminal, i.e., a bypass control terminal **366**, coupled to at least one bypass switch controller **368**. Bypass switch controller **368** is configured to transmit a control signal **370** to bypass control terminal **366** to close bypass switch **360** when at least one characteristic state associated with bi-directional AC-to-DC BIICM **302**, including, without limitation, physically quantifiable states such as voltage, current, charge, and temperature, associated with energy storage device **208** is present. Likewise, bypass switch controller **368** is configured to transmit control signal **370** to bypass control terminal **366** to open bypass switch **360** when at least one characteristic state associated with bi-directional AC-to-DC BIICM **302** is not present. In an alternative embodiment, not shown, bypass switch **360** and bypass switch controller **368** are not coupled to bi-directional AC-to-DC BIICM **302**. Further, in the exemplary embodiment, first DC terminal **304** is equivalent to a fifth node **372** defined between seventh switching device **350** and eighth switching device **352**. Furthermore, in the exemplary embodiment, second DC terminal **306** is equivalent to fourth node **356**.

In operation, in the exemplary embodiment, bi-directional AC-to-DC BIIC **300** converts AC power received on first AC line **318** into DC power transmitted to electrical device **122**, not shown. Bi-directional AC-to-DC BIIC **300** is also capable to convert DC power received on high voltage DC link **314** into AC power transmitted on first AC line **318**. Thus, in the exemplary embodiment, bi-directional AC-to-DC BIIC **300** functions as a bi-directional converter.

Also, in operation of in the exemplary embodiment, bi-directional AC-to-DC BIICM **302** converts a phase of AC power received on first node **308** into DC power transmitted to electrical device **122**, not shown, on first DC terminal **304** and second DC terminal **306**. Depending on a predetermined configuration of switching controllers and switching states, it is possible to divert a portion of DC power converted by second side **342** into energy storage device **208** to, for example, charge it. Also, in operation of the exemplary embodiment, it is possible to divert a portion of DC power stored in energy storage device **208**, i.e., to discharge it, to supplement DC power transmitted on first DC terminal **304** and second DC terminal **306**. Bi-directional AC-to-DC BIICM **302** is also capable to convert DC power received on first DC terminal **304** and second DC terminal **306** into AC power transmitted on first node **308**. Thus, in the exemplary embodiment, each module of bi-directional AC-to-DC BIIC **300** functions as bi-directional AC-to-DC BIICM **302**.

Also, in operation of the exemplary embodiment, the flow of at least one of an AC current and a DC current in the switching devices of both first side **340** and second side **342** is controlled through at least one switch control signal transmitted from at least one switching controller to at least one switch control terminal **358** of switching devices. As such, switching controller, along with the other aforementioned features and functions of bi-directional AC-to-DC BIICM **302**, facilitates maintaining a desired charging or discharging state of energy storage device **208**. Further, in operation of the exemplary embodiment, bypass switch controller **368** is configured to transmit control signal **370** to close bypass switch **360** when at least one BIICM state has a first predetermined value, and open bypass switch **360** when the at least one BIICM state has a second predetermined value different from the first predetermined value.

FIG. **4** is a schematic diagram of an alternative bi-directional AC-to-DC BIIC **400** that may be used in the electric vehicle propulsion system **200** shown in FIG. **2**. In the alternative embodiment, bi-directional AC-to-DC BIIC **400** includes at least one bi-directional AC-to-DC BIICM **402** including a first node **308** and a second terminal **406**. Second terminal **406** is equivalent to third node **338**. Also, in the alternative embodiment, a plurality of bi-directional AC-to-DC BIICMs **402** are arranged in at least one BIICM string **408**. First node **308** of a first bi-directional AC-to-DC BIICM **402** of BIICM string **408**, i.e., the topmost bi-directional AC-to-DC BIICM **402** (topmost BIICM **409**) in FIG. **4**, couples to first DC line **312** of high voltage DC link **314**. Second terminal **406** of a last bi-directional AC-to-DC BIICM **402** of BIICM string **408**, i.e., the bottommost bi-directional AC-to-DC BIICM **402** (bottommost BIICM **410**) in FIG. **4**, couples to second DC line **316** of high voltage DC link **314**.

Further, in the alternative embodiment, first node **308** and second terminal **406** of each bi-directional AC-to-DC BIICM **402** of BIICM string **408**, other than the first BIICM **402** and second BIICM **402**, respectively, are serially coupled. Furthermore, in the alternative embodiment, a phase of AC power is received to or transmitted from bi-directional AC-to-DC BIIC **400** on first AC line **318** at a power terminal **412**. First AC line **318** includes BIIC cable **210** as shown and described with reference to FIGS. **3-5**. In other alternative embodiments shown and described below, first AC line **318** also includes AC type generator cable **204**.

Moreover, in the alternative embodiment, bi-directional AC-to-DC BIIC **400** includes at least one inductor **413** coupled to and between power terminal **412** and BIICMs **402** adjacent power terminal **412**. In other alternative embodiments, not shown, bi-directional AC-to-DC BIIC **400** does not include at least one inductor **413**.

Furthermore, in the alternative embodiment, bi-directional AC-to-DC BIICM **402** that may be used in bi-directional AC-to-DC BIIC **400** includes first node **308** coupled to and between first switching device **320** and second switching device **322**. First switching device **320** is serially coupled to second switching device **322**. Further, in the exemplary embodiment, second terminal **406** is coupled to third node **338** of first side **340**. Otherwise, first side **340** of bi-directional AC-to-DC BIICM **402** is as shown and described above with reference to FIG. **3**. Furthermore, in the alternative embodiment, bi-directional AC-to-DC BIICM **402** also includes a secondary side **414**, i.e., a second BIICM circuit. Secondary side **414** includes fifth switching device **344** serially coupled to sixth switching device **346**. Second winding **348** of BIICM high-frequency transformer **336** is coupled in parallel to sixth switching device **346**. In an alternative embodiment, not shown, second winding **348** is coupled is parallel to fifth switching device **344**. At least one energy storage device **208** is coupled in parallel across both of fifth switching device **344** and sixth switching device **346**. In an alternative embodiment, not shown, energy storage device **208** and capacitor **326** are swapped in bi-directional AC-to-DC BIICM **402**. Moreover, in the alternative embodiment, first side **340** and secondary side **414** are inductively coupled through BIICM high-frequency transformer **336**.

Moreover, in the exemplary embodiment, first **320**, second **322**, third **328**, fourth **330**, fifth **344**, and sixth **346** switching devices include at least one switch control terminal **358** coupled to at least one switching controller, not shown in FIG. **4**. Switching controller is configured to transmit at least one switch control signal to at least one of first **320**, second **322**, third **328**, fourth **330**, fifth **344**, and sixth **346** switching devices to control its switching states. In other alternative embodiments, not shown, switching controller receives and transmits other control signals to and from other controllers located elsewhere within or outside bi-directional AC-to-DC BIIC **400**, also not shown in FIG. **4**. In still other embodiments, not shown, bi-directional AC-to-DC BIICM **402** also includes at least one bypass switch **360** coupled to and between first node **308** and second terminal **406**, and further coupled to bypass switch controller **368** and controlled thereby, substantially as shown and described above with reference to FIG. **3**.

In operation, in the alternative embodiment, a phase of an AC power is transmitted to or received from first AC line **318** through power terminal **412** to/from each of the plurality of bi-directional AC-to-DC BIICMs **402** of BIICM string **408** above and below power terminal **412**. Also, in operation of the alternative embodiment, first node **308** of first bi-directional AC-to-DC BIICM **402** of BIICM string **408**, i.e., the topmost bi-directional AC-to-DC BIICM **402** in FIG. **4**, transmits or receives DC power to/from first DC line **312**. Second terminal **406** of last bi-directional AC-to-DC BIICM **402** of BIICM string **408**, i.e., the bottommost bi-directional AC-to-DC BIICM **402** in FIG. **4**, transmits or receives DC power to/from second DC line **314**. Further, in operation of the alternative embodiment, bi-directional AC-to-DC BIIC **400** converts AC power received on first AC line **318** into DC power transmitted on high voltage DC link **314** to electrical device **122**, not shown. Bi-directional AC-to-DC BIIC **402** is also capable to convert DC power received on high voltage DC link **314** into AC power transmitted on first AC line **318** to electrical device **122**, not shown. Thus, in the exemplary embodiment, bi-directional AC-to-DC BIIC **400** functions as bi-directional AC-to-DC BIIC **400**.

Also, in operation of the alternative embodiment, bi-directional AC-to-DC BIICM **302** converts a phase of AC power received on first node **308** and second terminal **406** into DC power transmitted to electrical device **122**, not shown, on first node **308** of first bi-directional AC-to-DC BIICM **402** of BIICM string **408** and second terminal **406** of last bi-directional AC-to-DC BIICM **402** of BIICM string **408**, i.e., the topmost and the bottommost bi-directional AC-to-DC BIICMs **402** in FIG. **4**, respectively. Depending on a predetermined configuration of switching controllers and switching states, it is possible to divert a portion of DC power converted by secondary side **414** into energy storage device **208** to, for example, charge it. Also, in operation of the alternative embodiment, it is possible to divert a portion of DC power stored in energy storage device **208**, i.e., to discharge it, to supplement DC power transmitted on first node **308** of first bi-directional AC-to-DC BIICM **402** and second terminal **406** of last bi-directional AC-to-DC BIICM **402** of BIICM string **408**, i.e., the topmost and the bottommost bi-directional AC-to-DC BIICMs **402** in FIG. **4**, respectively. Bi-directional AC-to-DC BIICM **402** is also capable to convert DC power received on first node **308** of first bi-directional AC-to-DC BIICM **402** and second terminal **406** of last bi-directional AC-to-DC BIICM **402** of BIICM string **408**, i.e., the topmost and the bottommost bi-directional AC-to-DC BIICMs **402** in FIG. **4**, respectively, into AC power transmitted from power terminal **412** to first AC line **318**. Thus, in the exemplary embodiment, each module of bi-directional AC-to-DC BIIC **400**, not shown, functions as bi-directional AC-to-DC BIICM **402**.

