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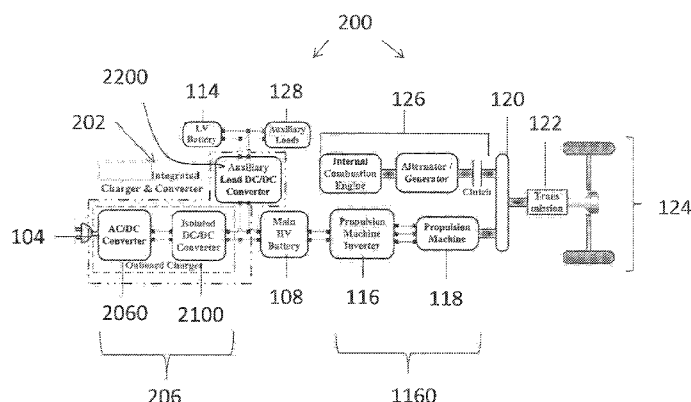


FIG. 4

- (57) Abstract: An integrated and isolated onboard charger for plug-in electric vehicles, includes an ac-dc converter and a dual-output dc-dc resonant converter, for both HV traction batteries and LV loads. In addition, the integrated and isolated onboard charger may be configured as unidirectional or bidirectional, and is capable of delivering power from HV traction batteries to the grid for vehicle-to-grid (V2G) applications. To increase the power density of the converter, the dual-output DC-DC resonant converter may combine magnetic components of resonant networks into a single three-winding electromagnetically integrated transformer (EMIT). The resonant converter may be configured as a half-bridge topology with split capacitors as the resonant network components to further reduce the size of converter. The integrated charger may be configured for various operating modes, including grid to vehicle (G2V), vehicle to grid (V2G) and high voltage to low voltage, HV-to-LV (H2L) charging.

AN INTEGRATED DUAL-OUTPUT GRID-TO-VEHICLE (G2V) AND VEHICLE-TO-GRID (V2G) ONBOARD CHARGER FOR PLUG-IN ELECTRIC VEHICLES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to, and benefit of, U.S. Provisional Patent Application No. 62/011,649 filed on June 13, 2014, entitled “INTEGRATED POWER ELECTRONIC CHARGER FOR PLUG-IN ELECTRIC VEHICLES”, by Alireza Khaligh, the entire contents of which is incorporated by reference herein.

BACKGROUND

1. Technical Field

The present disclosure relates to plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) and more particularly to on-board chargers for such vehicles.

2. Description of Related Art

[0002] Plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs), cumulatively called plug-in electric vehicles (PEVs), need to be equipped with an on-board charger. Such on-board chargers are generally categorized as onboard level-1 (L1) grid-to-vehicle (G2V) chargers and level-2 (L2) grid-to-vehicle (G2V) chargers to charge the high-voltage (HV) traction batteries in plug-in electric vehicles (PEVs).

[0003] FIGS. 1 and 2 illustrate schematic diagrams of an onboard power electronic interface (PEI) 102 of a PEV powertrain in presence of an onboard charger and a step-down dc-dc converter according to the prior art. More particularly, FIGS. 1 and 2 illustrate power electronic interface (PEI) 102 that includes a typical on-board charger 106 that is mounted on a PEV 100 according to the prior art. On-board charger 106 is supplied 1-phase alternating current (AC) electrical power by an external power supply interface connection 104. The on-board charger 106 includes two stages: (a) first stage 1060 is an AC/DC (direct current) converter for rectification and power factor correction; (b) second stage 1068 is an isolated DC/DC converter for galvanic isolation and battery current/voltage regulation [2-5]. Second stage DC/DC converter 1068 is in electrical communication with HV traction batteries 108.

[0004] The HV traction batteries 108 are in electrical communication with a low voltage (LV) system 110 that includes a step-down dc-dc converter 112 in electrical communication with LV batteries 114 and that steps down the voltage of HV traction batteries 108 to a typical 12-V low voltage (LV) to the level of LV batteries 114.

- [0005] As defined herein, HV traction batteries 108 may include a single battery or multiple batteries. Similarly, LV batteries 114 may include a single battery or multiple batteries. HV traction batteries 108 and LV batteries 114 may also be referred to herein as battery packs, even if there is only a single battery present.
- [0006] to energize dc electrical loads, such as steering system, air conditioning, radios and consumer electronics. Such step-down dc-dc converter 112 is independent of the grid-connected onboard charger 106.
- [0007] The most commonly used ac-dc converter 1064 includes a single-phase power factor correction (PFC) boost converter, which converts the 110V~240V single-phase ac voltages received at external power supply interface connection 104 to a regulated dc voltage (typically around 390V). At the second stage, isolated dc-dc converter 1068 is utilized to regulate the current/voltage (typically 250V~420V) of HV batteries 108 and provide galvanic isolation. A majority of the commercially available and upcoming onboard L1 and L2 chargers are unidirectional.
- [0008] The DC output of HV batteries 108 is supplied to a 3-phase inverter 116 that is in electrical communication with a 3-phase motor 118 to form an electric propulsion system 1160. The 3-phase motor 118 is mechanically coupled to torque converter 120 and in turn transmission 122 and axle and wheel assembly 124. Internal combustion engine (ICE) propulsion system 126 is also mechanically coupled in parallel to the torque converter 120 and in turn transmission 122 and axle and wheel assembly 124.
- [0009] In the case of availability of other renewable energy sources such as wind, solar, or fuel cell energy systems, the output of the energy source are sometimes directly connected to DC-link 1066, which is the stage between AC/DC stage 1064 and DC/DC stage 1068 and shown by V_{DC} , enabling DC charging from the renewable energy source.
- [00010] An efficient approach toward topology integration can increase the power density and specific power while reducing the cost of onboard PEIs. Prior efforts to develop integrated PEV onboard chargers include integration of non-isolated single-stage chargers that combine an ac-dc PFC converter and a dc-dc bidirectional converter, which interfaces an HV battery pack and the propulsion inverter. However, such topologies require more transistors and diodes, and integrating a high-power dc-dc converter with a low-power onboard charger might reduce the charging efficiency. In addition, some PEVs might not be equipped with a bidirectional converter between HV battery pack and propulsion inverter.

[00011] Other researchers have studied the integration of isolated onboard chargers using either phase-shift active-bridge converters or series-parallel resonant converters; however, many of these topologies require more components and have lower efficiency in comparison to stand-alone converters. Moreover, these topologies include a discrete inductor as the resonant inductor in series with the transformer, which increases the size and weight of magnetic components. Some topologies do not provide isolation between the HV traction battery and LV dc loads, which does not comply with the requirements of IEC 61851-1 Standard.

[00012] As described herein throughout the drawings and specification, the sequential numbering of the various components, such as switches S1, S2..., diodes D1, D2..., capacitors C1, C2..., etc. are unique to the particular figure that is being described, and are not necessarily considered to carry over from one figure to the next unless the particular components are located on one or more other figures such that one of ordinary skill in the art would recognize that the component(s) in question is (are) in fact carried over from one or more previously described figures.

[00013] FIG. 3 demonstrates the topology of a typical onboard charger 106 and an individual dc-dc converter 110 according to the prior art. The first stage 1060 of charger 106 includes a unidirectional diode bridge 1051 for ac-dc conversion, followed by an interleaved boost converter 1052 (inductors L1 and L2, diodes D1 and D2, switches S1 and S2 and capacitor C_{DC1}) for power factor correction. The first stage 1060 is in electrical communication with unidirectional LLC resonant converter 1068 (switches S3, S4, S5, S6, resonant inductor L_{r1} , resonant capacitor C_{r1} , transformer T1, diodes D3, D4, D5, D6 and capacitor C_{dc2}) that forms the second stage 1068 to regulate the voltage/current of the HV traction battery 108.

[00014] Via HV battery 108, the second stage 1068 is in electrical communication with LV system 110 that includes another LLC resonant converter 112 (switches S7, S8, S9, S10, resonant inductor L_{r2} , resonant capacitor C_{r2} , transformer T2, diodes D7, D8, D9, D10, switches S15, S16 and capacitor C_{dc2}) that delivers power from HV traction battery pack 108 to LV battery pack 114 that is electrically coupled to LV dc loads (not shown).

SUMMARY

[00015] The present disclosure relates to an integrated and isolated onboard charger for plug-in electric vehicles that includes an ac-dc converter and a dual-output dc-dc resonant converter, for both HV traction batteries and LV loads. In addition, the integrated and isolated onboard charger may be configured as unidirectional or bidirectional, and is capable of delivering power from HV traction batteries to the grid for vehicle-to-grid (V2G) applications. To increase the power density

of the converter, the dual-output DC-DC resonant converter may combine magnetic components of resonant networks into a single three-winding electromagnetically integrated transformer (EMIT). The resonant converter may be configured as a half-bridge topology with split capacitors as the resonant network components to further reduce the size of the converter. The integrated charger is configured for various operation modes, including grid to vehicle (G2V), vehicle to grid (V2G) and high voltage to low voltage, HV-to-LV (H2L) charging. More particularly, the present disclosure relates to an integrated power electronics interface that includes a first stage power factor correction AC-DC converter; and a second stage integrated DC-DC converter that includes a dual-output CLLLC resonant converter; and a LLC converter.

[00016] In one embodiment, the dual-output CLLLC resonant converter may be intertwined with the LLC converter. The LLC converter may be one of a half-bridge LLC converter or a full-bridge LLC converter.

[00017] The dual-output CLLLC resonant converter may be intertwined with the half-bridge LLC converter or may be intertwined with the full-bridge LLC converter.

[00018] The present disclosure relates also to an integrated power electronics interface that includes a first stage. The first stage includes a power factor correction AC-DC converter; and a DC/DC converter. The second stage is an integrated DC-DC converter.

[00019] In one embodiment, the power factor correction AC-DC converter of the first stage may be a diode bridge. In still further embodiments, the diode bridge may be one of a full-bridge diode bridge or a half-bridge diode bridge.

[00020] In still another embodiment, the first stage DC-DC converter may be (a) a single-leg boost converter; (b) a single-leg buck-boost converter; (c) an interleaved boost converter; (d) an interleaved buck-boost converter; (e) a single-ended primary-inductor converter (SEPIC) converter; (f) a bidirectional half bridge converter; (g) a bidirectional full bridge converter; (h) a bidirectional totem pole converter; (m) a bidirectional interleaved half bridge converter; (n) a bidirectional interleaved full-bridge converter; (l) a bridgeless boost PFC converter; (l) an interleaved bridgeless boost PFC converter; (i) a bridgeless interleaved resonant PFC boost converter; (j) a phase shifted semi-bridgeless converter, or any other potential AC/DC bidirectional and unidirectional PFC circuit.

[00021] In one embodiment, the second stage integrated DC-DC converter may include a three-winding transformer. The three-winding transformer may be one of a transformer configured with individual, discrete inductors or an electromagnetically integrated transformer.

[00022] In one embodiment, the electromagnetically integrated transformer may include: a first EE core defining a base portion, a central leg and first and second peripheral legs; a second EE core defining a base portion, a central leg and first and second peripheral legs; a primary winding wound around the central leg of the first EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the first EE core; a secondary winding wound around the central leg of the second EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the second EE core; and a tertiary winding wound around the central leg of the second EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the second EE core.

[00023] In one embodiment, the edges of the legs of the first EE core may align with edges of the legs of the second EE core and the secondary winding and tertiary winding may be adjacent to one another along an axis defined by the central leg of the first EE core and the central leg of the second EE core.

[00024] In still another embodiment, the edges of the legs of the first EE core may align with edges of the legs of the second EE core and the secondary winding may be formed concentrically around the tertiary winding and both the secondary winding and the tertiary winding may be formed concentrically around the central leg of the second EE core. In yet another embodiment, a peripheral winding gap may be formed between a lower edge of the primary winding on the first EE core and an upper edge of the secondary winding on the second EE core. In still another embodiment, a central gap may be formed between the central leg of the first EE core and the central leg of the second EE core.