Further, in operation of the exemplary embodiment, the flow of at least one of an AC current and a DC current in the switching devices of both first side **340** and secondary side **414** is controlled through at least one switch control signal transmitted from at least one switching controller to the switching devices. As such, switching controller, along with the other aforementioned features and functions of bi-directional AC-to-DC BIICM **402**, facilitates maintaining a desired charging or discharging state of energy storage device **208**.

FIG. **5** is a schematic diagram of an alternative bi-directional AC-to-DC BIIC **500** configured for 3-phase AC power conversion. In the alternative embodiment, bi-directional AC-to-DC BIIC **500** includes three bi-directional AC-to-DC BIICs **400**, i.e., three bi-directional AC-to-DC BIIC panels **501**. Each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501** includes one BIICM string **408** including a plurality bi-directional AC-to-DC BIICMs **402** serially coupled above and below power terminal **412**. Also, in the alternative embodiment, each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501** includes at least one first inductor **502** coupled to and between power terminal **412** and second terminal **406**, i.e., third node **338**, of a first bottommost bi-directional AC-to-DC BIICM **402** (first bottommost BIICM **503**) of a first half string **504** of BIICM string **408**. Each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501** also includes at least one second inductor **506** coupled to and between power terminal **412** and first node **308** of a second topmost bi-directional AC-to-DC BIICM **402** (second topmost BIICM **507**) of a second half string **508** of BIICM string **408**. In other alternative embodiments, not shown, bi-directional AC-to-DC BIIC **500** does not include at least one first inductor **502** and at least one second inductor **506**.

Also, in the alternative embodiment, bi-directional AC-to-DC BIIC **500** includes three power terminals **412**, one power terminal **412** on each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501**. Each power terminal **412** is configured to transmit and/or receive at least one phase of a 3-phase AC power to/from first AC line **318**. Further, in the alternative embodiment, each first node **308** of a first topmost bi-directional AC-to-DC BIICM **402** (first topmost BIICM **509**) of first half string **504** of each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501** couples to first DC line **312**. Likewise, each second terminal **406** of a second bottommost bi-directional AC-to-DC BIICM **402** (second bottommost BIICM **510**) of second half string **508** of each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501** couples to second DC line **316**. Furthermore, in the alternative embodiment, first DC line **312** and second DC line **316** together form high voltage DC link **314**. Moreover, in the alternative embodiment, in first string **504** of each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501**, first nodes **308** of all BIICMs other than first node **308** of first topmost BIICM **509** are serially coupled to third nodes **338** of all BIICMs other than third node **338** of first bottommost BIICM **503**. Also, in the alternative embodiment, in second half string **508** of each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501**, first nodes **308** of all BIICMs other than first node **308** of second topmost BIICM **507** are serially coupled to third nodes **338** of all BIICMs other than third node **338** of second bottommost BIICM **510**.

In operation, in the alternative embodiment, a phase of 3-phase AC power is transmitted to or received from bi-directional AC-to-DC BIIC **500** on three first AC lines **318** through power terminals **412** on each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501**. Also, in operation of the alternative embodiment, each first node **308** of first topmost BIICM **509** of first string **504** of each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501** transmits or receives DC power to/from first DC line **312**. Likewise, each second terminal **406** of second bottommost BIICM **510** of second half string **508** of each bi-directional AC-to-DC BIIC panel **501** of the three bi-directional AC-to-DC BIIC panels **501** transmits or receives DC power to/from second DC line **316**. Further, in operation of the alternative embodiment, bi-directional AC-to-DC BIIC **500** converts 3-phase AC power received on first AC lines **318** into DC power transmitted on high voltage DC link **314** to electrical device **122**, not shown. Bi-directional AC-to-DC BIIC **500** is also capable to convert DC power received on high voltage DC link **314** into AC power transmitted on first AC lines **318** to electrical device **122**, not shown. Thus, in the exemplary embodiment, bi-directional AC-to-DC BIIC **500** functions as a bi-directional AC-to-DC converter configured for 3-phase AC power.

Also, in operation of the alternative embodiment, depending on a predetermined configuration of switching controllers and switching states, it is possible to divert a portion of AC and/or DC power converted by bi-directional AC-to-DC BIIC **500** into energy storage device **208**, not shown, i.e., to charge it. Also, in operation of the alternative embodiment, it is possible to divert a portion of AC and/or DC power stored in energy storage device **208**, i.e., to discharge it, to supplement DC power transmitted by bi-directional AC-to-DC BIIC **500** on high voltage DC link **314**. Further, in operation of the exemplary embodiment, the flow of at least one of an AC current and a DC current in the switching devices of both first side **340** and secondary side **414** is controlled through at least one switch control signal transmitted from at least one switching controller, not shown, to the switching devices of each bi-directional AC-to-DC BIICM **402** of the plurality of bi-directional AC-to-DC BIICMs **402**. As such, switching controller, along with the other aforementioned features and functions of each bi-directional AC-to-DC BIIC **500**, facilitates maintaining a desired charging or discharging state of at least one energy storage device **208**.

FIG. **6** is a schematic diagram of another alternative bi-directional AC-to-DC BIIC **600** configured for 3-phase AC power conversion. In the alternative embodiment, bi-directional AC-to-DC BIIC **600** includes three bi-directional AC-to-DC BIIC panels **602**. Each bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602** includes a plurality of first sides **340**, i.e., first sides **340** of bi-directional AC-to-DC BIICM **402**, not shown, serially coupled above and below power terminal **412**. Also, in the alternative embodiment, each bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602** includes at least one first inductor **502** coupled to and between power terminal **412** and second terminal **406** of an initial first side **340** of a first string half **604** of a strand **606**, i.e., a first bottommost first side **607** of first string half **604** in FIG. **6**. Each bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602** also includes at least one second inductor **506** coupled to and between power terminal **412** and first node **308** of an initial first side **340** of a second string half **608** of strand **606**, i.e., a second topmost first side **609** of second string half **608** in FIG. **6**. In other alternative embodiments, not shown, bi-directional AC-to-DC BIIC **600** does not include at least one first inductor **502** and at least one second inductor **506**.

Also, in the alternative embodiment, bi-directional AC-to-DC BIIC **600** includes three power terminals **412**, one power terminal **412** on each bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602**. Each power terminal **412** is configured to transmit and/or receive at least one phase of a 3-phase AC power to/from first AC line **318**. Further, in the alternative embodiment, each first node **308** of initial first side **340** of strand **606**, i.e., a first topmost first side **610** in FIG. **6**, of each bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602** couples to first DC line **312**. Likewise, each second terminal **406** of a final first side **340** of strand **606**, i.e., a second bottommost first side **612** in FIG. **6**, of each bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602** couples to second DC line **316**. Furthermore, in the alternative embodiment, first DC line **312** and second DC line **316** together form high voltage DC link **314**.

Further, in the alternative embodiment, bi-directional AC-to-DC BIIC **600** includes at least one, but less than a total number of first sides **340**, of secondary sides **414** inductively coupled to at least one first side **340** of the plurality of first sides **340** in at least one bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602**. As such, in the alternative embodiment, a multi-winding BIICM high-frequency transformer **614** includes at least one first winding **334** of at least one first side **340** and at least one second winding **348** of at least one secondary side **414**. Multi-winding BIICM high-frequency transformer **614** includes, without limitation, a high-frequency multi-winding transformer configured to operate at frequencies from kHz to MHz range. Furthermore, in the alternative embodiment, at least one secondary side **414** is coupled to bi-directional AC-to-DC BIIC **600**. In other alternative embodiments, not shown, at least one secondary side **414** is not coupled to bi-directional AC-to-DC BIIC **600**, but is, nevertheless, inductively coupled to at least one first winding **334** therein.

In operation, in the alternative embodiment, a phase of 3-phase AC power is transmitted to or received from bi-directional AC-to-DC BIIC **600** on three first AC lines **318** through power terminals **412** on each bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602**. Also, in operation of the alternative embodiment, each first node **308** of initial first side **340** of strand **606**, i.e., first topmost first sides **610**, of each bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602**, transmits or receives DC power to/from first DC line **312**. Likewise, each second terminal **406** of final first side **340** of strand **606**, i.e., second bottommost first sides **612**, in FIG. **6**, of each bi-directional AC-to-DC BIIC panel **602** of the three bi-directional AC-to-DC BIIC panels **602** transmits or receives DC power to/from second DC line **316**. Further, in operation of the alternative embodiment, bi-directional AC-to-DC BIIC **600** converts 3-phase AC power received on first AC lines **318** into DC power transmitted on high voltage DC link **314** to electrical device **122**, not shown. Bi-directional AC-to-DC BIIC **600** is also capable to convert DC power received on high voltage DC link **314** into AC power transmitted on first AC lines **318** to electrical device **122**, not shown. Thus, in the exemplary embodiment, bi-directional AC-to-DC BIIC **600** functions as a bi-directional AC-to-DC converter configured for 3-phase AC power.

Also, in operation of the alternative embodiment, depending on a predetermined configuration of switching controllers and switching states, it is possible to divert a portion of AC and/or DC power converted by bi-directional AC-to-DC BIIC **600** into energy storage device **208**, i.e., to charge it. Also, in operation of the alternative embodiment, it is possible to divert a portion of DC power stored in energy storage device **208**, i.e., to discharge it, to supplement DC power transmitted by bi-directional AC-to-DC BIIC **600** on high voltage DC link **314**. Further, in operation of the exemplary embodiment, the flow of at least one of an AC current and a DC current in the switching devices of both first side **340** and secondary side **414** is controlled through at least one switch control signal transmitted from at least one switching controller, not shown, to the switching devices of each first side **340** and each secondary side **414** in bi-directional AC-to-DC BIIC **600**. Furthermore, in operation of the alternative embodiment, multi-winding BIICM high-frequency transformer **614** enables a single energy storage device **208** to share power with each first side **340** of the plurality of first sides **340** of bi-directional AC-to-DC BIIC **600**. Multi-winding BIICM high-frequency transformer **614** also facilitates adjusting the number of secondary sides **414** depending on the particular applications required by electric vehicle propulsion systems, including, without limitation, electric vehicle propulsion system **200**. As such, switching controller, along with the other aforementioned features and functions of bi-directional AC-to-DC BIIC **600**, facilitates maintaining a desired charging or discharging state of energy storage device **208**.

FIG. **7** is a schematic view of an alternative embodiment of an electric vehicle propulsion system **700** superimposed on a plan view of an aircraft. In the alternative embodiment, vehicle **102** is an aircraft, as shown as described above with reference to FIG. **1**. Also, in the alternative embodiment, generator **106** is coupled to drive engine **104** of vehicle **102** and to AC type generator cable **204**. Further, in the alternative embodiment, drive engine **104** is configured as a prime mover for generator **106**, and generator **106** is configured to induce a 3-phase AC power output transmitted on generator cable **204**. Generator cable **204** is coupled to and between generator **106** and at least one first converter set **702** including at least one bi-directional AC-to-DC BIIC **500**, i.e., a fore BIIC. Moreover, in the alternative embodiment, first converter set **702** is located in fuselage **108** proximate wing **110**. In other alternative embodiments, not shown, first converter set **702** includes at least one bi-directional AC-to-DC BIIC **600**.

Also, in the alternative embodiment, electric vehicle propulsion system **700** includes at least one second converter set **704**. Second converter set **704** includes at least one bi-directional AC-to-DC BIIC **500**, i.e., an aft BIIC. Further, in the alternative embodiment, second converter set **704** is located in aft portion **112** proximate tail **114**. In other alternative embodiments, not shown, second converter set **704** includes at least one bi-directional AC-to-DC BIIC **500**. Furthermore, in the alternative embodiment, at least one BIIC-to-BIIC cable **706** of a DC type is coupled to and between first converter set **702** and second converter set **704**. As shown and described above with reference to FIGS. **4** and **5**, bi-directional AC-to-DC BIIC **500** of first converter set **702** is configured to function as an AC-to-DC power converter which receives AC power from generator **106** and transmits DC power to second converter set **704** on BIIC-to-BIIC cable **706**. Moreover, in the alternative embodiment, bi-directional AC-to-DC BIIC **500** of second converter set **704** is configured to function as a DC-to-AC power converter which receives DC power from first converter set **702** and transmits AC power to electrical device **122** on AC type BIIC cable **210**. Electrical device **122** includes fan motor **212** used for vehicle propulsion, including, without limitation, during taxiing on a runway, i.e., where vehicle **102** is an aircraft.

Further, in the alternative embodiment, in cases where a DC interconnect **708** is coupled to and between at least two first converter sets **702**, a first DC bus, not shown, is coupled to and between first DC line **312** of a first bi-directional AC-to-DC BIIC **500** and a second bi-directional AC-to-DC BIIC **500**. Likewise, a second DC bus, not shown, is coupled to and between second DC line **316** of first bi-directional AC-to-DC BIIC **500** and second bi-directional AC-to-DC BIIC **500**. Together, first DC bus and second DC bus form DC interconnect **708**. Similarly, in cases where DC interconnect **708** is coupled to and between at least two second converter sets **704**, first DC bus, not shown, is coupled to and between first DC line **312** of a first bi-directional AC-to-DC BIIC **500** and a second bi-directional AC-to-DC BIIC **500**. Likewise, a second DC bus, not shown, is coupled to and between second DC line **316** of first bi-directional AC-to-DC BIIC **500** and second bi-directional AC-to-DC BIIC **500**. Including DC interconnect **708** facilitates balancing or sharing the power received and/or transmitted by each first converter set **702** of at least two first converter sets **702** from generator **106** and/or to second converter set **704**, respectively. Similarly, including DC interconnect **708** facilitates balancing or sharing the power received and/or transmitted by each second converter set **704** of at least two second converter sets **704** to first converter set **702** and/or to electrical device **122**, respectively.

In operation of the alternative embodiment, AC power from generator **106** is converted by first converter set **702** into DC power transmitted to second converter set **704** on BIIC-to-BIIC cable **706**. Also, in operation of the alternative embodiment, it is possible for first converter set **702** to divert at least a portion of AC and/or DC power to charge energy storage device **208**, not shown, in bi-directional AC-to-DC BIIC **500**. It is also possible for first converter set **702** to discharge energy storage device **208** to supply at least a portion of DC power transmitted on BIIC-to-BIIC cable **706** to second converter set **704**. Further, in operation of the exemplary embodiment, inclusion of first converter set **702** and second converter set **704** facilitates coupling of DC cable, rather than larger and heavier AC cable, between generator **106** and electrical device **122**, thus increasing the specific power, i.e., kW/kg, of the exemplary electric vehicle propulsion system **700** relative to the electric vehicle propulsion system **100** shown and described above with reference to FIG. **1**.

FIG. **8** is a schematic diagram of another alternative bi-directional AC-to-DC BIIC **800** configured for 3-phase AC power conversion. In the alternative embodiment, bi-directional AC-to-DC BIIC **800** includes at least three BIICM sets **801** of at least one bi-directional AC-to-DC BIICM **302**. The at least three BIICM sets **801** includes a topmost BIICM set **802** and a bottommost BIICM set **804**. Also, in the alternative embodiment, each BIICM set **801** of the three BIICM sets **801** in bi-directional AC-to-DC BIIC **800** includes a plurality of bi-directional AC-to-DC BIICMs **302**. Each BIICM set **801** of the at least three BIICM sets **801** also includes a topmost BIICM **806** and a bottommost BIICM **808**. Each first node **308** of each bi-directional AC-to-DC BIICM **302** of each BIICM set **801** of the three BIICM sets **801** are coupled together and further coupled to one first AC line **318** of at least three first AC lines **318**. Each first AC line **318** transmits a phase of a 3-phase AC power to/from each first node **308** of each bi-directional AC-to-DC BIICM **302** within each BIICM set **801** of the three BIICM sets **801** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **800**.

Also, in the alternative embodiment, all second nodes **332** of each bi-directional AC-to-DC BIICM **302** of each BIICM set **801** of the three BIICM sets **801** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **800** are coupled together through a first nodal bus **810**. Similarly, all third nodes **338** of each bi-directional AC-to-DC BIICM **302** of each BIICM set **801** of the three BIICM sets **801** of bi-directional AC-to-DC BIICMs **302** are coupled together through a second nodal bus **812**. In other alternative nodes, not shown, one or both of first nodal bus **810** and second nodal bus **812** are not present in bi-directional AC-to-DC BIIC **800**.

Further, in the alternative embodiment, first DC terminal **304**, i.e., fifth node **372**, of topmost BIICM **806** of topmost BIICM set **802** of bi-directional AC-to-DC BIIC **800** couples to first DC line **312**. Likewise, second DC terminal **306**, i.e., fourth node **356**, of bottommost BIICM **808** of bottommost BIICM set **804** of bi-directional AC-to-DC BIIC **800** couples to second DC line **316**. Furthermore, in the alternative embodiment, first DC line **312** and second DC line **316** together form high voltage DC link **314**. Moreover, in the alternative embodiment, fourth nodes **356** and fifth nodes **372** of all bi-directional AC-to-DC BIICMs **302** other than topmost BIICM **806** of topmost BIICM set **802** and bottommost BIICM **808** of bottommost BIICM set **804** are serially coupled together. Also, in the alternative embodiment, each bi-directional AC-to-DC BIICM **302** of each BIICM set **801** of the three BIICM sets **801** of bi-directional AC-to-DC BIICMs **302** includes bypass switch **360**, as shown and described above with reference to FIG. **3**. In an alternative embodiment, not shown, bi-directional AC-to-DC BIIC **800** does not include bypass switch **360**. In another alternative embodiment, not shown, positions of energy storage device **208** and capacitor **326** in bi-directional AC-to-DC BIICMs **302** are swapped in bi-directional AC-to-DC BIIC **800**.

In operation, in the alternative embodiment, a phase of 3-phase AC power is transmitted to or received from bi-directional AC-to-DC BIIC **800** on three first AC lines **318** through first nodes **308** within each BIICM set **801** of the three BIICM sets **801** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **800**. Also, in operation of the alternative embodiment, first DC terminal **304** of topmost BIICM **806** of topmost BIICM set **802** of bi-directional AC-to-DC BIIC **800** transmits or receives DC power to/from first DC line **312**. Likewise, second DC terminal **306** of bottommost BIICM **808** of bottommost BIICM set **804** of bi-directional AC-to-DC BIIC **800** transmits or receives DC power to/from second DC line **316**. Further, in operation of the alternative embodiment, bi-directional AC-to-DC BIIC **800** converts 3-phase AC power received on first AC lines **318** into DC power transmitted on high voltage DC link **314** to electrical device **122**, not shown. Bi-directional AC-to-DC BIIC **800** is also capable to convert DC power received on high voltage DC link **314** into AC power transmitted on first AC line **318** to electrical device **122**, not shown. Thus, in the exemplary embodiment, bi-directional AC-to-DC BIIC **800** functions as a bi-directional AC-to-DC converter configured for 3-phase AC power.