[00025] The present disclosure relates also to a three-winding electromagnetically integrated transformer for an integrated power electronics interface that includes: a first EE core defining a base portion, a central leg and first and second peripheral legs; a second EE core defining a base portion, a central leg and first and second peripheral legs; a primary winding wound around the central leg of the first EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the first EE core; a secondary winding wound around the central leg of the second EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the second EE core; and a tertiary winding wound around the central leg of the second EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the second EE core.

[00026] In one embodiment, edges of the legs of the first EE core may align with edges of the legs of the second EE core and the secondary winding and tertiary winding may be adjacent to one another along an axis defined by the central leg of the first EE core and the central leg of the second EE core.

[00027] In still another embodiment, edges of the legs of the first EE core may align with edges of the legs of the second EE core and the secondary winding may be formed concentrically around the tertiary winding and both the secondary winding and the tertiary winding may be formed concentrically around the central leg of the second EE core.

[00028] In yet another embodiment, a peripheral winding gap may be formed between a lower edge of the primary winding on the first EE core and an upper edge of the secondary winding on the second EE core. In another embodiment, a central gap may be formed between the central leg of the first EE core and the central leg of the second EE core.

BRIEF DESCRIPTION OF THE DRAWINGS

[00029] The above-mentioned advantages and other advantages will become more apparent from the following detailed description of the various exemplary embodiments of the present disclosure with reference to the drawings wherein:

[00030] **FIG. 1** illustrates a schematic diagram of the onboard PEIs in a PEV powertrain according to the prior art;

[00031] **FIG. 2** illustrates the conventional system level structure of an on-board charger and 12V or 24V or 42V auxiliary dc/dc converter for a PEV according to the prior art;

[00032] **FIG. 3** illustrates a stand-alone onboard charger and the step-down dc-dc converter topology of a PEV charger according to the PRIOR ART;

[00033] **FIG. 4** is a schematic of a parallel PEV powertrain in presence of an onboard charger and auxiliary load dc-dc converter for LV auxiliary loads illustrating the components that are integrated into an onboard charger according to one embodiment of the present disclosure;

[00034] **FIG. 5A** is a system level diagram of the integrated PEV power electronic interface according to embodiments of the present disclosure;

[00035] **FIG. 5B** is another system level diagram of the integrated PEV power electronic interface according to embodiments of the present disclosure;

[00036] **FIG. 6** is a first embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;

- [00037] **FIG. 7** is a second embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00038] **FIG. 8** is a third embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00039] **FIG. 9** is a fourth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00040] **FIG. 10** is a fifth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00041] **FIG. 11** is a sixth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00042] **FIG. 12** is a seventh embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00043] **FIG. 13** is an eighth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00044] **FIG. 14** is a ninth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00045] **FIG. 15** is a tenth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00046] **FIG. 16** is an eleventh embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00047] **FIG. 17** is a twelfth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00048] **FIG. 18** is a thirteenth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00049] **FIG. 19** is a fourteenth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00050] **FIG. 20** is a fifteenth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00051] **FIG. 21** is a sixteenth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;
- [00052] **FIG. 22** is a seventeenth embodiment of an integrated power electronic interface for a PEV according to one embodiment of the present disclosure;

- [00053] **FIG. 23A** illustrates winding arrangements inside gapped E cores of an electromagnetically integrated transformer (EMIT) according to one embodiment of the present disclosure;
- [00054] **FIG. 23B** is a perspective view of the EMIT of FIG. 23A;
- [00055] **FIG. 24A** illustrates winding arrangements inside gapped E cores of an electromagnetically integrated transformer (EMIT) according to another embodiment of the present disclosure;
- [00056] **FIG. 24B** is a perspective view of the EMIT of FIG. 24A;
- [00057] **FIG. 24C** illustrates details of the EMIT of FIGS. 24A and 24B;
- [00058] **FIG. 25** illustrates topology of a half-bridge CLLC resonant converter of FIG. 22 configured for G2V charging;
- [00059] **FIG. 26A** is a nonlinear non-sinusoidal circuit model of the half-bridge CLLC resonant converter of FIG. 25;
- [00060] **FIG. 26B** is a linear sinusoidal circuit model of the nonlinear non-sinusoidal circuit model of FIG. 26A for G2V operation.
- [00061] **FIG. 27A** illustrates gain curves versus frequency at different quality factors (Q) and frequency ratio (p) wherein
- [00062] $p=1$;
- [00063] **FIG. 27B** illustrates gain curves versus frequency at different quality factors (Q) and frequency ratio (p) wherein $p>1$;
- [00064] **FIG. 27C** illustrates gain curves versus frequency at different quality factors (Q) and frequency ratio (p) wherein $p<1$;
- [00065] **FIG. 28** illustrates circuit topology of the half-bridge CLLC resonant converter of FIG. 22 for V2G operation;
- [00066] **FIG. 29A** is a nonlinear non-sinusoidal circuit model of the half-bridge CLLC resonant converter of FIG. 28;
- [00067] **FIG. 29B** is a linear sinusoidal circuit model of the nonlinear non-sinusoidal circuit model of FIG. 29A for V2G operation;
- [00068] **FIG. 30** illustrates circuit topology of the half-bridge LLC resonant converter of FIG. 22 for H2L operation;
- [00069] **FIG. 31A** is a nonlinear non-sinusoidal circuit model of the half-bridge LLC resonant converter of FIG. 30;
- [00070] **FIG. 31B** is a linear sinusoidal circuit model of the nonlinear non-sinusoidal circuit model of FIG. 31A for H2L operation;

[00071] **FIG. 32** shows the measured current and voltage waveforms of AC-DC interleaved PFC converter during G2V operation at 500W;

[00072] **FIG. 33** illustrates graphical plots of gate-to-source voltage of S_7 , drain-to-source voltage of S_7 , switch current of S_7 , and primary side resonant current;

[00073] **FIG. 34** illustrates graphical plots of gate-to-source voltage of S_9 , drain-to-source voltage of S_9 , switch current of S_9 , and primary side resonant current.

[00074] **FIG. 35** illustrates graphical plots of drain-to-source voltage of S_9 , gate-to-source voltage of S_{11} , drain-to-source voltage of S_{11} , and primary side resonant current.

DETAILED DESCRIPTION

[00075] For the purposes of promoting an understanding of the principles of the present disclosure, reference will now be made to the exemplary embodiments illustrated in the drawings, and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the present disclosure is thereby intended. Any alterations and further modifications of the inventive features illustrated herein, and any additional applications of the principles of the present disclosure as illustrated herein, which would occur to one skilled in the relevant art and having possession of this disclosure, are to be considered within the scope of the present disclosure.

[00076] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments.

[00077] It is to be understood that the method steps described herein and claimed in the claim below need not necessarily be performed in the order as described. Further, words such as “thereafter,” “then,” “next,” etc., are not intended to limit the order of the steps. These words are simply used to guide the reader through the description of the method steps.

[00078] The implementations described herein may be implemented in, for example, a method or a process, an apparatus, a software program, a data stream, or a signal. Even if only discussed in the context of a single form of implementation (for example, discussed only as a method), the implementation of features discussed may also be implemented in other forms (for example, an apparatus or program). An apparatus may be implemented in, for example, appropriate hardware, software, and firmware. The methods may be implemented in, for example, an apparatus such as, for example, a processor, which refers to processing devices in general, including, for example, a computer, a microprocessor, an integrated circuit, or a programmable logic device. Processors also include communication devices, such as, for

example, computers, cell phones, tablets, portable/personal digital assistants, and other devices that facilitate communication of information between end-users within a network.

[00079] The general features and aspects of the present disclosure remain generally consistent regardless of the particular purpose. Further, the features and aspects of the present disclosure may be implemented in system in any suitable fashion, e.g., via the hardware and software configuration of system or using any other suitable software, firmware, and/or hardware. For instance, when implemented via executable instructions, such as the set of instructions, various elements of the present disclosure are in essence the code defining the operations of such various elements. The executable instructions or code may be obtained from a computer-readable medium (e.g., a hard drive media, optical media, EPROM, EEPROM, tape media, cartridge media, flash memory, ROM, memory stick, and/or the like) or communicated via a data signal from a communication medium (e.g., the Internet). In fact, readable media may include any medium that may store or transfer information.

[00080] The present disclosure describes a highly integrated grid-connected onboard charger topology capable of G2V, V2G and HV-to-LV charging. In certain embodiments of the present disclosure, the topology includes a bridgeless interleaved boost converter as the PFC stage and a dual-output half-bridge CLLC resonant converter as the isolated stage. The design of the second stage of the proposed integrated charger is such that, without using additional passive components, the resonant converter takes advantage of the half-bridge capacitors, the leakage inductance and magnetizing inductance of a three-winding electromagnetic integrated transformer (EMIT) to build a resonant network. In comparison to two stand-alone converters, the integrated topology requires fewer components, is smaller in size, and is potentially lower cost. Moreover, the integrated topology provides more operating modes than conventional stand-alone converters.

[00081] The embodiments of the present disclosure provide a series of novel power electronic interfaces, which may allow the following:

- (a) Innovatively integrate an isolated onboard charger and the auxiliary load dc/dc converter in PEVs,
- (b) Incorporate a maximum efficiency point tracking controller to substantially enhance charger efficiency not only at full load but also particularly in light loads,
- (c) Provide charging capability over much wider range of battery voltages (100V - 420V), and
- (d) Provide bidirectional charging, e.g., enabling both grid-to-vehicle (G2V) charging and vehicle-to-grid (V2G) capabilities.

[00082] FIG. 4 illustrates system 200 that includes an integrated PEV power electronic interface 202 according to embodiments of the present disclosure. As compared to prior art system 100 and

power electronic interface 102 in FIG. 1, power electronic interface 202 now includes an onboard charger 206 that includes an AC/DC converter 2060 and an isolated DC/DC converter 2100. The AC/DC converter 2060 is supplied 1-phase alternating current (AC) electrical power by external power supply interface connection 104. The AC/DC converter 2060 is in electrical communication with isolated DC/DC converter 2100.

[00083] Integrated power electronic interface 202 further includes auxiliary load DC/DC converter 2200 that is integrated with onboard charger 206 according to embodiments of the present disclosure. The auxiliary load DC/DC converter 2200 may be in electrical communication with LV battery pack 114 (e.g., 12 V or 24 V or 42 V) which supplies LV power to auxiliary loads 128 (e.g., 12 V or 24 V or 42 V) or the auxiliary load DC/DC converter 2200 may be in electrical communication directly with the auxiliary loads 128 without the presence of LV battery pack 114. The embodiments of the present disclosure are not limited with respect to these features.

[00084] Referring also to FIGS. 5A and 5B, the integrated PEV interface 202 may be configured as providing either unidirectional electrical power or may be configured as providing bidirectional electrical power.

[00085] In the case of bidirectional power as illustrated in FIG. 5A, integrated PEV interface 202a may also include as onboard charger 2060 an electromagnetic interference (EMI) filter 2062 that filters electrical power received from or transmitted to external power supply interface connection 104. In the example of FIG. 5A, EMI filter 2062 is in electrical communication with bidirectional AC/DC converter 2100. Bidirectional AC/DC converter 2100 may also be, in turn, in electrical communication with bidirectional DC/DC converter 2200, as shown by double arrow A1, and with HV battery pack 108, or may be in direct electrical communication with LV battery pack 114, as shown by double arrow B1, thereby bypassing bidirectional DC/DC converter 2200 and HV battery pack 108. In the case of availability of other renewable energy sources such as wind, solar, or fuel cell energy systems, in a similar manner as described with respect to FIG. 4 above, the output of the energy source may sometimes be directly connected to DC-link 2066, which is the stage between bidirectional AC/DC converter 2100 and bidirectional DC/DC converter 2200 and shown by V_{DC} , enabling DC charging from the renewable energy source. Therefore, onboard charger 2060 may also include DC-link 2066.