Also, in operation of the alternative embodiment, depending on a predetermined configuration of switching controllers and switching states, it is possible to divert a portion of AC and/or DC power converted by bi-directional AC-to-DC BIIC **800** into energy storage device **208**, not shown, i.e., to charge it. Also, in operation of the alternative embodiment, it is possible to divert a portion of power stored in energy storage device **208**, i.e., to discharge it, to supplement AC and/or DC power transmitted by bi-directional AC-to-DC BIIC **800** on high voltage DC link **314** and/or first AC line **318**. Further, in operation of the exemplary embodiment, the flow of at least one of an AC current and a DC current in the switching devices of each bi-directional AC-to-DC BIICM **302** of each BIICM set **801** of the three BIICM sets **801** of bi-directional AC-to-DC BIIC **800** is controlled through at least one switch control signal transmitted from at least one switching controller. As such, switching controller along with the other aforementioned features and functions of bi-directional AC-to-DC BIIC **800** facilitates maintaining a desired charging or discharging state of energy storage device **208**.

FIG. **9** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system **900** superimposed on a plan view of an aircraft. In the exemplary embodiment, vehicle **102** is an aircraft, as shown as described above with reference to FIG. **1**. Also, in the alternative embodiment, generator **106** is coupled to drive engine **104** of vehicle **102** and to generator rectifier **202**, as shown and described above with reference to FIG. **2**. Generator cable **204** of a DC type is coupled to and between generator rectifier **202** and at least one converter set **902** including at least one bi-directional AC-to-DC BIIC **800**.

Further, in the alternative embodiment, converter set **902** is located in fuselage **108** proximate wing **110**. In other alternative embodiments, not shown, converter set **902** is located in aft portion **112** proximate tail **114**. Locating converter set **902** in aft portion **112** provides enhanced specific power to electric vehicle propulsion system **900**, as described above with reference to FIG. **2**.

Also, in the alternative embodiment, electric vehicle propulsion system **900** includes AC type BIIC cable **210** coupled to and between converter set **902** and electrical device **122**. Further, in the alternative embodiment, bi-directional AC-to-DC BIIC **800** of converter set **902** is configured to function as a DC-to-AC power converter which receives DC power from generator rectifier **202** and transmits AC power to electrical device **122** on BIIC cable **210**. Furthermore, in the alternative embodiment, electrical device **122** includes fan motor **212** used for vehicle propulsion, including, without limitation, during taxiing on a runway, i.e., where vehicle **102** is an aircraft. Moreover, in the alternative embodiment, electric vehicle propulsion system **900** includes DC interconnect **708**. DC interconnect **708** is coupled to and between at least two converter sets **902**. DC interconnect **708** includes a first DC bus, not shown, coupled to and between first DC line **312** of a first bi-directional AC-to-DC BIIC **800** and first DC line **312** of a second bi-directional AC-to-DC BIIC **800**. Likewise, DC interconnect **708** includes a second DC bus, not shown, coupled to and between second DC line **316** of first bi-directional AC-to-DC BIIC **800** and second DC line **316** of second bi-directional AC-to-DC BIIC **800**. Together, first DC bus and second DC bus form DC interconnect **708**. Also, in the alternative embodiment, electric vehicle propulsion system **900** includes a rectifier bus **904**. Rectifier bus **904** is coupled to and between at least two generator rectifiers **202**, i.e., where at least two generators **106** are coupled to vehicle **102**. In other alternative embodiments, not shown, rectifier bus **904** is not present.

With the exception of added functionality provided to electric vehicle propulsion system **900** by DC interconnect **708** and rectifier bus **904**, operation of the alternative embodiment and attendant benefits thereof are as described above with reference to FIG. **2**. DC interconnect **708** facilitates balancing or sharing the power received and/or transmitted by each of at least two converter sets **902** from generator rectifier **202** and/or to electrical device **122**, respectively. Rectifier bus **904** facilitates balancing or sharing the power generated by and/or rectified by each of at least two generators **106** and/or at least two generator rectifiers **202**, respectively.

FIG. **10** is a schematic diagram of yet another alternative bi-directional AC-to-DC BIIC **1000** configured for 3-phase AC power conversion. In the alternative embodiment, bi-directional AC-to-DC BIIC **1000** includes at least three BIICM sets **1002** of at least one bi-directional AC-to-DC BIICM **302**. The at least three BIICM sets **1002** include a topmost BIICM set **1004** and a bottommost BIICM set **1106**. Also, in the alternative embodiment, each BIICM set **1002** of the three BIICM sets **1002** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **1000** includes a plurality of bi-directional AC-to-DC BIICMs **302**. Each BIICM set **1002** of the at least three BIICM sets **1002** also includes a topmost BIICM **1008** and a bottommost BIICM **1010**. Each first node **308** of each bi-directional AC-to-DC BIICM **302** of each BIICM set **1002** of the three BIICM sets **1002** are coupled together and further coupled to one first AC line **318** of at least three first AC lines **318**. Each first AC line **318** of the at least three first AC lines **318** transmits a phase of a 3-phase AC power to/from each first node **308** of each bi-directional AC-to-DC BIICM **302** within each BIICM set **1002** of the three BIICM sets **1002** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **1000**.

Also, in the alternative embodiment, all second nodes **332** of each bi-directional AC-to-DC BIICM **302** of each BIICM set **1002** of the three BIICM sets **1002** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **1000** are coupled together through a first nodal bus **810**. Similarly, all third nodes **338** of each bi-directional AC-to-DC BIICM **302** of each BIICM set **1002** of the three BIICM sets **1002** of bi-directional AC-to-DC BIICMs **302** are coupled together through a second nodal bus **812**. In other alternative nodes, not shown, one or both of first nodal bus **810** and second nodal bus **812** are not present in bi-directional AC-to-DC BIIC **1000**.

Further, in the alternative embodiment, first DC terminals **304**, i.e., fifth nodes **372**, of each topmost BIICM **1008** of each BIICM set **1002** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **1000** is coupled to first DC line **312**. Likewise, second DC terminal **306**, i.e., fourth node **356**, of each bottommost BIICM **1010** of each BIICM set **1002** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **1000** is coupled to second DC line **316**. Furthermore, in the alternative embodiment, first DC line **312** and second DC line **316** together form high voltage DC link **314**. Moreover, in the alternative embodiment, fourth nodes **356** and fifth nodes **372** within each BIICM set **1002** other than the topmost BIICM **1008** and bottommost BIICM **1010** of each BIICM set **1002** are serially coupled together. Also, in the alternative embodiment, each bi-directional AC-to-DC BIICM **302** of each BIICM set **1002** of the three BIICM sets **1002** of bi-directional AC-to-DC BIICMs **302** includes at least one bypass switch **360**, as shown and described above with reference to FIG. **3**. In an alternative embodiment, not shown, bi-directional AC-to-DC BIIC **800** does not include at least one bypass switch **360**. In another alternative embodiment, not shown, positions of energy storage device **208** and capacitor **326** in bi-directional AC-to-DC BIICMs **302** are swapped in bi-directional AC-to-DC BIIC **1000**.

In operation, in the alternative embodiment, a phase of 3-phase AC power is transmitted to or received from bi-directional AC-to-DC BIIC **1000** on three first AC lines **318** through first nodes **308** within each BIICM set **1002** of the three BIICM sets **1002** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **1000**. Also, in operation of the alternative embodiment, first DC terminals **304** of each topmost BIICM **1008** of each BIICM set **1002** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **1000** transmits or receives DC power to/from first DC line **312**. Likewise, second DC terminals **306** of each bottommost BIICM **1010** of each BIICM set **1002** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **1000** transmits or receives DC power to/from second DC line **316**. Further, in operation of the alternative embodiment, bi-directional AC-to-DC BIIC **1000** converts 3-phase AC power received on first AC lines **318** into DC power transmitted on high voltage DC link **314** to electrical device **122**, not shown. Bi-directional AC-to-DC BIIC **1000** is also capable to convert DC power received on high voltage DC link **314** into AC power transmitted on first AC line **318** to electrical device **122**. Thus, in the exemplary embodiment, bi-directional AC-to-DC BIIC **1000** functions as a bi-directional AC-to-DC converter configured for 3-phase AC power.

Also, in operation of the alternative embodiment, depending on a predetermined configuration of switching controllers and switching states, it is possible to divert a portion of AC and/or DC power converted by bi-directional AC-to-DC BIIC **1000** into energy storage device **208**, not shown, i.e., to charge it. Also, in operation of the alternative embodiment, it is possible to divert a portion of power stored in energy storage device **208**, i.e., to discharge it, to supplement AC and/or DC power transmitted by bi-directional AC-to-DC BIIC **1000** on high voltage DC link **314** and/or first AC line **318**. Further, in operation of the exemplary embodiment, the flow of at least one of an AC current and a DC current in the switching devices of each bi-directional AC-to-DC BIICM **302** of each BIICM set **1002** of the three BIICM sets **1002** of bi-directional AC-to-DC BIICMs **302** in bi-directional AC-to-DC BIIC **1000** is controlled through at least one switch control signal transmitted from at least one switching controller, not shown. As such, switching controller along with the other aforementioned features and functions of bi-directional AC-to-DC BIIC **1000** facilitates maintaining a desired charging or discharging state of energy storage device **208**.

FIG. **11** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system **1100** superimposed on a plan view of an aircraft. In the exemplary embodiment, vehicle **102** is an aircraft, as shown as described above with reference to FIG. **1**. Also, in the alternative embodiment, generator **106** is coupled to drive engine **104** of vehicle **102** and to generator rectifier **202**, as shown and described above with reference to FIG. **2**. Generator cable **204** of a DC type is coupled to and between generator rectifier **202** and at least one converter set **1102** including at least one bi-directional AC-to-DC BIIC **1000**. Further, in the alternative embodiment, converter set **1102** is located in fuselage **108** proximate wing **110**. In other alternative embodiments, not shown, converter set **1102** is located in aft portion **112** proximate tail **114**. Locating converter set **1102** in aft portion **112** provides enhanced specific power to electric vehicle propulsion system **1100**, as described above with reference to FIG. **2**.

Also, in the alternative embodiment, electric vehicle propulsion system **1100** includes at least one BIIC cable **210** of an AC type coupled to and between converter set **1102** and electrical device **122**. Further, in the alternative embodiment, bi-directional AC-to-DC BIIC **1000** of converter set **1102** is configured to function as a DC-to-AC power converter which receives DC power from generator rectifier **202** and transmits AC power to electrical device **122** on BIIC cable **210**. Furthermore, in the alternative embodiment, electrical device **122** includes fan motor **212** used for vehicle propulsion, including, without limitation, during taxiing on a runway, i.e., where vehicle **102** is an aircraft. Moreover, in the alternative embodiment, electric vehicle propulsion system **1100** includes a rectifier bus **904**. Rectifier bus **904** is coupled to and between at least two generator rectifiers **202**, i.e., where at least two generators **106** are coupled to vehicle **102**. In other alternative embodiments, not shown, rectifier bus **904** is absent.

Further, in the alternative embodiment, electric vehicle propulsion system **1100** also includes a first extension **1104** and a second extension **1106**. In cases where at least two generators **106** are coupled to vehicle **102**, first extension **1104** is coupled to and between generator cable **204** of a first generator rectifier **202** of at least two generator rectifiers **202** and first DC lines **312** of each bi-directional AC-to-DC BIIC **1000** of at least two converter sets **1102**. Likewise, second extension **1106** is coupled to and between generator cable **204** of a second generator rectifier **202** of at least two generator rectifiers **202** and second DC lines **316** of each bi-directional AC-to-DC BIIC **1000** of at least two converter sets **1102**. In other alternative embodiments, not shown, first extension **1104** and second extension **1106** are absent.

With the exception of added functionality provided to electric vehicle propulsion system **1100** by DC interconnect **708**, first extension **1104**, and second extension **1106**, operation of the alternative embodiment and attendant benefits thereof are as described above with reference to FIG. **2**. Rectifier bus **904** facilitates balancing or sharing the power generated by and/or rectified by each of at least two generators **106** and/or at least two generator rectifiers **202**, respectively. First extension **1104** and second extension **1106** facilitate balancing or sharing the power received by each of at least two converter sets **1102** from each generator rectifier **202** of at least two generator rectifiers **202** of electric vehicle propulsion system **1100**.

FIG. **12** is a schematic diagram of an exemplary AC-to-AC BIIC **1200** configured for 3-phase AC power conversion. In the exemplary embodiment, AC-to-AC BIIC **1200** includes at least three BIICM sets **1201** of at least one AC-to-AC BIICM **1202**. The at least three BIICM sets **1201** include a topmost BIICM set **1204** and a bottommost BIICM set **1206**. Also, in the alternative embodiment, each BIICM set **1201** of the three BIICM sets **1201** of at least one AC-to-AC BIICM **1202** in AC-to-AC BIIC **1200** includes a plurality of AC-to-AC BIICMs **1202**. Each BIICM set **1201** of the at least three BIICM sets **1201** also includes a topmost BIICM **1208** and a bottommost BIICM **1210**. Further, in the exemplary embodiment, each AC-to-AC BIICM **1202** includes first side **340**, including first node **308**. First side **340** is as shown and described above with reference to FIG. **3**. Each AC-to-AC BIICM **1202** also includes a full-bridge side **1212**. Full-bridge side **1212** includes fifth switching device **344** serially coupled to sixth switching device **346**. Second winding **348** of BIICM high-frequency transformer **336** is coupled in parallel to sixth switching device **346**. In an alternative embodiment, not shown, second winding **348** is coupled in parallel to fifth switching device **344**. At least one energy storage device **208** is coupled in parallel across both of fifth switching device **344** and sixth switching device **346**. Furthermore, in the exemplary embodiment, full-bridge side **1212** includes seventh switching device **350** serially coupled to eighth switching device **352**. Serially coupled seventh switching device **350** and eighth switching device **352** are coupled in parallel across both of fifth switching device **344** and sixth switching device **346**.

Also, in the exemplary embodiment, full-bridge side **1212** of each AC-to-AC BIICM **1202** of AC-to-AC BIIC **1200** includes a ninth switching device **1214** serially coupled to a tenth switching device **1216**. Serially coupled ninth switching device **1214** and tenth switching device **1216** are coupled in parallel across both of seventh switching device **350** and eighth switching device **352**. A tertiary node **1218** includes connections to and between fifth switching device **344**, energy storage device **208**, seventh switching device **350**, and ninth switching device **1214**. A quaternary node **1220** includes connections to and between sixth switching device **346**, energy storage device **208**, eighth switching device **352**, and tenth switching device **1216**. Further, in the exemplary embodiment, each AC-to-AC BIICM **1202** of AC-to-AC BIIC **1200** includes a second AC node **1222** and a third AC node **1224**. Second AC node **1222** is defined between seventh switch device **350** and eighth switching device **352**. Second AC node **1222** is equivalent to fifth node **372**. Third AC node **1224** is defined between ninth switching device **1214** and tenth switching device **1216**. Third AC node **1224** is equivalent to a sixth node **1226**. In an alternative embodiment, not shown, energy storage device **208** and capacitor **326** are swapped in AC-to-AC BIICM **1202**. Furthermore, in the alternative embodiment, first side **340** and full-bridge side **1212** are inductively coupled through BIICM high-frequency transformer **336**.

Further, in the exemplary embodiment, first **320**, second **322**, third **328**, fourth **330**, fifth **344**, sixth **346**, seventh **350**, eighth **352**, ninth **1214**, and tenth **1216** switching devices include at least one switch control terminal **358** coupled to at least one switching controller, not shown in FIG. **12**. Switching controller is configured to transmit at least one switch control signal to at least one of first **320**, second **322**, third **328**, fourth **330**, fifth **344**, sixth **346**, seventh **350**, eighth **352**, ninth **1214**, and tenth **1216** switching devices to control its switching states. In an alternative embodiment, not shown, switching controller receives and transmits other control signals to and from other controllers located elsewhere within or outside AC-to-AC BIICM **1202**.

Furthermore, in the exemplary embodiment, each first node **308** of each bi-directional AC-to-AC BIICM **1202** within each BIICM set **1201** of the three BIICM sets **1201** of AC-to-AC BIICMs **1202** in AC-to-AC BIIC **1200** are coupled together and further coupled to one first AC line **318** of at least three first AC lines **318**. Each first AC line **318** of the at least three first AC lines **318** transmits a phase of a 3-phase AC power to/from each first node **308** of each bi-directional AC-to-AC BIICM **1202** within each BIICM set **1201** of the three BIICM sets **1201** of AC-to-AC BIICMs **1202** in AC-to-AC BIIC **1200**. Moreover, in the exemplary embodiment, each second AC node **1222** of each topmost BIICM **1208** of each BIICM set **1201** of the three BIICM sets **1201** is coupled to one second AC line **1228** of the three second AC lines **1228**. Each second AC line **1228** of the three second AC lines **1228** transmits a phase of a 3-phase AC power to/from each full-bridge side **1212** of each bi-directional AC-to-AC BIICM **1202** within each BIICM set **1201** of the three BIICM sets **1201** of AC-to-AC BIICMs **1202** in AC-to-AC BIIC **1200**.

Moreover, in the exemplary embodiment, each third AC node **1224** of each bottommost BIICM within each BIICM set **1201** of the three BIICM sets **1201** are coupled together in AC-to-AC BIIC **1200**. Also, in the exemplary embodiment, fifth nodes **372** and sixth nodes **1226** within each BIICM set **1201** other than topmost BIICM **1208** of topmost BIICM set **1204** and bottommost BIICM **1210** of bottommost BIICM set **1206** are serially coupled together. Further, in the exemplary embodiment, all second nodes **332** of each AC-to-AC BIICM **1202** of each BIICM set **1201** of the three BIICM sets **1201** of bi-directional AC-to-AC BIICMs **1202** in AC-to-AC BIIC **1200** are coupled together through a first nodal bus **810**. Similarly, all third nodes **338** of each AC-to-AC BIICM **1202** within each BIICM set **1201** of the three BIICM sets **1201** of AC-to-AC BIICMs **1202** are coupled together through a second nodal bus **812**. In other alternative nodes, not shown, one or both of first nodal bus **810** and second nodal bus **812** are not present in AC-to-AC BIIC **1200**.

In operation, in the exemplary embodiment, AC-to-AC BIIC **1200** converts AC power transmitted to and/or received on three first AC lines **318** into AC power transmitted to and/or received on three second AC lines **1228**. Depending on a predetermined configuration of switching controllers and switching states, it is possible to divert a portion of AC power received and/or converted by AC-to-AC BIIC **1200** into energy storage device **208** to, for example, charge it. Also, in operation of the exemplary embodiment, it is possible to divert a portion of DC power stored in energy storage device **208**, i.e., to discharge it, to supplement AC power transmitted on either first AC lines **318** or second AC lines **1228**. Thus, in the exemplary embodiment, AC-to-AC BIIC **1200** functions as an AC-AC power converter.

Also, in operation of the exemplary embodiment, the flow of at least one of an AC current and a DC current in the switching devices of both first side **340** and full-bridge side **1212** is controlled through at least one switch control signal transmitted from at least one switching controller to at least one switch control terminal **358** of switching devices. As such, switching controller, along with the other aforementioned features and functions of AC-to-AC BIIC **1200**, facilitates maintaining a desired charging or discharging state of energy storage device **208**.