[00086] Thus, integrated PEV interface 202a is configured to be capable of the following:

- [00087] Charging both the main high-voltage (HV) and low-voltage (LV) battery packs 108 and 114, respectively, from the grid (G2V) simultaneously, or charging only the main HV battery pack 108;
- [00088] Providing power from the vehicle to grid (V2G) through either HV battery pack 108 or LV battery pack 114 or both;
- [00089] Powering onboard low-voltage loads 128 (see FIG. 4) through high voltage battery pack 108 during propulsion by the electric propulsion system 1160; and
- [00090] Powering the HV battery pack 108 during regenerative braking during propulsion by the ICE propulsion system 126.
- [00091] In the case of either unidirectional or bidirectional power, as illustrated in FIG. 5B, integrated PEV interface 202b may also include as onboard charger 2060 electromagnetic interference (EMI) filter 2062 that filters electrical power received from or transmitted to external power supply interface connection 104. In a similar manner as with respect to FIG. 5A, in the example of FIG. 5B, EMI filter 2062 is in electrical communication with AC/DC converter 2100'. AC/DC converter 2100' may also be, in turn, in electrical communication with DC/AC converter 2300 that is included within DC/DC converter 2250, as shown by double arrow A2.
- [00092] DC/AC converter 2300 is, in turn, in electrical communication with HV AC/DC converter 2500 and with HV battery pack 108 via induction windings 2410 and 2420 of electromagnetically integrated transformer (EMIT) 2400, and may be in direct electrical communication with LV AC/DC converter 2600 and LV battery pack 114, as shown by double arrow B2.
- [00093] Thus, DC/DC converter 2250 includes DC/AC converter 2300, EMIT 2400 and induction windings 2410, 2420, 2430 and HV AC/DC converter 2500 and LV AC/DC converter 2600.
- [00094] In FIGS. 6-22 which follow, various circuit topologies for the integrated power electronic interface converter structures 202, 202a and 202b are illustrated.
- [00095] In all these topologies, the first stage, which is the rectification and power factor correction (PFC) stage, may be either a full-bridge or half-bridge diode bridge followed by any dc/dc converter such as a single-leg or an interleaved boost or buck-boost or single-ended primary-inductor converter (SEPIC) converter. Other first stage topologies may include a bidirectional half bridge converter; a bidirectional full bridge converter, a bidirectional totem pole converter; a bidirectional interleaved half-bridge converter; a bidirectional interleaved full-bridge converter; a bridgeless boost PFC converter; an interleaved bridgeless boost PFC converter; a bridgeless

interleaved resonant PFC boost converter; a phase shifted semi-bridgeless converter; and any other potential AC/DC bidirectional and unidirectional PFC circuit.

[00096] Alternatively, the first stage may be a bridgeless configuration capable of bidirectional AC/DC rectification and power factor correction for G2V operation, as well as DC/AC inversion for V2G operation.

[00097] Integration of the charger and the auxiliary load dc/dc converter may be exhibited in the second stage of the charger using a three-winding transformer 2400 via the following:

[00098] Configuring a transformer and individual discrete inductors 2401 or

[00099] Configuring an electromagnetically integrated transformer (EMIT), e.g., EMIT 2451.

[000100] The integration can be configured through these proposed topologies or a combination of them. By combination, the first stage (ac/dc stage) of either topology can be connected to, or in electrical communication with, the second stage (isolated dc/dc stage) of another configuration. That is, the first stage AC/DC converter of the topologies in FIGS. 6-22 may be connected to, or in electrical communication with, the second stage DC/DC converter of the power electronics interfaces disclosed in another of FIGS. 6-22 to result in an integrated power electronic interface according to embodiments of the present disclosure.

[000101] It is important to note that the utilized semiconductor components in all of the topologies presented in the present disclosure may be replaced with diodes, MOSFETs, IGBTs and any other unidirectional and bidirectional switching semiconductor devices. Therefore, the embodiments of the present disclosure are directed to both unidirectional and bidirectional topologies.

[000102] In all these topologies the DC-link voltage connections 1066 and 2006 may be either fixed or variable enabling the possibilities of (a) maximizing the converter efficiency at light loads; and (b) charging fully depleted batteries (battery trickle mode charging).

[000103] In the case of availability of other renewable energy sources such as wind, solar, or fuel cell energy systems, the output of the energy source can potentially be directly connected to DC-link voltage connections 1066 and 2006, enabling DC charging, without a need for additional converter topology.

[000104] The PEI interfaces 202 including 202a and 202b may be controlled through either phased shift pulse width modulation (PWM) or pulse frequency modulation (PFM), or other feasible control strategy known or to become known in the art.

[000105] Those skilled in the art will recognize that other topologies for the integrated power electronics interface may be configured which fall within the scope of the present disclosure.

[000106] More particularly, **FIG. 6** illustrates one embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20201, wherein the first stage 20601 includes a bidirectional AC/DC half-bridge boost converter (switches S1, S2, inductor L, capacitors C1, C2) that performs rectification and power factor correction (PFC).

[000107] The second stage 22501 includes a multi-output resonant DC/DC converter having a three-winding (W1, W2, W3) transformer 2400 for integration of the first stage converter 20601 and the second stage converter 22501. The integrated configuration of PEI 20201 may be achieved via independent three-winding (W1, W2, W3) transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant conductors Cr1, Cr2 or through an electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer. The LLC resonant stage is developed using the resonant capacitors (Cr1, Cr2), resonant inductors (Lr1, Lr2) and magnetizing inductance of the transformer 2400. The main HV battery pack 108 interfaces with the transformer 2400 using two switches (S5, S6) and two split capacitors (C3, C4). The LV battery pack or auxiliary load 114 is connected to the third winding W3 of the transformer 2400 either using two individual switches (not shown) or two pairs of back-to-back switches (S7, S8, S9, S10) and two capacitors (C5, C6). (The two individual switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000108] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (S7, S8, S9, S10), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108. During V2G operation, the HV battery pack 108 mainly provides power back to the grid.

[000109] **FIG. 7** illustrates another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20202, wherein the first stage 20602 includes an AC/DC full-bridge (D1, D2, D3, D4) followed by a single-phase boost converter (S, L, C1, C2, D), which is used for rectification and power factor correction (PFC).

[000110] In a similar manner, second stage 22502 includes a multi-output LLC DC/DC converter having three-winding (W1, W2, W3) transformer (2400, 2401, 2402) for integration of two converters. The integrated configuration of PEI 20202 may be achieved via independent three-winding (W1, W2, W3) transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant conductors Cr1, Cr2 or through electromagnetically integrated transformer (EMIT) 2451,

where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. The LLC resonant stage is developed using the resonant capacitors (Cr1, Cr2), resonant inductors (Lr1, Lr2) and magnetizing inductance of the transformer 2400. The main HV battery pack 108 interfaces with the transformer 2400 via two switches (S5, S6) and two split capacitors (C3, C4). The LV battery or auxiliary load is connected to the third winding of the transformer 2400 either via two individual switches (not shown) or two pairs of back-to-back switches (S7, S8, S9, S10) and two capacitors (C5, C6). (The two individual switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000111] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (S7, S8, S9, S10), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108. During V2G operation the HV battery pack 108 mainly provides power back to the grid.

[000112] **FIG. 8** illustrates still another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20203, wherein the first stage 20603 includes a full bridge diode rectifier (D1, D2, D3, D4) followed by an interleaved boost converter (L1, L2, S1, S2, D5, D6) for AC/DC rectification and PFC.

[000113] The second stage 22503 includes two DC/DC LLC converters, which share three-winding (W1, W2, W3) transformer 2400. The primary W1 of transformer 2400 includes a full bridge inverter (S3, S4, S5, S6), a resonant capacitor (Cr1) and may further include a resonant inductor (Lr1). Resonant inductor Lr1 may be integrated in the transformer or be an independent inductor. The secondary W2 of transformer 2400, which interfaces the main HV battery pack 108, may include a full bridge rectifier (D7, D8, D9, D10). The third winding W3, which interfaces the auxiliary loads and/or LV battery pack 114, may also include a full bridge rectifier (D11, D12, D13, D14).

[000114] All of the diodes may be replaced with other bidirectional or unidirectional switches, enabling bidirectional or unidirectional power flow, respectively.

[000115] **FIG. 9** illustrates yet another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20204, wherein the first stage 20604 includes a unidirectional AC/DC diode bridge (D1, D2, D3, D4) followed by a single-ended primary-inductor converter (SEPIC), (S, D, L1, L2, C1, C2), which is used for rectification and power factor correction (PFC).

[000116]The second stage 22504 includes a multi-output LLC DC/DC converter having three-winding (W1, W2, W3) transformer (2400, 2401, 2402) for integration of two converters. The integrated configuration of PEI 20204 may be achieved via independent three-winding (W1, W2, W3) transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitors Cr1, Cr2 or through an electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. The LLC resonant stage is developed via the resonant capacitors (Cr1, Cr2), resonant inductors (Lr1, Lr2) and magnetizing inductance of the transformer 2400. The main HV battery pack 108 interfaces with the transformer 2400 via two switches (S7, S8) and two split capacitors (C3, C4). The LV battery pack or auxiliary load 114 is connected to the third winding W3 of the transformer 2400 either via two individual switches (not shown) or two pairs of back-to-back switches (S7, S8, S9, S10) and two capacitors (C5, C6). (The two individual switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000117]During charging the main HV battery pack 108 from the grid, the two back-to-back switches S11, S12, which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108.

[000118]In order to enable V2G operation, the diodes D1, D2, D3, D4 in the AC/DC first stage 20604 may be either replaced by bidirectional switches or replaced by two parallel-connected switches.

[000119]**FIG. 10** illustrates still another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20205, wherein the first stage 20605 includes a unidirectional AC/DC diode bridge (D1, D2, D3, D4) followed by an interleaved single-ended primary-inductor converter (SEPIC), (S1, S2, D5, D6, L1, L2, L3, L4, C1, C2, C3, C4), which is used for rectification and power factor correction (PFC). It should be noted that structure of the SEPIC could be simply extended to account for multiple interleaving legs.

[000120]The second stage 22505 includes a multi-output LLC DC/DC converter having three-winding (W1, W2, W3) transformer (2400, 2401, 2451) for integration of two converters. The integrated configuration of PEI 20205 may be achieved via independent three-winding transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitors Cr1, Cr2 or through an electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. The LLC resonant

stage is developed via the resonant capacitors (Cr1, Cr2), resonant inductors (Lr1, Lr2) and magnetizing inductance of the transformer 2400. The main HV battery pack 108 interfaces with the transformer 2400 via two switches (S5, S6) and two split capacitors (C5, C6). The LV battery pack or auxiliary load 114 is connected to the third winding W3 of the transformer either via two individual switches (not shown) or two pairs of back-to-back switches (S7, S8, S9, S10) and two capacitors (C7, C8). (The two individual switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000121] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (not shown), which interface the LV battery, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery 114.

[000122] In order to enable V2G operation, the diodes D1, D2, D3, D4 in the AC/DC first stage 20605 may be either replaced by bidirectional switches or replaced by two parallel-connected switches.

[000123] **FIG. 11** illustrates another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20206, wherein the first stage 20606 includes a unidirectional AC/DC diode bridge (D1, D2, D3, D4) followed by a non-inverting buck-boost converter (S1, S2, S3, S4, L, C1, C2), which is used for rectification and power factor correction (PFC).