FIG. **13** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system **1300** superimposed on a plan view of an aircraft. In the alternative embodiment, vehicle **102** is an aircraft, as shown and described above with reference to FIG. **1**. Also, in the alternative embodiment, generator **106** is coupled to drive engine **104** of vehicle **102** and to generator cable **204** of an AC type. Generator cable **204** is coupled to and between generator **106** and at least one converter set **1302** including at least one AC-to-AC BIIC **1200**. Further, in the alternative embodiment, converter set **1302** is located in fuselage **108** proximate wing **110**. In other alternative embodiments, not shown, converter set **1302** is located in aft portion **112** proximate tail **114**. Converter set **1302** is configured to function as an AC-to-AC power converter which receives AC power from generator **106** and transmits AC power to electrical device **122** on at least one BIIC cable **210** of an AC type. Electrical device **122** includes fan motor **212** used for vehicle propulsion, including, without limitation, during taxiing on a runway, i.e., where vehicle **102** is an aircraft.

In operation of the alternative embodiment, AC power from generator **106** is converted by converter set **1302** into AC power transmitted to second converter set **704** on BIIC cable **210** of an AC type. Also, in operation of the alternative embodiment, it is possible for converter set **1302** to divert at least a portion of AC power received from generator **106** to charge energy storage device **208**, not shown, in AC-to-AC BIIC **1200**. It is also possible for converter set **1302** to discharge energy storage device **208** to convert power therefrom to supplement at least a portion of AC power transmitted on BIIC cable **210** to electrical device **122**. Further, in operation of the exemplary embodiment, inclusion of AC-to-AC BIIC **1200** facilitates installation of electric vehicle propulsion system **1300** in vehicles **102** without requiring installation of generator rectifier **202** and replacement of AC type cable with DC type cable. Thus, electric vehicle propulsion system **1300** is particularly suited to applications involving retrofitting operations of vehicles **102** to increase specific power of known systems including, without limitation, electric vehicle propulsion system **100** shown and described above with reference to FIG. **1**.

FIG. **14** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system **1400** superimposed on a plan view of an aircraft. In the alternative embodiment, vehicle **102** is an aircraft, as shown and described above with reference to FIG. **1**. Also, in the alternative embodiment, generator **106** is coupled to drive engine **104** of vehicle **102** and to generator cable **204** of an AC type. Generator cable **204** is coupled to and between generator **106** and at least one first converter set **1402** including AC-to-AC BIIC **1200**, i.e., a fore BIIC. Moreover, in the alternative embodiment, first converter set **1402** is located in fuselage **108** proximate wing **110**.

Also, in the alternative embodiment, electric vehicle propulsion system **1400** includes at least one second converter set **1404**. Second converter set **1404** includes at least one AC-to-AC BIIC **1200**, i.e., an aft BIIC. Further, in the alternative embodiment, second converter set **1404** is located in aft portion **112** proximate tail **114**. Furthermore, in the alternative embodiment, BIIC-to-BIIC cable **706** of AC type is coupled to and between first converter set **1402** and second converter set **1404**. AC-to-AC BIIC **1200** of first converter set **1402** is configured to function as an AC-to-AC power converter which receives AC power from generator **106** and transmits AC power to second converter set **1404** on BIIC-to-BIIC cable **706**. Moreover, in the alternative embodiment, AC-to-AC BIIC **1200** of second converter set **1404** is configured to function as an AC-to-AC power converter which receives AC power from first converter set **1402** and transmits AC power to electrical device **122** on BIIC cable **210** of an AC type. Electrical device **122** includes fan motor **212** used for vehicle propulsion, including, without limitation, during taxiing on a runway, i.e., where vehicle **102** is an aircraft.

Further, in the alternative embodiment, it is possible to include an AC interconnect **1406** coupled to and between at least two first converter sets **1402**. It is also possible to include AC interconnect **1406** coupled to and between at least two second converter sets **1404**. Including AC interconnects **1406** facilitates balancing or sharing the power received and/or transmitted by each first converter set **1402** of at least two first converter sets **1402** from generator **106** and/or to at least one second converter set **1404**, respectively. Similarly, including AC interconnects **1406** facilitates balancing or sharing the power received and/or transmitted by each of at least two first converter sets **1402** from at least two generators **106** and at least two second converter sets **1404**, respectively. Likewise, including AC interconnects **1406** facilitates balancing or sharing the power received and/or transmitted by each of at least two second converter sets **1404** from at least two first converter sets **1402** and at least two electrical devices **122**, respectively. Furthermore, in the alternative embodiment, including AC interconnects **1406** facilitates AC power transmission on a single cable, including, without limitation, a bundled BIIC-to-BIIC cable **1408**, to/from at least two first converter sets **1402** and at least two second converter sets **1404** in electric vehicle propulsion system **1400**.

In operation of the alternative embodiment, AC power from generator **106** is converted by first converter set **1402** into AC power transmitted to second converter set **1404** on BIIC-to-BIIC cable **706**. Also, in operation of the alternative embodiment, it is possible for first converter set **1402** to divert at least a portion of AC power received from generator **106** to charge energy storage device **208**, not shown, in AC-to-AC BIIC **1200**. It is also possible for first converter set **1402** to discharge energy storage device **208** to convert power therefrom to supplement at least a portion of AC power transmitted on BIIC-to-BIIC cable **706** to second converter set **1404**. Similarly, it is possible for second converter set **1404** to divert at least a portion of AC power received first converter set **1402** to charge energy storage device **208**, not shown, in AC-to-AC BIIC **1200**. It is also possible for second converter set **1404** to discharge energy storage device **208** to convert power therefrom to supplement at least a portion of AC power transmitted on BIIC cable **210** to electrical device **122**.

Also, in operation of the alternative embodiment, inclusion of first converter set **1402** and second converter set **1404**, each including at least one AC-to-AC BIIC **1200**, facilitates installation of electric vehicle propulsion system **1400** in vehicles **102** without requiring installation of generator rectifier **202** and replacement of AC type cable with DC type cable. Thus, electric vehicle propulsion system **1400** is particularly suited to applications involving retrofitting operations of vehicles **102** to increase specific power of known systems including, without limitation, electric vehicle propulsion system **100** shown and described above with reference to FIG. **1**. Further, in operation of the alternative embodiment, it is possible to further increase the specific power of electric vehicle propulsion system **1400** by inclusion of AC interconnects **1406** and bundled BIIC-to-BIIC cable **1408**, which provides opportunities to reduce the weight of BIIC-to-BIIC cable **706** where vehicle **102** includes a plurality of first converter sets **1402** and a plurality of second converter sets **1404**.

FIG. **15** is a schematic diagram of an exemplary shunt type BIIC **1500** configured for bidirectional DC-to-AC power conversion. In the exemplary embodiment, shunt type BIIC **1500** includes at least one bi-directional AC-to-DC BIICM **402** including a first node **308** and a second terminal **406**. Second terminal **406** is equivalent to third node **338**. Also, in the exemplary embodiment, a plurality of bi-directional AC-to-DC BIICMs **402** are arranged in at least one shunt string **1502**. First node **308** of a first bi-directional AC-to-DC BIICM **402** of shunt string **1502**, i.e., a topmost BIICM **1504** of each shunt string **1502** of the three shunt strings **1502** in FIG. **15**, receives and/or transmits a phase of 3-phase AC power transmitted on one AC line **116** of at least three AC lines **116**. Second terminal **406** of a last bi-directional AC-to-DC BIICM **402** of shunt string **1502**, i.e., a bottommost BIICM **1506** of each shunt string **1502** of the three shunt strings **1502** in FIG. **15**, couples to all other second terminals **406** of all other bottommost BIICMs **1506** in shunt type BIIC **1500**. Further, in the exemplary embodiment, first node **308** and second terminal **406** of each bi-directional AC-to-DC BIICM **402** of shunt string **1502**, other than topmost BIICM **1504** and bottommost BIICM **1506**, respectively, are serially coupled.

Also, in the exemplary embodiment, bi-directional AC-to-DC BIICM **402** that may be used in shunt type BIIC **1500** includes first side **340** inductively coupled to secondary side **414** through BIICM high-frequency transformer **336**, as shown and described above with reference to FIG. **4**. Further, in the exemplary embodiment, bi-directional AC-to-DC BIICM **402** that may be used in shunt type BIIC **1500** includes at least one energy storage device **208** coupled in parallel across both of fifth switching device **344** and sixth switching device **346**, not shown, of secondary side **414**. Furthermore, in the exemplary embodiment, bi-directional AC-to-DC BIICM **402** that may be used in shunt type BIIC **1500** also includes at least one capacitor **326** coupled in parallel across both of fifth switching device **344** and sixth switching device **346**, not shown, of secondary side **414**. In other alternative embodiments, not shown, capacitor **326** is not present in secondary side **414**.

Moreover, in the exemplary embodiment, bi-directional AC-to-DC BIICM **402** that may be used in shunt type BIIC **1500** also includes at least one switching controller, not shown in FIG. **15**. Switching controller is configured to transmit at least one switch control signal to at least one of first **320**, second **322**, third **328**, fourth **330**, fifth **344**, and sixth **346** switching devices, not shown, to control its switching states. In other alternative embodiments, not shown, switching controller receives and transmits other control signals to and from other controllers located elsewhere within or outside shunt type BIIC **1500**, also not shown in FIG. **15**. In still other embodiments, not shown, bi-directional AC-to-DC BIICM **402** that may be used in shunt type BIIC **1500** also includes at least one bypass switch **360** coupled to and between first node **308** and second terminal **406**, and further coupled to bypass switch controller **368** and controlled thereby, as shown and described above with reference to FIG. **3**.