[000124] The second stage 22506 includes a multi-output LLC DC/DC converter having a three-winding (W1, W2, W3) transformer (2400, 2401, 2451) for integration of two converters. The integrated configuration of PEI 20206 may be achieved via independent three-winding (W1, W2, W3) transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitors Cr1, Cr2 or through an electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. The LLC resonant stage is developed via the resonant capacitors (Cr1, Cr2), resonant inductors (Lr1, Lr2) and magnetizing inductance of the transformer 2400. The main HV battery pack 108 interfaces with the transformer 2400 via two switches (S9, S10) and two split capacitors (C3, C4). The LV battery pack or auxiliary load 114 is connected to the third winding W3 of the transformer 2400 either via two individual switches (S9, S10) or two pairs of back-to-back switches (S11, S12, S13, S14) and two capacitors (C5, C6).

[000125] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (S11, S12, S13, S14), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 114.

[000126] In order to enable V2G operation, the diodes D1, D2, D3, D4 in the AC/DC FIRST stage 20606 may be either replaced by bidirectional switches or replaced by two parallel-connected switches.

[000127] **FIG. 12** illustrates another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20207, wherein the first stage 20607 includes a unidirectional AC/DC diode bridge (D1, D2, D3, D4) followed by a two-leg interleaved non-inverting buck-boost converter (S1, S2, S3, S4, S5, S6, S7, S8, L1, L2, C1, C2), which is used for rectification and power factor correction (PFC). It should be noted that the structure of the two-leg interleaved non-inverting buck-boost converter (S1, S2, S3, S4, S5, S6, S7, S8, L1, L2, C1, C2) could be simply extended to account for multiple interleaving legs.

[000128] The second stage 22507 includes a multi-output LLC DC/DC converter having a three-winding W1, W2, W3 transformer 2400, 2401, 2451 for integration of two converters. The integrated configuration of PEI 20207 may be achieved via independent three-winding (W1, W2, W3) transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitors Cr1, Cr2 or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. The LLC resonant stage is developed via the resonant capacitors (Cr1, Cr2), resonant inductors (Lr1, Lr2) and magnetizing inductance of the transformer 2400. The main HV battery pack 108 interfaces with the transformer 2400 via two switches (S13, S14) and two split capacitors (C3, C4). The LV battery pack or auxiliary load 114 is connected to the third winding W3 of the transformer either via two individual switches (not shown) or two pairs of back-to-back switches (S15, S16, S17, S18) and two capacitors (C5, C6). (The two individual switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000129] During charging the main HV battery 108 from the grid, the two back-to-back switches which interface the LV battery back 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108.

[000130] In order to enable V2G operation, the diodes D1, D2, D3, D4 in the AC/DC first stage 20607 may be either replaced by bidirectional switches or replaced by two parallel-connected switches.

[000131] **FIG. 13** illustrates another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20208, wherein the first stage 20608 includes a bidirectional AC/DC full-bridge boost converter (S1, S2, S3, S4, L, C1), which is used for rectification and power factor correction (PFC).

[000132] The second stage 22508 includes a multi-output LLC DC/DC converter having three-winding transformer for integration of two converters. The integrated configuration of PEI 20208 may be achieved via independent three-winding (W1, W2, W3) transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitors Cr1, Cr2 or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. The LLC resonant stage is developed via the resonant capacitors (Cr1, Cr2), resonant inductors (Lr1, Lr2) and magnetizing inductance of the transformer 2440. The main HV battery pack 108 interfaces with the transformer 2400 via four switches (S9, S10, S11, S12) and a capacitor (C2). The LV battery pack or auxiliary load 114 is connected to the third winding W3 of the transformer either via two individual switches (not shown) or two pairs of pairs of back-to-back switches in a full bridge structure (S13, S14, S15, S16, S17, S18, S19, S20) and a capacitor (C3). (The two individual switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000133] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (not shown), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108. During V2G operation, the HV battery pack 108 mainly provides power back to the grid.

[000134] **FIG. 14** illustrates still another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20209, wherein the first stage 20609 includes a bidirectional AC/DC full-bridge boost converter (S1, S2, S3, S4, L, C1), which is used for rectification and power factor correction (PFC).

[000135] The second stage 22509 includes a multi-output LLC DC/DC converter having three-winding (W1, W2, W3) transformer 2400, 2401, 2451 for integration of two converters. The integrated configuration of PEI 20209 may be achieved via independent three-winding

transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitor Cr or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. The LLC resonant stage is developed via the resonant capacitors (Cr1, Cr2), resonant inductors (Lr1, Lr2) and magnetizing inductance of the transformer 2400. The main HV battery pack 108 interfaces with the transformer 2400 via four switches (S9, S10, S11, S12) and a capacitor (C2). The LV battery pack or auxiliary load 114 is connected to the third winding W3 of the transformer either via two individual switches (not shown) or two pairs of back-to-back switches (S13, S14, S15, S16) and two capacitors (C3, C4).

[000136] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (not shown), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108. During V2G operation the HV battery pack 108 mainly provides power back to the grid.

[000137] **FIG. 15** illustrates yet another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20210, wherein the first stage 20610 includes a bidirectional AC/DC half-bridge boost converter (S1, S2, L, C1, C2), which is used for rectification and power factor correction (PFC).

[000138] The second stage 22510 includes a multi-output DC/DC converter having three-winding (W1, W2, W3) transformer 2400, 2401, 2451 for integration of two converters. The integrated configuration of PEI 20210 may be achieved via independent three-winding (W1, W2, W3) transformer 2401 and additional resonant inductors (Lr1, Lr2, Lr3) or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer. The main HV battery pack 108 interfaces with the transformer via two switches (S5, S6) and two capacitors (C3, C4). The LV battery pack or auxiliary load is connected to the third winding of the transformer either via two individual switches (S7, S8) or two pairs of back-to-back switches and two capacitors (C5, C6).

[000139] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (not shown), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108. During V2G operation the HV battery pack 108

mainly provides power back to the grid. (The two back-to-back switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000140] **FIG. 16** illustrates an embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20211, wherein the first stage 20611 includes a bidirectional AC/DC full-bridge boost converter (S1, S2, S3, S4, L, C1), which is used for rectification and power factor correction (PFC).

[000141] The second stage 22511 includes a multi-output DC/DC converter having three-winding (W1, W2, W3) transformer 2400, 2401, 2451 for integration of two converters. The integrated configuration of PEI 20211 may be achieved via independent three-winding (W1, W2, W3) transformer 2401 and additional resonant inductors (Lr1, Lr2, Lr3) or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. The main HV battery pack 108 may interface with the transformer via full switches (S9, S10, S11, S12) and a capacitor (C2). The LV battery pack or auxiliary load 114 may be connected to the third winding W1 of the transformer either via four switches (S13, S14, S15, S16) or two pairs of back-to-back switches (not shown) and a capacitor (C3). (The two pairs of back-to-back switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000142] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (not shown), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108. During V2G operation the HV battery pack 108 mainly provides power back to the grid.

[000143] **FIG. 17** illustrates an embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20212, wherein the first stage 20612a bidirectional AC/DC half-bridge boost converter (S1, S2, L, C1, C2), which is used for rectification and power factor correction (PFC).

[000144] The second stage 22512 includes a resonant multi-output DC/DC converter having three-winding (W1, W2, W3) transformer 2400, 2401, 2451 for integration of two converters. The integrated configuration of PEI 20212 may be achieved via independent three-winding transformer 2401 and additional resonant inductors (Lr1, Lr2) or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. Capacitor Cr and inductors Lr1, Lr2, and the

magnetizing inductance of the transformer form a resonant tank circuit which stores the energy oscillating at the resonant frequency. The main HV battery pack 108 may interface with the transformer via full switches (S5, S6) and two capacitors (C3, C4). The LV battery pack or auxiliary load 114 may be connected to the third winding W1 of the transformer either via two switches (not shown) or two pairs of back-to-back switches (S7, S8, S9, S10) and two capacitors (C5, C6).

[000145] During charging the main HV battery through grid, the two back-to-back switches, which interface the LV battery, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery may be charged through HV battery. During V2G operation the HV battery will mainly provide power back to the grid.

[000146] **FIG. 18** illustrates another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20213, wherein the first stage 20613 includes a bidirectional AC/DC full-bridge boost converter (S1, S2, S3, S4, L, C1), which is used for rectification and power factor correction (PFC).

[000147] The second stage 22513 includes a resonant multi-output DC/DC converter having three-winding (W1, W2, W3) transformer 2400, 2401, 2451 for integration of two converters. The integrated configuration of PEI 20213 may be achieved via independent three-winding transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitor Cr or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. Capacitor Cr and inductors Lr1, Lr2, and the magnetizing inductance of the transformer form a resonant tank circuit which stores the energy oscillating at the resonant frequency. The main HV battery pack 108 may interface with the transformer 2400 via full switches (S9, S10, S11, S12) and a capacitor (C2). The LV battery pack or auxiliary load 114 may be connected to the third winding W1 of the transformer 2400 either via two switches (not shown) or two pairs of back-to-back switches (S13, S14, S15, S16) and two capacitors (C3, C4). (The two switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000148] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (not shown), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108. During V2G operation, the HV battery pack 108 mainly provides power back to the grid.

[000149]**FIG. 19** illustrates yet another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20214, wherein the first stage 20614 includes a bidirectional AC/DC full-bridge boost converter (S1, S2, S3, S4, L, C1), which is used for rectification and power factor correction (PFC).

[000150]The second stage 20614 includes a resonant multi-output DC/DC converter having three-winding (W1, W2, W3) transformer 2400, 2401, 2451 for integration of two converters. The integrated configuration of PEI 20214 may be achieved via independent three-winding transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitor Cr or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. Capacitor Cr and inductors Lr1, Lr2, and the magnetizing inductance of the transformer form a resonant tank circuit which stores the energy oscillating at the resonant frequency. The main HV battery pack 108 may interface with the transformer 2401 via full switches (S9, S10, S11, S12) and a capacitor (C2). The LV battery pack or auxiliary load 114 may be connected to the third winding W3 of the transformer via four pairs of back-to-back switches (S13, S14, S15, S16, S17, S18, S19, S20) and a capacitor (C3). (The two back-to-back switches are applied in a similar manner as back to back switches S15 and S16 described below with respect to FIG. 22).

[000151]During charging the main HV battery pack 108 from the grid, the two back-to-back switches (not shown), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108. During V2G operation, the HV battery pack 108 mainly provides power back to the grid.

[000152]**FIG. 20** illustrates yet another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20215, wherein the first stage 20615 includes a bidirectional AC/DC half-bridge boost converter (S1, S2, L, C1, C2), which is used for rectification and power factor correction (PFC).

[000153]The second stage 22515 includes a resonant multi-output DC/DC converter having three-winding (W1, W2, W3) transformer 2400, 2401, 2451 for integration of two converters. The integrated configuration of PEI 20215 may be achieved via independent three-winding transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitor Cr or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. Capacitor Cr and

inductors Lr1, Lr2, and the magnetizing inductance of the transformer form a resonant tank circuit which stores the energy oscillating at the resonant frequency. The main HV battery pack 108 may interface with the transformer 2401 via full switches (S5, S6) and two capacitors (C3, C4). The LV battery pack or auxiliary load 114 may be connected to the third winding W3 of the transformer via two switches (S7, S8) and two capacitors (C5, C6) followed by a bidirectional buck converter (S9, S10, L2).

[000154] During charging the main HV battery pack 108 from the grid, the two back-to-back switches, which interface the LV battery, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery 108. During V2G operation, the HV battery pack mainly provides power back to the grid.

[000155] **FIG. 21** illustrates still another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20216, wherein the first stage 20216 includes a bidirectional AC/DC full-bridge boost converter (S1, S2, S3, S4, L, C1), which is used for rectification and power factor correction (PFC).

[000156] The second stage 22516 includes a resonant multi-output DC/DC converter having three-winding (W1, W2, W3) transformer 2400, 2401, 2451 for integration of two converters. The integrated configuration of PEI 20216 may be achieved via independent three-winding transformer 2401 and additional resonant inductors (Lr1, Lr2) and resonant capacitors Cr1 and Cr2 or through electromagnetically integrated transformer (EMIT) 2451, where the resonant inductors are built into the magnetic structure of the three-winding transformer 2400. Capacitor Cr and inductors Lr1, Lr2, and the magnetizing inductance of the transformer form a resonant tank circuit which stores the energy oscillating at the resonant frequency. The main HV battery pack 108 may interface with the transformer via full switches (S9, S10, S11, S12) and a capacitor (C2). The LV battery pack or auxiliary load 114 may be connected to the third winding of the transformer via a full bridge (S13 S14, S15, S16) and a capacitor (C3) followed by a bidirectional buck converter (S17, S18, L2).

[000157] During charging the main HV battery pack 108 from the grid, the two back-to-back switches (S7, S8, S9, S10), which interface the LV battery pack 114, may be either deactivated or both batteries may be cross-regulated and charged simultaneously. During propulsion, the LV battery pack 114 may be charged through HV battery pack 108. During V2G operation, the HV battery pack 108 mainly provides power back to the grid.

[000158] **FIG. 22** illustrates another embodiment of an integrated power electronics interface according to the present disclosure, i.e., PEI 20217, that not only requires fewer components as compared to power electronics interfaces of the prior art but also enables multiple operation modes. The first stage 20617 includes a bridgeless interleaved boost PFC converter is used for both G2V and V2G operation. The second stage 22517 includes a bidirectional dual-output CLLC resonant converter that is integrated with an LLC resonant converter. The CLLC converter utilizes the leakage inductances (L_{lk1} and L_{lk2}) of three-winding EMIT (T_1) as the resonant inductors. In order to achieve V2G and H2L charging, resonant capacitors are placed at both primary side (C_{r1} and C_{r2}) and secondary side (C_{r3} and C_{r4}) of EMIT T_1 . Therefore, C_{r1} , C_{r2} and L_{lk1} form a resonant network during G2V operation (analogous to first winding W1 in FIGS. 6-21) while C_{r3} , C_{r4} and L_{lk2} form a resonant network during V2G and H2L operations (analogous to second winding W2 in FIGS. 6-21). Thus, the integrated topology utilizes the active bridge leg (S_9 and S_{10}) at secondary side during both V2G and H2L operations with no need for an additional dc-ac bridge.

[000159] At primary side 22517A and secondary side 22517B of the transformer EMIT T_1 that form the charger portion of the PEI 20217, two half-bridge topologies are used to reduce the number of components. At the low-voltage side, i.e. tertiary winding W3, a full-bridge rectifier is used to reduce the circulating current. In addition, synchronous rectification ($S_{11} \sim S_{12}$) is adopted to minimize the turn-on resistance and conduction losses. A back-to-back switch module (S_{13} and S_{14}) is used for (a) disconnecting LV loads when necessary; and (b) providing protection against reverse polarity.

[000160] *Electromagnetic Integration*

[000161] In conventional chargers the required large resonant inductance of the LLC stage is typically realized using an additional external inductor in series with the primary side of the transformer. Classically, U cores are utilized to design individual inductors and transformers. However, using an EMIT with high leakage inductance can (i) remove the external inductor; (ii) reduce the converter size; and (iii) reduce magnetic component losses. Modifications of magnetic-core shapes and winding structures have been studied to develop EMITs; however, the integration of two large leakage inductances in a three-winding transformer has not been investigated. Since the modification of magnetic-core shapes is expensive, difficult and non-universal, the resonant inductive components of the converter are electromagnetically integrated inside a single three-winding transformer through simple modification of winding arrangements.

[000162]The resonant inductances are integrated into a gapped transformer with a singular arrangement of primary and secondary windings.

[000163]To integrate leakage inductances inside the transformer, the E cores can be employed due to their flexibility to shape leakage flux path (LFP), commercial availability and cost-effectiveness [7, 10]. As illustrated in FIGS. 23A, 23B, 24A, 24B and 24C, according to embodiments of the present disclosure, the equivalent resonant and magnetizing inductances of two intertwined LLC converters can be acquired through a primary winding, a secondary winding, a tertiary winding, and gaps between windings and transformer's cores. E cores are employed due to their flexibility to shape leakage flux path (LFP), commercial availability and cost-effectiveness.

[000164]**FIGS. 23A AND 23B** illustrate one embodiment of EMIT 2451 according to the present disclosure wherein EMIT 2451 includes first EE core 2452 shown on the upper portion and second EE core 2454 on the lower portion. In one embodiment, the EE cores 2452 and 2454 are made from ferrite. Other materials may include, but are not limited to, silicon steel, specialized alloys such as mu-metal, permalloy, supermalloy, amorphous metal, carbonyl iron powdered cores, hydrogen reduced iron powdered cores, ferrite ceramics, and air cores, for laminated and non-laminated cores. The designations of "upper", "upper portion", "lower", and "lower portion" or the like are for convenience of description herein and are not intended to limit the actual orientation of the components in the EMIT 2451 (or EMIT 2451' described with respect to FIGS. 24A, 24B, 24C below) as designed, as manufactured or as installed in a PEV.

[000165]The first EE core 2452 includes a base portion 2453 and a first peripheral or side leg 2452a and a second peripheral or side leg 2452b, both legs projecting orthogonally from the base portion 2453 and peripheral to a central leg 2452c that also projects orthogonally from the base portion 2453, thereby forming the E core configuration.

[000166]Similarly, the second EE core 2454 includes a base portion 2455 and a first peripheral or side leg 2454a and a second peripheral or side leg 2454b, both legs projecting orthogonally from the base portion 2455 and peripheral to a central leg 2454c that also projects orthogonally from the base portion 2455, thereby forming the E core configuration.

[000167]Primary winding 2456 (representing W1 in FIGS. 6-21) is wound around the central leg 2452c in the gaps formed between the central leg 2452c and the peripheral legs 2452a and 2452b located on upper EE core 2452 while the secondary winding 2462 (representing W2 in FIGS. 6-21) is wound around the central leg 2454c in the gaps formed between the central leg 2454c and the peripheral legs 2454a and 2454b located on lower EE core 2454. A peripheral winding gap 2458

is formed between the lower edge of primary winding 2456 on the upper EE core 2452 and the upper edge of secondary winding 2462 on lower EE core 2454. A central gap 2460 is formed between the central leg 2452c and the central leg 2454c. The lower edge of peripheral leg 2452a and the upper edge of peripheral leg 2454a are in direct contact with each other as are the lower edge of peripheral leg 2452b and the upper edge of peripheral leg 2454b also in direct contact with each other.

[000168] Since the depth of the primary winding 2456 is greater than the depth of the secondary winding 2462, a greater portion of the peripheral winding gap 2458 exists within the lower EE core 2454. Therefore, tertiary winding 2464 (representing W3 in FIGS. 6-21) is wound around the central leg 2454c of the lower EE core 2454 and in the greater portion of the peripheral winding gap 2458 existing within the lower EE core 2454 so that both the secondary winding 2462 and the tertiary winding 2464 are wound around the central leg 2454c of the lower EE core 2454 and are adjacent to each other along the central axis defined by the central legs 2452c and 2454c such that tertiary winding 2464 is elevated with respect to secondary winding 2462.

[000169] Leakage flux path (LFP) 2470a is formed in the first peripheral legs 2454a and 2452a, in the upper base portion 2453, in central legs 2452c and 2454c and in the lower base portion 2455 while LFP 2470b is formed in the second peripheral legs 2454b and 2452b, in the upper base portion 2453, in central legs 2452c and 2454c and in the lower base portion 2455. In the base portions 2453 and 2455, the LFP 2470a and 2470b are each perpendicular to the axis of the windings 2456, 2462 and 2464, becoming parallel to the axis of the windings (the central legs 2452c and 2454c effectively defining the central axis of the windings 2456, 2462 and 2464) and passing through the central legs 2452c and 2454c and the central gap 2460 between the separated windings 2456 and 2464. This trajectory of LFP substantially contributes to the leakage inductance. In fact, the air gap 2460 between the central legs 2452c and 2454c of the two E cores 2452 and 2454 and the gaps 2458 and 2460 amongst the three windings 2456, 2462 and 2464 can be adjusted to precisely set the leakage and magnetizing inductances. Therefore, large leakage and magnetizing inductances can be achieved, although the variation of gap between two E cores has less influence on the leakage inductance in comparison to the gaps among three windings. The air gap between E cores significantly reduces the saturation effect. Furthermore, the gaps 2458 and 2460 among the three windings 2456, 2462 and 2464 helps to increase the voltage isolation.

[000170] FIGS. 24A, 24B and 24C illustrate an alternate embodiment of EMIT 2451 of FIGS. 23A and 23B. More particularly, EMIT 2451' illustrated in FIGS. 24A and 24B is identical to EMIT

2451 except that the length of peripheral legs 2452a and 2452b of upper E core 2452' is equal to the length of central leg 2452c and the length of peripheral legs 2454a and 2455b of lower E core 2454' is equal to the length of central leg 2454c.

[000171] Accordingly, a peripheral gap 2460a is formed between the lower edge of peripheral leg 2452a and the upper edge of peripheral leg 2454a while a peripheral gap 2460b is formed between the lower edge of peripheral leg 2452b and the upper edge of peripheral leg 2454b. Thus, the upper E core 2452 and the lower E core 2454 are spaced apart from each other by the width of central gap 2460 and the width of peripheral gaps 2460a and 2460b.

[000172] In addition, secondary winding 2462' is now formed concentrically around tertiary winding 2464' and both secondary winding 2462' and tertiary winding 2464' are formed concentrically around central leg 2454c of the lower E core 2454'.

[000173] FIG. 24C illustrates the EMIT 2451' showing (1) center leg of core, (2) side leg of core, (3) primary winding (N_p), (4) secondary winding #1 (N_{s1}), (5) secondary winding #2 (N_{s2}), (6) core gap (l_g), (7) winding gap #1 (L_{w1}), and (8) winding gap #2 (L_{w2}).

[000174] In a similar manner, leakage flux path (LFP) 2470a is formed in the first peripheral legs 2454a and 2452a, in the upper base portion 2453, in central legs 2452c and 2454c and in the lower base portion 2455 of the upper E core 2452' and lower E core 2454', as applicable, while LFP 2470b is formed in the second peripheral legs 2454b and 2452b, in the upper base portion 2453, in central legs 2452c and 2454c and in the lower base portion 2455 of the upper E core 2452' and lower E core 2454', as applicable. In the base portions 2453 and 2455, the LFP 2470a and 2470b are each perpendicular to the axis of the windings 2456, 2462 and 2464, becoming parallel to the axis of the windings (the central legs 2452c and 2454c effectively defining the central axis of the windings 2456, 2462 and 2464) and passing through the central legs 2452c and 2454c and the central gap 2460 between the separated windings 2456 and 2464.

[000175] Again, this trajectory of LFP substantially contributes to the leakage inductance. In fact, in this configuration, the gap between two E cores and windings displacement can easily be adjusted to set the leakage and magnetization inductances precisely. Therefore, large leakage and magnetization inductances can be achieved; although the variation of gap has minimal influence on the leakage inductance in comparison to the winding displacement.

[000176] Table I demonstrates sample design parameters of the three-winding EMIT for the integrated onboard charger and power electronic interface 20217 of FIGS. 22 and EMIT 2451 illustrated in FIGS. 23A and 23B.

[000177]It should be noted that the design parameters disclosed herein are applied as an example of only one specific embodiment and are in no way intended to limit this embodiment or other embodiments of the present disclosure to these design parameters.