In operation, in the exemplary embodiment, a phase of a 3-phase AC power is transmitted to or received from one AC line **116** of three AC lines **116** to each shunt string **1502** of the three shunt strings **1502** of shunt type BIIC **1500**. Also, in operation of the exemplary embodiment, each shunt string **1502** of the three shunt strings **1502** of shunt type BIIC **1500** converts AC power received on AC line **116** into DC power to charge energy storage device **208**. Shunt type BIIC **1500** is also capable to convert DC power stored in energy storage device **208**, i.e., to discharge energy storage device **208**, into AC power transmitted on each AC line **116** of the three AC lines **116** to electrical device **122**, not shown. The proportion of AC power converted and diverted to charge energy storage device **208**, and likewise, the proportion of DC power of energy storage device **208** converted and diverted to each AC line **116** of the three AC lines **116**, depends on a predetermined configuration of switching controllers and switching states of shunt type BIIC **1500**, as described above with reference to FIG. **4**. Thus, in the exemplary embodiment, shunt type BIIC **1500** functions as a bi-directional DC-to-AC power converter.

FIG. **16** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system **1600** superimposed on a plan view of an aircraft. In the alternative embodiment, vehicle **102** is an aircraft, as shown and described above with reference to FIG. **1**. Also, in the alternative embodiment, electric vehicle propulsion system **1600** includes drive engine **104**, generator **106**, AC line **116**, and electrical device **122**, as shown and described above with reference to FIG. **1**. Electric vehicle propulsion system **1600** also includes AC line **116** coupled to and between at least one first AC/AC converter set **1602** and at least one second AC/AC converter set **1604**. First AC/AC converter set **1602** and second AC/AC converter set **1604** include conventional AC/AC power convertors, i.e., not BIICs as described herein. First AC/AC converter set **1602** and second AC/AC converter set **1604** each include at least one AC/AC power converter **1606**, i.e., a fore AC/AC power converter **1606** and an aft AC/AC power converter **1606**, respectively. Further, in the alternative embodiment, first AC/AC converter set **1602** is located in fuselage **108** proximate wing **110**. Furthermore, in the alternative embodiment, second AC/AC converter set **1604** is located in aft portion **112** proximate tail **114**. Also, in the alternative embodiment, at least one shunt type BIIC **1500** is coupled to AC line **116**. Further, in the alternative embodiment, shunt type BIIC **1500** is located in fuselage **108** proximate wing **110**. In other alternative embodiments, not shown, shunt type BIIC **1500** is located in other locations in fuselage **108**, including, without limitation, in aft portion **112** proximate tail **114**.

Also, in the alternative embodiment, it is possible to include an AC interconnect **1406** coupled to and between at least two first converter sets **1602**. It is also possible to include AC interconnect **1406** coupled to and between at least two second AC/AC converter sets **1604**. Including AC interconnects **1406** facilitates balancing or sharing the power received and/or transmitted by each of at least two first AC/AC converter sets **1602** from generator **106** and/or to second AC/AC converter set **1604**, respectively. Similarly, including AC interconnects **1406** facilitates balancing or sharing the power received and/or transmitted by each of at least two first AC/AC converter sets **1602** from at least two generators **106** and at least two second AC/AC converter sets **1604**, respectively. Likewise, including AC interconnects **1406** facilitates balancing or sharing the power received and/or transmitted by each of at least two second AC/AC converter sets **1604** from at least two first AC/AC converter sets **1602** and at least two electrical devices **122**, respectively. Furthermore, in the alternative embodiment, including AC interconnects **1406** facilitates AC power transmission on a single cable, including, without limitation, a bundled AC line **1608**, to/from at least two first AC/AC converter sets **1602** and at least two second AC/AC converter sets **1604** in electric vehicle propulsion system **1600**.

In operation, in the alternative embodiment, AC current is transmitted on AC line **116** from first AC/AC converter set **1602** to second AC/AC converter set **1604**. DC power from at least one energy storage device **208**, not shown, within shunt type BIIC **1500** is converted to AC power, i.e., by discharging energy storage device **208**, by shunt type BIIC **1500**. AC power from shunt type BIIC **1500** is transmitted to AC line **116** to supply at least a portion of AC power to second AC/AC converter set **1604**. Also, in operation of the alternative embodiment, it is possible for shunt type BIIC **1500** to convert AC power received on AC line **116** into DC power to charge energy storage device **208** within shunt type BIIC **1500**. Thus, in the alternative embodiment, shunt type BIIC **1500** functions as a bidirectional DC-to-AC power converter.

FIG. **17** is a schematic view of yet another alternative embodiment of an electric vehicle propulsion system **1700** superimposed on a plan view of an aircraft. In the alternative embodiment, vehicle **102** is an aircraft, as shown and described above with reference to FIG. **1**. Also, in the alternative embodiment, electric vehicle propulsion system **1700** includes drive engine **104**, generator **106**, and electrical device **122**, as shown and described above with reference to FIG. **1**. Further, in the alternative embodiment, electric vehicle propulsion system **1700** includes at least one AC line **116** coupled to and between generator **106** and at least one AC/AC converter set **1702**. AC/AC converter set **1702** includes conventional AC/AC power convertors, i.e., not BIICs as described herein. AC/AC converter set **1702** includes at least one AC/AC power converter **1606**. Furthermore, in the alternative embodiment, AC/AC converter set **1702** is located in aft portion **112** proximate tail **114**. In other alternative embodiments, not shown, AC/AC converter set **1702** is located in other locations in fuselage **108**, including, without limitation, proximate wing **110**.

Also, in the alternative embodiment, at least one shunt type BIIC **1500** is coupled to AC line **116**. Further, in the alternative embodiment, shunt type BIIC **1500** is located in fuselage **108** proximate wing **110**. In still other alternative embodiments, not shown, shunt type BIIC **1500** is located in other locations in fuselage **108**, including, without limitation, in aft portion **112** proximate tail **114**. Furthermore, in the alternative embodiment, it is possible to exclude at least one AC/AC converter set **1702** from electric vehicle propulsion system **1700**. Where AC/AC converter set **1702** is excluded from electric vehicle propulsion system **1700**, AC line **116** is coupled to and between generator **106** and electrical device **122** directly, and without an intervening AC/AC power converter **1606**.

In operation, in the alternative embodiment, AC current is transmitted on AC line **116** from generator **106** to AC/AC converter set **1702**. DC power from energy storage device **208**, not shown, within shunt type BIIC **1500** is converted to AC power, i.e., by discharging energy storage device **208**, by shunt type BIIC **1500**. AC power from shunt type BIIC **1500** is transmitted to AC line **116** to supply at least a portion of AC power to AC/AC converter set **1702**. Also, in operation of the alternative embodiment, it is possible for shunt type BIIC **1500** to convert AC power received on AC line **116** into DC power to charge energy storage device **208** within shunt type BIIC **1500**. Thus, in the alternative embodiment, shunt type BIIC **1500** functions as a bidirectional DC-to-AC power converter.

The above-described embodiments of BIICs described herein are suited to increasing the specific power, i.e., kilowatt/kilogram (kW/kg), of electric vehicle propulsion systems by reducing the number and weight of passive components and cables. Specifically, the above-described BIICs do not require a large number of passive filtering capacitors because the rates of change of voltage with time, i.e., dv/dt, of individual battery integrated power converter modules (BIICMs) are small relative to known power converters in known electric vehicle propulsion systems. Further, specifically, tight control of dv/dt in individual BIICMs results in low levels of harmonic distortion and electromagnetic interference (EMI) relative to known power converters for electric vehicle propulsion systems. Further, the above-described BIICs are more modular, sealable, reliable, as well as easier to maintain and manufacture relative to known power converters for electric vehicle propulsion systems. Furthermore, a wide variety of energy storage devices are adaptable to use with the above-described BIICs, which facilitates incorporation of more advanced energy storage devices into electric vehicle propulsion systems without replacement of power converter components. Moreover, the above-described BIICs provide effective physical and galvanic isolation of energy storage devices, including, without limitation, DC batteries, from other components of the BIICs and the overall power system, thus enhancing safety and reliability in electric vehicle propulsion systems. As such, the above-described BIICs utilize energy storage devices to not only provide energy for electric vehicle propulsion, but also to act as voltage sources to enable multi-level power converter operations without additional film capacitors, and at the same time reduce the requirements of using filtering component elements relative to known power converters for electric vehicle propulsion systems.

Exemplary technical effects of the above-described apparatus and systems include at least one of: (a) increasing the specific power, i.e., kW/kg, of electric vehicle propulsion systems; (b) decreasing the weight of power converter components and cables of electric vehicle propulsion systems; (c) reducing the number and weight of passive components including filtering capacitors in power converter components of electric vehicle propulsion systems; (d) lowering levels of harmonic distortion and EMI in electric vehicle propulsion systems; (e) making power converter components of electric vehicle propulsion systems more modular, sealable, reliable, as well as easier to maintain and manufacture; (f) enabling utilization of energy storage devices in electric vehicle propulsion systems to not only provide energy for electric propulsion, but also to act as voltage sources to enable multi-level power converter operation without additional film capacitors; (g) facilitating incorporation of more advanced energy storage devices into electric vehicle propulsion systems without replacement of power converter components; and (h) providing physical and galvanic isolation of energy storage devices, including, without limitation, DC batteries, from other components of the BIICs and the overall power system.

Exemplary embodiments of the above-described apparatus and systems for BIICs are not limited to the specific embodiments described herein, but rather, components of apparatus and systems may be utilized independently and separately from other components described herein. For example, the apparatus and systems may also be used in combination with other systems requiring increasing the specific power of power system components including, without limitation, power converters, generators, motors, cables, and energy storage devices, and the associated methods, and are not limited to practice with only the apparatus and systems as described herein. Rather, the exemplary embodiment can be implemented and utilized in connection with many other applications, equipment, and systems that may benefit from using BIICs to improve the specific power, performance, reliability, power efficiency, EMI behavior, maintainability, and manufacturability of power converters and other power systems in various applications.