[000178]The transformer is simulated by the finite element analysis (FEA) software MagNet. The transformer core size is calculated based on switching frequency, voltage and power level of the converter. The 3F3 from Ferroxcube Corporation (New Taipei City, Taiwan) with low loss (up to 700kHz) is selected as the ferrite E core. An air gap is generated between the central legs of two E cores. The Litz wire size is determined considering the current rating and skin effect. Since core loss constitutes to the majority of loss in the transformer, winding turns are increased to reduce core loss through increasing the magnetic flux density. Nonetheless, the winding area around transformer's bobbin causes limitation on the winding turns.

Table I. Example of Design Parameters of the Three-Winding EMIT.

Parameters
Power rating (kW)
Nominal input voltage (V)
Nominal HV voltage (V)
Nominal LV voltage (V)
Primary winding turns
Secondary winding turns
Tertiary winding turns
Core shape
Core material
Primary wire size (AWG)
First secondary wire size (AWG)
Second secondary wire size (AWG)
Gap between cores (mm)
Equivalent primary leakage inductance (μH)
Magnetizing inductance (μH)

TABLE I is not necessarily intended to represent an exclusive list of design parameters and others may be included by those skilled in the art if necessary.

[000179]OPERATION MODE ANALYSIS

[000180]In conjunction with FIG. 22, FIG. 25 illustrates dual-output CLLLC resonant converter 22517C formed within the primary side 22517A and secondary side 22517B of secondary stage 22517 of PEI 20217. The dual-output CLLLC resonant converter 22517C is the integration of a

half-bridge CLLC resonant converter intertwined with a half-bridge LLC converter, and for this reason, the half-bridge CLLC resonant converter and the half-bridge LLC converter is not separately identified by component numbers. Rather, the half-bridge CLLC resonant converter includes the primary leakage inductance (L_{lk1}), secondary leakage inductance (L_{lk2}) and magnetizing inductance (L_m) of transformer (T_1), two bridge legs ($S_7 \sim S_{10}$), and four split resonant capacitors ($C_{r1} \sim C_{r4}$). On the other hand, the half-bridge LLC resonant converter includes the secondary leakage inductance (L_{lk2}) and magnetizing inductance (L_m) of transformer (T_1), one bridge leg (S_9 and S_{10}), one full-bridge synchronized rectifier ($S_{11} \sim S_{14}$), and two split resonant capacitors (C_{r3} and C_{r4}).

[000181] Alternatively, the dual-output CLLC resonant converter 22517C may be the integration of a half-bridge CLLC resonant converter intertwined with a full-bridge LLC converter.

[000182] *HV Traction Battery Charging (G2V)*

[000183] **FIG. 25** illustrates the circuit topology of the half-bridge CLLC resonant converter during charging HV traction battery 108. The synchronized rectification at tertiary side W3 is disabled and the series-connected back-to-back switches (S_{15} and S_{16}) are turned off to disconnect the LV DC loads 114.

[000184] At the primary side 22517A, V_{in} can be considered as a constant voltage due to the large dc capacitance C_{dc1} . Two square-wave voltage sources with 180° phase shift (v_{in} and $-v_{in}$) are generated by the bridge leg (S_7 and S_8). All the component values at secondary side are referred to the primary side with prime symbol. At the secondary side 22517B, V_{HV} can be considered as a constant voltage due to the large C_{dc2} . $V'_{HV} = nV_{HV}$, and $n = N_1:N_2$ is the transformer turns ratio. Two square-wave voltage sources with 180° phase shift (v'_{HV} and $-v'_{HV}$) are generated by the diode rectifier (body diodes of S_9 and S_{10}).

[000185] Hence, the nonlinear non-sinusoidal equivalent circuit model 22517A1 referred to the primary side 22517A can be presented as shown in **FIG. 26A**.

[000186] Using the first harmonic approximation (FHA), only the first-order harmonic components of voltage and current contribute to the power transfer.

[000187] As shown in **FIG. 26B**, the equivalent linear sinusoidal circuit model 22517A2 is derived. The split resonant capacitors are connected in parallel in ac domain, yielding $C_{rs1} = C_{r1} + C_{r2}$ and

$C'_{rs2} = C'_{r3} + C'_{r4} = (C_{r3} + C_{r4})/n^2$. The first-order harmonic of v_{in} , which is a sinusoidal voltage at the input of resonant network, can be represented as

$$\tilde{v}_{in} = \frac{4}{\pi} \frac{V_{in}}{2} \sin(\omega_r t) \quad (1)$$

[000189] On the other hand, the first-order harmonic of v'_{HV} , which is a sinusoidal voltage at the output of resonant network, can be expressed as

$$\tilde{v}'_{HV} = \frac{4}{\pi} \frac{V'_{HV}}{2} \sin(\omega_r t + \theta) = \frac{4n}{\pi} \frac{V_{HV}}{2} \sin(\omega_r t + \theta) \quad (2)$$

where θ is the phase shift with respect to the first-order component of input voltage.

[000190] As a consequence of FHA assumption, the resonant network current ($\tilde{i}'_{HV}$) will be sinusoidal, with a phase shift with respect to the first-order component of the input voltage. $\tilde{i}'_{HV}$ equals to the sum of sinusoidal currents ($\tilde{i}'_{c3} + \tilde{i}'_{c4}$) passing through C'_{r3} and C'_{r4} . Since the average of $|\tilde{i}'_{c3}|$ or $|\tilde{i}'_{c4}|$ is the output current I'_{HV} , $\tilde{i}'_{HV}$ can be presented as

$$\tilde{i}'_{HV} = \pi I'_{HV} \sin(\omega_r t + \theta) = \frac{\pi}{n} I_{HV} \sin(\omega_r t + \theta) \quad (3)$$

[000192] Thus, the ac equivalent load in linear sinusoidal circuit model can be determined as,

$$R'_{e,HV} = \frac{\tilde{v}'_{HV}}{\tilde{i}'_{HV}} = \frac{2n^2}{\pi^2} R_{HV} \quad (4)$$

[000194] The transfer function of the resonant converter can be derived from the impedance network,

$$H_{G2V}(s) = \frac{\tilde{v}'_{HV}}{\tilde{v}_{in}} = \frac{n\tilde{v}_{HV}}{\tilde{v}_{in}} = \frac{Z_{3,G2V}(s)}{Z_{1,G2V}(s) + Z_{3,G2V}(s)} \cdot \frac{R'_{e,HV}}{Z_{2,G2V}(s)} \quad (5)$$

[000195]

Where,

$$Z_{1,G2V}(s) = sL_{lk1} + \frac{1}{sC_{rs1}} \quad (6)$$

$$Z_{2,G2V}(s) = sL'_{lk2} + \frac{1}{sC'_{rs2}} + R'_{e,HV} \quad (7)$$

$$Z_{3,G2V}(s) = Z_{2,G2V}(s) \parallel sL_m \quad (8)$$

[000197] Therefore, using the ac equivalent circuit in Fig. 26B, the voltage gain, $M(s)$, can be represented as

$$M_{G2V}(s) = |H_{G2V}(s)|$$

$$= \left| \frac{j(\frac{\omega}{\omega_0})(\frac{\omega}{\omega'_0})^2(m-1)}{\left\{ \left[(\frac{\omega}{\omega_0})^2 + (\frac{\omega}{\omega'_0})^2 \right] m - (\frac{\omega}{\omega_0})^2 (\frac{\omega}{\omega'_0})^2 (2m-1) - 1 \right\} Q + j(\frac{\omega}{\omega_0})(\frac{\omega}{\omega'_0})^2 m - (\frac{\omega}{\omega'_0})(\frac{\omega_0}{\omega'_0})} \right| \quad (9)$$

Where, the primary total inductance is $L_p = L_m + L_{lk1}$, the ratio of primary total inductance to primary leakage inductance is $m = \frac{L_p}{L_{lk1}}$, the equivalent ac output resistor referred to primary side is

$$R'_{e,HV} = \frac{2n^2}{\pi^2} R_{HV}, \text{ the quality factor is } Q = \sqrt{\frac{L_{lk1}}{C_{rs1}}} \frac{1}{R'_{e,HV}}, \text{ the angular resonance frequency of}$$

resonant network at primary side is $\omega_0 = \frac{1}{\sqrt{L_{lk1} C_{rs1}}}$, and the angular resonance frequency of resonant

network at secondary side is $\omega'_0 = \frac{1}{\sqrt{L'_{lk2} C'_{rs2}}}$.

[000198] There are two resonant frequencies, $f_0 = \omega_0/2\pi$, the resonance frequency of resonant network at primary side, and $f'_0 = \omega'_0/2\pi$, the resonance frequency of resonant network at secondary side, respectively. In addition to the two aforementioned resonant frequencies, two series resonance frequencies, $f_{r1,G2V}$ and $f_{r2,G2V}$, can be determined, in which the voltage gain in Eq. (6) becomes independent of load condition,

$$f_{r1,G2V} = \frac{1}{2\pi\sqrt{L_{lk1} C_{rs1}}} \sqrt{\frac{(p^2 + 1)m + \sqrt{(p^2 + 1)^2 m^2 - 4p^2(2m-1)}}{2p^2(2m-1)}} \quad (14)$$

$$f_{r2,G2V} = \frac{1}{2\pi\sqrt{L_{lk1} C_{rs1}}} \sqrt{\frac{(p^2 + 1)m - \sqrt{(p^2 + 1)^2 m^2 - 4p^2(2m-1)}}{2p^2(2m-1)}} \quad (15)$$

$$p = \frac{f_0}{f'_0} = \sqrt{\frac{C'_{rs2}}{C_{rs1}}} \quad (16)$$

[000200] Where, p is the resonant frequency ratio, which is the ratio of the resonance frequency of primary network to the resonance frequency of secondary network. At series resonant frequencies, regardless of the load condition, the voltage gain would become

$$M_{G2V}(s) = \frac{\left(\frac{f}{f_0}\right)^2(m-1)}{\left(\frac{f}{f_0}\right)^2 m - 1} \bigg|_{f=f_{r1,G2V}, f_{r2,G2V}} \quad (13)$$

[000202] FIGS. 27A, 27B, 27C illustrate the voltage gain curves (nV_{HV}/V_{in}) versus frequency (kHz) at different quality factors Q and resonant frequency ratios $f_{r1,G2V}$, $f_{r2,G2V}$. To ensure converter operation in the inductive region to acquire zero-voltage switching, the switching frequency should be selected in the vicinity of $f_{r1,G2V}$.

[000203] As observed from FIGS. 27A- 27C, similar to the LLC resonant converter, the gain characteristics of CLLLC converter 22517C is almost independent of the load when the switching frequency is around the resonant frequency ($f_{r1,G2V}$). However, in a CLLLC converter, $f_{r1,G2V}$ is not only dependent on the LC network at primary side ($L_{lk1}C_{rs1}$), but also the LC network at secondary side ($L'_{lk2}C'_{rs2}$).

[000204] Assuming $L_{lk1} = L'_{lk2}$, for $C_{rs1} = C'_{rs2}$, as shown in Fig. 7(a), the frequencies of LC networks at primary and secondary sides are equal ($f_0 = f'_0$). $f_{r1,G2V}$ equals to the resonant frequencies of the LC network at both sides ($f_{r1,G2V} = f_0 = f'_0$). Hence, a unity gain can be obtained at $f_{r1,G2V}$, regardless of the ratio of primary total inductance to primary leakage inductance (m).

[000205] For $C_{rs1} \neq C'_{rs2}$, $f_{r1,G2V}$ resides between f_0 and f'_0 . Decreasing either f_0 or f'_0 will reduce $f_{r1,G2V}$. In addition, the gain at $f_{r1,G2V}$ is no longer a unity gain due to the fact that $f_{r1,G2V} \neq f_0 \neq f'_0$. The gain at $f_{r1,G2V}$ is higher than unity for $f_0 > f'_0$; and, it is lower than unity for $f_0 < f'_0$.