Although specific features of various embodiments of the disclosure may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the disclosure, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

This written description uses examples to disclose the embodiments, including the best mode, and also to enable any person skilled in the art to practice the embodiments, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

What is claimed is:

1. A battery integrated isolated power converter (BIIC) comprising:

at least one BIIC module (BIICM) string comprising a plurality of BIICMs coupled to each other, each BIICM of the plurality of BIICMs comprising:

a first BIICM circuit comprising first, second, third, and fourth switching devices coupled together, the first switching device coupled to the second switching device, the third switching device coupled to the fourth switching device, both of the first switching device and the second switching device coupled in parallel across both of the third switching device and the fourth switching device;

a second BIICM circuit comprising a fifth switching device and a sixth switching device coupled to the fifth switching device;

a BIICM high-frequency transformer coupled to and between the first BIICM circuit and the second BIICM circuit, the BIICM high-frequency transformer including a first winding and a second winding, the first winding coupled in parallel across at least one of the third switching device or the fourth switching device, the second winding coupled in parallel across at least one of the fifth switching device or the sixth switching device, wherein the first

BIICM circuit and the second BIICM circuit are physically isolated and inductively coupled through the BIICM high-frequency transformer;

one or more of: (a) at least one energy storage device or (b) at least one capacitor coupled in parallel across at least one of:

both of the first switching device and the second switching device; or

both of the fifth switching device and the sixth switching device.

2. The BIIC in accordance with claim **1**, wherein the BIICM high-frequency transformer comprises first windings and at least a second winding, the BIICM high-frequency transformer including more of the first windings than the at least a second winding.

3. The BIIC in accordance with claim **1**, wherein:

the at least one BIICM string further comprises at least three shunt strings, each of the shunt strings comprising at least a topmost BIICM and a bottommost BIICM;

wherein the first BIICM circuit further comprises:

a first node defined between the first switching device and the second switching device;

a second node defined between the first switching device and the third switching device; and

a third node defined between the second switching device and the fourth switching device; and

at least one of the BIICs further comprises:

at least three alternating current (AC) lines, each of the AC lines configured to transmit a phase of a 3-phase AC power to and from the at least one BIIC, wherein:

the first node of the topmost BIICM of each of the shunt strings coupled to one of the AC lines;

the third node of the bottommost BIICM of each of the shunt strings coupled together; and

the first nodes and the third nodes of the BIICMs other than the topmost BIICM and the bottommost BIICM of the shunt strings are serially coupled with each other.

4. The BIIC in accordance with claim **1**, further comprising:

a bypass switch coupled in parallel across at least one of the first switching device or the second switching device; and

a bypass switch controller coupled to the bypass switch, the bypass switch controller configured to transmit a first control signal to the bypass switch to open the bypass switch responsive to at least one characteristic associated with at least one of the BIICMs having a first predetermined value, the bypass switch controller also configured to transmit a second control signal to the bypass switch to close the bypass switch responsive to the at least one characteristic having a second predetermined value that is different from the first predetermined value.

5. The BIIC in accordance with claim **1**, wherein the first BIICM circuit further comprises:

a first node defined between the first switching device and the second switching device;

a second node defined between the first switching device and the third switching device;

a third node defined between the second switching device and the fourth switching device;

a direct current (DC) link; and

a first AC line configured to transmit a phase of a 3-phase AC power to and from the BIIC, wherein the at least one BIICM string further comprises:

a first half string comprising a first plurality of the BIICMs comprising at least a first topmost BIICM and a first bottommost BIICM;

a second half string comprising a second plurality of the BIICMs comprising at least a second topmost BIICM and a second bottommost BIICM; and

a power terminal coupled to and between the first half string and the second half string, the power terminal further coupled to the first AC line.

6. The BIIC in accordance with claim **5**, further comprising a first inductor and a second inductor, wherein:

the first inductor is coupled to and between the power terminal and the third node of the first bottommost BIICM; and

the second inductor is coupled to and between the power terminal and the first node of the second topmost BIICM.

7. The BIIC in accordance with claim **5**, further comprising at least three of the first AC line and at least three panels, each of the panels comprising one of the BIICM strings, wherein:

both of the third node of the first bottommost BIICM and the first node of the second topmost BIICM are coupled to the power terminal;

both of the first node of the first topmost BIICM and the third node of the second bottommost BIICM are coupled to the DC link;

the first nodes of the BIICMs of the first half string other than the first node of the first topmost BIICM are serially coupled to the third nodes of the BIICMs of the first half string other than the third node of the first bottommost BIICM; and

the first nodes of the BIICMs of the second half string other than the first node of the second topmost BIICM are serially coupled to the third nodes of the BIICMs of the second half string other than the third node of the second bottommost BIICM.

8. The BIIC in accordance with claim **1**, wherein the second BIICM circuit further comprises a seventh switching device and an eighth switching device coupled to the seventh switching device, both of the seventh switching device and the eighth switching device coupled in parallel across both of the fifth switching device and the sixth switching device.

9. The BIIC in accordance with claim **8**, further comprising:

a bypass switch coupled in parallel across at least one of the seventh switching device or the eighth switching device; and

a bypass switch controller coupled to the bypass switch, the bypass switch controller configured to transmit a control signal to the bypass switch to open the bypass switch responsive to at least one characteristic associated with at least one of the BIICMs having a first predetermined value and to close the bypass switch responsive to the at least one characteristic having a second predetermined value that is different from the first predetermined value.

10. The BIIC in accordance with claim **8**, wherein:

the first BIICM circuit further comprises:

a first node defined between the first switching device and the second switching device;

a second node defined between the first switching device and the third switching device; and

a third node defined between the second switching device and the fourth switching device;

the second BIICM circuit further comprises:

a fourth node defined between the sixth switching device and the eighth switching device; and

a fifth node defined between the seventh switching device and the eighth switching device; and

the BIIC further comprises:

a DC link;

a first nodal bus;

a second nodal bus; and

at least three first AC lines, wherein:

the at least one BIICM string further comprises at least three BIICM sets with each of the BIICM sets comprising at least a topmost BIICM and a bottommost BIICM, wherein:

the first nodes of the BIICM sets are coupled together and are further coupled to the first AC lines, each of the first AC lines configured to transmit a phase of a 3-phase AC power to and from the BIIC;

both of the fifth node of the topmost BIICM of the topmost BIICM set and the fourth node of the bottommost BIICM of the bottommost BIICM set are coupled to the DC link;

the second nodes of the BIICMs of the BIIC are coupled together through the first nodal bus;

the third nodes of the BIICMs of the BIIC are coupled together through the second nodal bus; and

the fourth nodes and the fifth nodes of the BIICMs other than the topmost BIICM of the topmost BIICM set and the bottommost BIICM of the bottommost BIICM set are serially coupled.

11. The BIIC in accordance with claim **8**, wherein:

the first BIICM circuit further comprises:

a first node defined between the first switching device and the second switching device;

a second node defined between the first switching device and the third switching device; and

a third node defined between the second switching device and the fourth switching device;

the second BIICM circuit further comprises:

a fourth node defined between the sixth switching device and the eighth switching device; and

a fifth node defined between the seventh switching device and the eighth switching device;

the BIIC further comprises:

a DC link;

a first nodal bus;

a second nodal bus; and

at least three AC lines; and

the at least one BIICM string further comprises at least three BIICM sets with each of the BIICM sets comprising at least a topmost BIICM and a bottommost BIICM, wherein:

the first nodes of of the BIICM sets are coupled together and further coupled to the AC lines, each of the AC lines configured to transmit a phase of a 3-phase AC power to and from the BIIC;

each of the fifth node of the topmost BIICM and the fourth node of the bottommost BIICM of each of the BIICM sets are coupled to the DC link;

the second nodes of the BIICMs of the BIIC are coupled together through the first nodal bus;

the third nodes of the BIICMs of the BIIC are coupled together through the second nodal bus; and

the fourth nodes and the fifth nodes of the BIICMs other than the topmost BIICM and the bottommost BIICM of each of the BIICM sets are serially coupled together.

12. The BIIC in accordance with claim **8**, wherein the second BIICM circuit further comprises a ninth switching device and a tenth switching device coupled to the tenth switching device, both of the ninth switching device and the tenth switching device coupled in parallel across both of the seventh switching device and the eighth switching device.

13. The BIIC in accordance with claim **12**, wherein:

the first BIICM circuit further comprises:

a first node defined between the first switching device and the second switching device;

a second node defined between the first switching device and the third switching device; and

a third node defined between the second switching device and the fourth switching device;

the second BIICM circuit further comprises:

a fifth node defined between the seventh switching device and the eighth switching device; and

a sixth node defined between the ninth switching device and the tenth switching device;

the BIIC further comprises:

a DC link;

a first nodal bus;

a second nodal bus;

at least three first AC lines; and

at least three second AC lines; wherein:

the at least one BIICM string further comprises at least three BIICM sets comprising a topmost BIICM set and a bottommost BIICM set, each of the BIICM sets comprising at least a topmost BIICM and a bottommost BIICM, wherein:

the first node of each of the topmost BIICM and the bottommost BIICM of each of the BIICM sets are coupled together and further coupled to one of the first AC lines, each of the first AC lines configured to transmit a phase of a 3-phase AC power to and from the BIIC;

the fifth node of the topmost BIICM of said of the BIICM sets is coupled to one of the second AC lines, each of the second AC lines configured to transmit a phase of a 3-phase AC power to and from the BIIC;

the second nodes of the BIICMs are coupled together through the first nodal bus;

the third nodes of the BIICMs are coupled together through the second nodal bus;

the fifth nodes and the sixth nodes and the fifth nodes of the BIICMs other than the topmost BIICM and the bottommost BIICM of each of the BIICM sets are serially coupled; and

the sixth nodes of all the bottommost BIICMs of each of the BIICM sets are coupled together.

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