[000206] For a half-bridge CLLLC converter, a relatively large m is necessary for efficient operation. A small m will significantly increase the magnetizing current that has no use for power transfer but increases the resonant losses. Since the resonant current of a half-bridge converter is two times of the resonant current of a full-bridge converter, a large m is necessary to reduce the resonant losses. At heavy load condition, reducing m has limited effect on the maximum gain. At light load condition, reducing m may increase the maximum gain at frequencies lower than $f_{r1,G2V}$, and in turn increases the converter's capability of regulating wide output voltage ranges. However, the converter needs to operate in region 1 ($f_s > f_{r1,G2V}$) and consequently the switching frequency should be slightly higher than $f_{r1,G2V}$ for efficient operation. Thus, reducing m is not an effective and efficient way to increase capability of regulating wide output voltage ranges. In fact, with a wide input voltage range, the converter can handle a wide output voltage range at a fixed switching frequency close to $f_{r1,G2V}$.

[000207] *V2G Operation*

[000208] **FIG. 28** illustrates the dual-output CLLLC resonant converter 22517C during V2G operation, wherein the full-bridge rectifier at tertiary side W3 is still disabled by turning off S_{15} and S_{16} . The half-bridge CLLLC resonant converter operates in a reversed direction. V_{HV} at secondary side 22517B is considered as the input while V_{in} at primary side is the output. S_9 and S_{10} operate as a bridge leg while the body diodes of S_7 and S_8 serve as a rectifier. The half-bridge topology uses the same CLLLC resonant network; however, the network impedance, voltage gain and resonant frequency are different from those during G2V operation.

[000209] **FIG. 29A** illustrates the nonlinear non-sinusoidal equivalent circuit model 22517B1 referred to the secondary side 22517B.

[000210] **FIG. 29B** illustrates that the equivalent linear sinusoidal circuit model 22517B2 can be derived using the FHA, where $C'_{rs1} = C'_{r1} + C'_{r2} = n^2(C_{r1} + C_{r2})$ and $C_{rs2} = C_{r3} + C_{r4}$. Using the similar approach for G2V operation, the equivalent load in linear sinusoidal circuit model for V2G operation can be expressed as

$$R'_{e,in} = \frac{\tilde{v}'_{in}}{\tilde{i}'_{in}} = \frac{2}{n^2 \pi^2} R_{in} \quad (17)$$

[000212] Therefore, the voltage gain, $M(s)$, for V2G operation can be represented as

$$M_{V2G}(s) = |H_{V2G}(s)|$$

$$= \left| \frac{j(\frac{\omega}{\omega_0})(\frac{\omega}{\omega'_0})^2(m'-1)}{\left\{ \left[\left(\frac{\omega}{\omega_0}\right)^2 + \left(\frac{\omega}{\omega'_0}\right)^2 \right] m' - \left(\frac{\omega}{\omega_0}\right)^2 \left(\frac{\omega}{\omega'_0}\right)^2 (2m'-1) - 1 \right\} Q' + j(\frac{\omega}{\omega_0})(\frac{\omega}{\omega'_0})^2 m' - \left(\frac{\omega}{\omega'_0}\right)(\frac{\omega_0}{\omega'_0})} \right| \quad (18)$$

Where, the secondary total inductance is $L_s = L'_m + L_{lk2}$, the ratio of secondary total inductance to secondary leakage inductance is $m' = \frac{L_s}{L_{lk2}}$, the equivalent ac output resistor referred to secondary

side is $R'_{e,in} = \frac{2}{n^2 \pi^2} R_{in}$, the quality factor is $Q' = \sqrt{\frac{L_{lk2}}{C_{rs2}}} \frac{1}{R'_{e,in}}$, the angular resonance frequency of

resonant network at secondary side is $\omega_0 = \frac{1}{\sqrt{L_{lk2} C_{rs2}}}$, and the angular resonance frequency of

resonant network at primary side is $\omega'_0 = \frac{1}{\sqrt{L_{lk2} C'_{rs1}}}$.

[000213] The two resonant frequencies can be obtained as

$$f_{r1,V2G} = \frac{1}{2\pi\sqrt{L_{lk2}C_{rs2}}} \sqrt{\frac{(p^2+1)m' + \sqrt{(p^2+1)^2 m'^2 - 4p^2(2m'-1)}}{2(2m'-1)}} \quad (19)$$

$$f_{r2,V2G} = \frac{1}{2\pi\sqrt{L_{lk2}C_{rs2}}} \sqrt{\frac{(p^2+1)m' - \sqrt{(p^2+1)^2 m'^2 - 4p^2(2m'-1)}}{2(2m'-1)}} \quad (20)$$

[000215] To ensure the converter operating in the inductive region for zero-voltage switching, the switching frequency needs to be close to $f_{r1,V2G}$.

[000216] *HV-to-LV Charging (H2L)*

[000217] **FIG. 30** illustrates that, during H2L operation, the grid is disconnected ($V_{in} = 0$) with the PFC stage. MOSFETs of the half-bridge converter at primary side (S_7 and S_8) 22517A are turned off. The body diodes of S_7 and S_8 will also be turned off when the dc link voltage (V_{in}) reaches its maximum value (in this case, 600V). The series-connected back-to-back switches (S_{15} and S_{16}) are turned on to enable the full-bridge rectifier at tertiary side 22517C' (W3). The full-bridge synchronized rectification ($S_{11} \sim S_{14}$) is used to reduce the conduction losses. Hence, a half-bridge LLC (L_{lk2} , L_m , C_{r3} , C_{r4}) resonant converter delivers the power from HV battery pack 108 to LV loads 114.

[000218] The nonlinear non-sinusoidal equivalent circuit model 22517B1 referred to the secondary side 22517B is presented in **FIG. 31A**, wherein four square-wave voltage sources ($\tilde{v}'_{LV}$) with 180° phase shift are generated by the synchronized rectification ($S_{11} \sim S_{14}$).

[000219] Referring to **FIG. 31B**, using the first harmonic approximation (FHA), the equivalent linear sinusoidal circuit model 22517B2 can be obtained. Therefore, the first-order harmonic of $\tilde{v}'_{LV}$ can be expressed as

$$\tilde{v}'_{LV} = \frac{4}{\pi} V'_{LV} \sin(\omega_r t + \varphi) = \frac{4n}{\pi} V_{LV} \sin(\omega_r t + \varphi) \quad (21)$$

[000220] Since the average of $|\tilde{i}'_{LV}|$ is the output current I'_{LV} , $\tilde{i}'_{LV}$ is presented as

$$\tilde{i}'_{LV} = \frac{\pi}{2} I'_{LV} \sin(\omega_r t + \varphi) = \frac{\pi}{2n} I_{LV} \sin(\omega_r t + \varphi) \quad (22)$$

[000222] Hence, the ac equivalent load in linear sinusoidal circuit model can be expressed as,

$$R'_{e,LV} = \frac{\tilde{v}'_{LV}}{\tilde{i}'_{LV}} = \frac{8n^2}{\pi^2} R_{LV} \quad (23)$$

[000224] Since the topology operates as a half-bridge LLC converter during H2L operation, the transfer function during H2L operation, the gain characteristics and resonant frequency are similar to those of an LLC converter.

[000225] EXPERIMENTAL RESULTS

[000226] **FIG. 32** illustrates the measured current and voltage waveforms of the ac-dc interleaved PFC converter during G2V operation at 500W.

[000227] The dc-link voltage V_{DC} , which is the input voltage of the dc-dc resonant stage could be variable from 400V to 600V, depending on the grid voltage. The HV battery 108 voltage output can be variable from 200V to 420V, and the LV load output 114 is variable from 8V to 14V. The resonant frequencies of LC networks at primary and secondary sides (f_0 and f'_0) are set to 190kHz. The dual-output dc-dc resonant converter has three operation modes: (1) G2V; (2) V2G; (3) H2L.

[000228] *Converter Performance in G2V Charging Operation*

[000229] As explained above, during G2V, the LV side (tertiary side) is disabled. The turn ratio of primary to secondary winding is set at 1.5:1. In order to reduce the resonant current, a relatively high ratio of total primary inductance to primary leakage inductance (m) is required. A 5.6 ratio ($m=5.6$) is acquired by adjusting the transformer air-gaps. The air-gap between the central legs of EE cores is set to 0.6mm, and the air-gap between the primary winding and the secondary winding is set to 3mm. At primary side, either C_{r1} or C_{r2} consists of four parallel film capacitors, each 1nF. At secondary side, C_{r3} or C_{r4} consists of three parallel film capacitors, each 3.3nF.

[000230] To ensure low conduction losses, 1200V CREE SiC MOSFETs with low turn-on resistance are selected at both primary and secondary sides. Experiments show that the secondary side rectification using body diodes of MOSFETs significantly reduces the efficiency due to the long reverse recovery time of SiC MOSFETs body diodes. Therefore, either additional diodes with better reverse recovery performances should be paralleled with MOSFETs, or alternatively in our design synchronous rectification is used to turn on MOSFETs at secondary side for efficient rectification.

[000231] During HV battery charging, the switches S_1 and S_2 serve as a high-frequency inverter while S_3 and S_4 serve as a rectifier bridge.

[000232] **FIG. 33** illustrates the measured current and voltage waveforms of the converter during G2V operation at full load condition (3.3kW).

[000233] To ensure the converter operation in region 1 and acquire a high gain, the switching frequency is set slightly higher than $f_{r1,G2V}$.

[000234] *Converter Performance in V2G Mode*

[000235] Since $C_{rs1} = C'_{rs2}$, the resonant frequency of primary side LC network would be equal to the resonant frequency of secondary side LC network ($f_0 = f'_0$). Therefore, the resonant frequency and gain characteristics are similar to those in G2V mode. The switches S_3 and S_4 serve as a high-frequency inverter while S_1 and S_2 serve as a rectifier bridge.

[000236] **FIG. 34** demonstrates the measured current and voltage waveforms of the converter during V2G operation at 60% of full load condition (3.3kW).

[000237] *Converter Performance in G2V Mode*

[000238] During H2L, the primary side of the dual-output dc-dc converter is disabled. The switches S_3 and S_4 serve as a high-frequency inverter while $S_{11} \sim S_{14}$ serve as a synchronous rectifier bridge. The converter uses the LLC resonant network at secondary side consisting of C_{r3} , C_{r4} , L_{lk2} and L'_m . The turns-ratio of secondary to tertiary winding is set to 20:1.

[000239] To increase the efficiency of synchronous rectification at tertiary side, five 60V/300A Infineon Si MOSFETs with very low turn-on resistance are connected in parallel and share one gating signal. 1 μ s deadbands are set in gating signals to ensure that a MOSFET is turned on after its body diode conducts and MOSFET is turned off before its body diode turns off. Large copper bars are used for external connection to reduce the conduction losses. The measured current and voltage waveforms of the converter during H2L operation at full load condition (1kW) are depicted in FIG. 35.

[000240] The embodiments of the present disclosure as described above present a unique dual-output integrated and isolated onboard charger topology for charging PEV's HV traction battery, LV dc loads and V2G application. The second stage of the power electronics interface presents the integration of a half-bridge CLLC converter intertwined with a half-bridge LLC converter with minimum number of passive and active components. The inductive components are integrated into a single three-winding electromagnetically integrated transformer, which leads to less

size/weight, less saturation effect, less magnetizing losses, and higher voltage isolation. The half-bridge CLLC converter operates during G2V and V2G operation while the half-bridge LLC converter operates during H2L operation. In comparison to conventional stand-alone converters, the integrated topology with small number of components reduces the size, weight and cost of the onboard PEI. Modeling, analyses and design guidelines are presented. Experimental results are presented for validation of the charging modes.

[000241] While several embodiments and methodologies of the present disclosure have been described and shown in the drawings, it is not intended that the present disclosure be limited thereto, as it is intended that the present disclosure be as broad in scope as the art will allow and that the specification be read likewise. Therefore, the above description should not be construed as limiting, but merely as exemplifications of particular embodiments and methodologies. Those skilled in the art will envision other modifications within the scope of the claims appended hereto.

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CLAIMS

What is claimed is:

1. An integrated power electronics interface comprising:
a first stage power factor correction AC-DC converter; and
a second stage integrated DC-DC converter including:
a dual-output CLLLC resonant converter; and
a LLC converter.
2. The integrated power electronic interface according to claim 1, wherein the dual-output CLLLC resonant converter is intertwined with the LLC converter.
3. The integrated power electronic interface according to claim 1, wherein the LLC converter is one of a half-bridge LLC converter or a full-bridge LLC converter.
4. The integrated power electronic interface according to claim 2, wherein the dual-output CLLLC resonant converter is intertwined with a half-bridge LLC converter.
5. The integrated power electronic interface according to claim 2, wherein the dual-output CLLLC resonant converter is intertwined with a full-bridge LLC converter.
6. An integrated power electronics interface comprising:
a first stage, the first stage including:
a power factor correction AC-DC converter; and
a DC/DC converter; and
a second stage integrated DC-DC converter.
7. The integrated power electronics interface according to claim 6, wherein the power factor correction AC-DC converter of the first stage is a diode bridge.
8. The integrated power electronics interface according to claim 7, wherein the diode bridge is one of a full-bridge diode bridge or a half-bridge diode bridge.

9. The integrated power electronics interface according to claim 6, wherein the first stage DC-DC converter is selected from the group consisting of:
- (a) a single-leg boost converter;
 - (b) a single-leg buck-boost converter;
 - (c) an interleaved boost converter;
 - (d) an interleaved buck-boost converter;
 - (e) a single-ended primary-inductor converter (SEPIC) converter;
 - (f) a bidirectional half bridge converter;
 - (g) a bidirectional full bridge converter;
 - (h) a bidirectional totem pole converter;
 - (m) a bidirectional interleaved half-bridge converter;
 - (n) a bidirectional interleaved full-bridge converter;
 - (l) a bridgeless boost PFC converter;
 - (l) an interleaved bridgeless boost PFC converter;
 - (i) a bridgeless interleaved resonant PFC boost converter; and
 - (j) a phase shifted semi-bridgeless converter.
10. The integrated power electronics interface according to claim 6, wherein the second stage integrated DC-DC converter includes a three-winding transformer.
11. The integrated power electronics interface according to claim 10, wherein the three-winding transformer is one of a transformer configured with individual, discrete inductors and an electromagnetically integrated transformer.
12. The integrated power electronics interface according to claim 10, wherein the electromagnetically integrated transformer includes:
- a first EE core defining a base portion, a central leg and first and second peripheral legs;
 - a second EE core defining a base portion, a central leg and first and second peripheral legs;
 - a primary winding wound around the central leg of the first EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the first EE core;

a secondary winding wound around the central leg of the second EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the second EE core; and

a tertiary winding wound around the central leg of the second EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the second EE core.

13. The integrated power electronics interface according to claim 12, wherein edges of the legs of the first EE core align with edges of the legs of the second EE core and the secondary winding and tertiary winding are adjacent to one another along an axis defined by the central leg of the first EE core and the central leg of the second EE core.

14. The integrated power electronics interface according to claim 12, wherein edges of the legs of the first EE core align with edges of the legs of the second EE core and the secondary winding is formed concentrically around the tertiary winding and both the secondary winding and the tertiary winding are formed concentrically around the central leg of the second EE core.

15. The integrated power electronics interface according to claim 13, wherein a peripheral winding gap is formed between a lower edge of the primary winding on the first EE core and an upper edge of the secondary winding on the second EE core.

16. The integrated power electronics interface according to claim 13, wherein a central gap is formed between the central leg of the first EE core and the central leg of the second EE core.

17. A three-winding electromagnetically integrated transformer for an integrated power electronics interface comprising:

a first EE core defining a base portion, a central leg and first and second peripheral legs;

a second EE core defining a base portion, a central leg and first and second peripheral legs;

a primary winding wound around the central leg of the first EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the first EE core;

a secondary winding wound around the central leg of the second EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the second EE core; and

a tertiary winding wound around the central leg of the second EE core between the first peripheral leg and the central leg and between the second peripheral leg and the central leg of the second EE core.

18. The three-winding electromagnetically integrated transformer according to claim 17, wherein edges of the legs of the first EE core align with edges of the legs of the second EE core and the secondary winding and tertiary winding are adjacent to one another along an axis defined by the central leg of the first EE core and the central leg of the second EE core.

19. The three-winding electromagnetically integrated transformer according to claim 17, wherein edges of the legs of the first EE core align with edges of the legs of the second EE core and the secondary winding is formed concentrically around the tertiary winding and both the secondary winding and the tertiary winding are formed concentrically around the central leg of the second EE core.

20. The three-winding electromagnetically integrated transformer according to claim 17, wherein a peripheral winding gap is formed between a lower edge of the primary winding on the first EE core and an upper edge of the secondary winding on the second EE core.

21. The three-winding electromagnetically integrated transformer according to claim 17, wherein a central gap is formed between the central leg of the first EE core and the central leg of the second EE core.

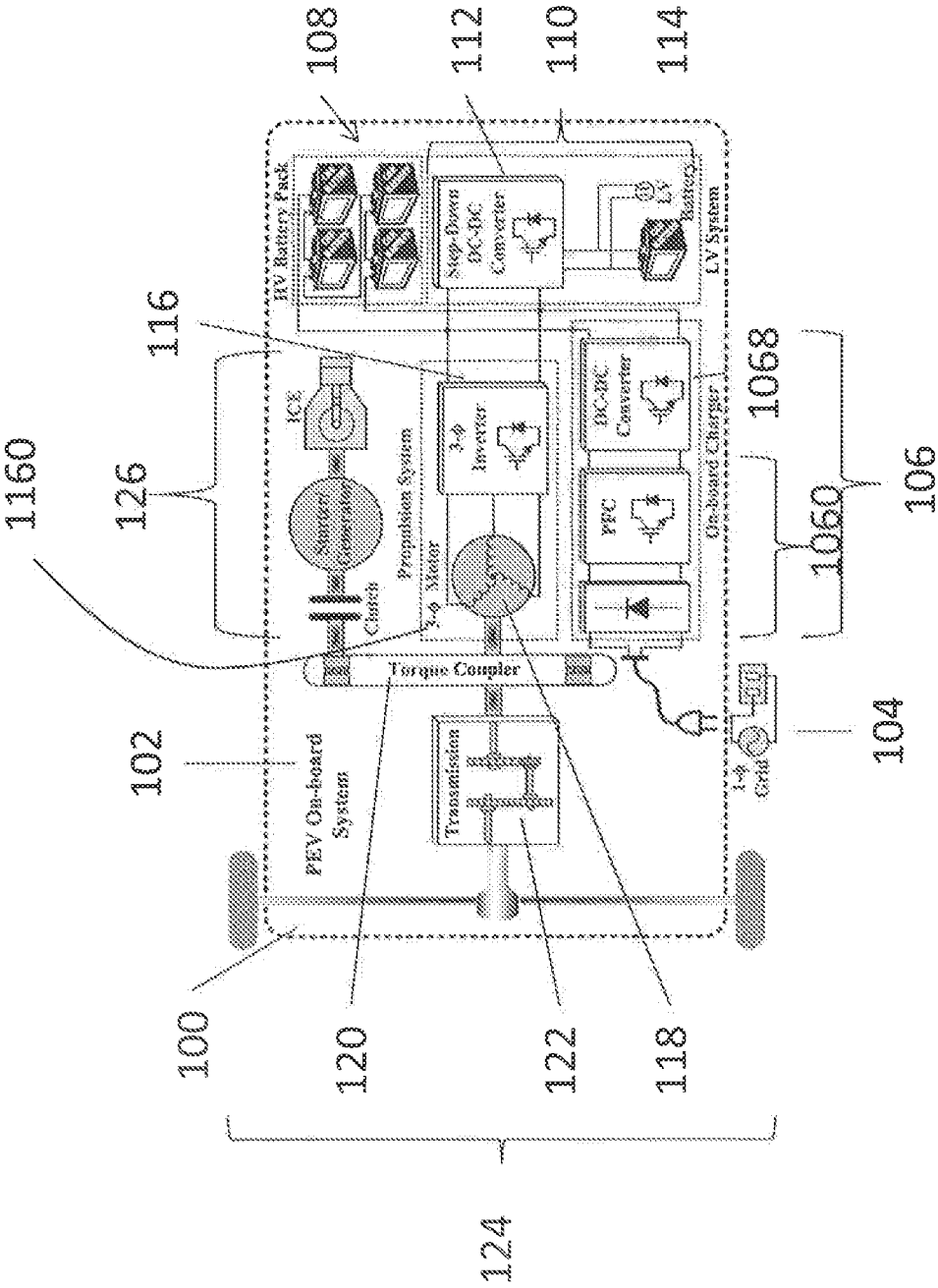


FIG. 1
PRIOR ART

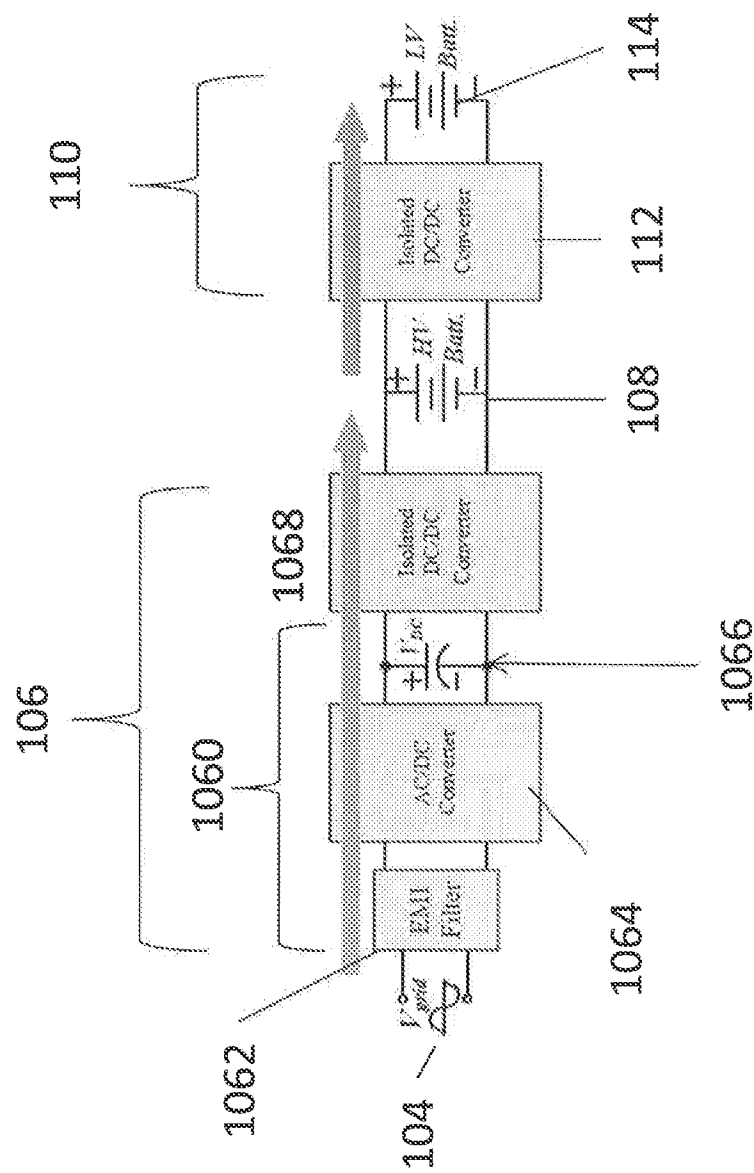


FIG. 2
PRIOR ART

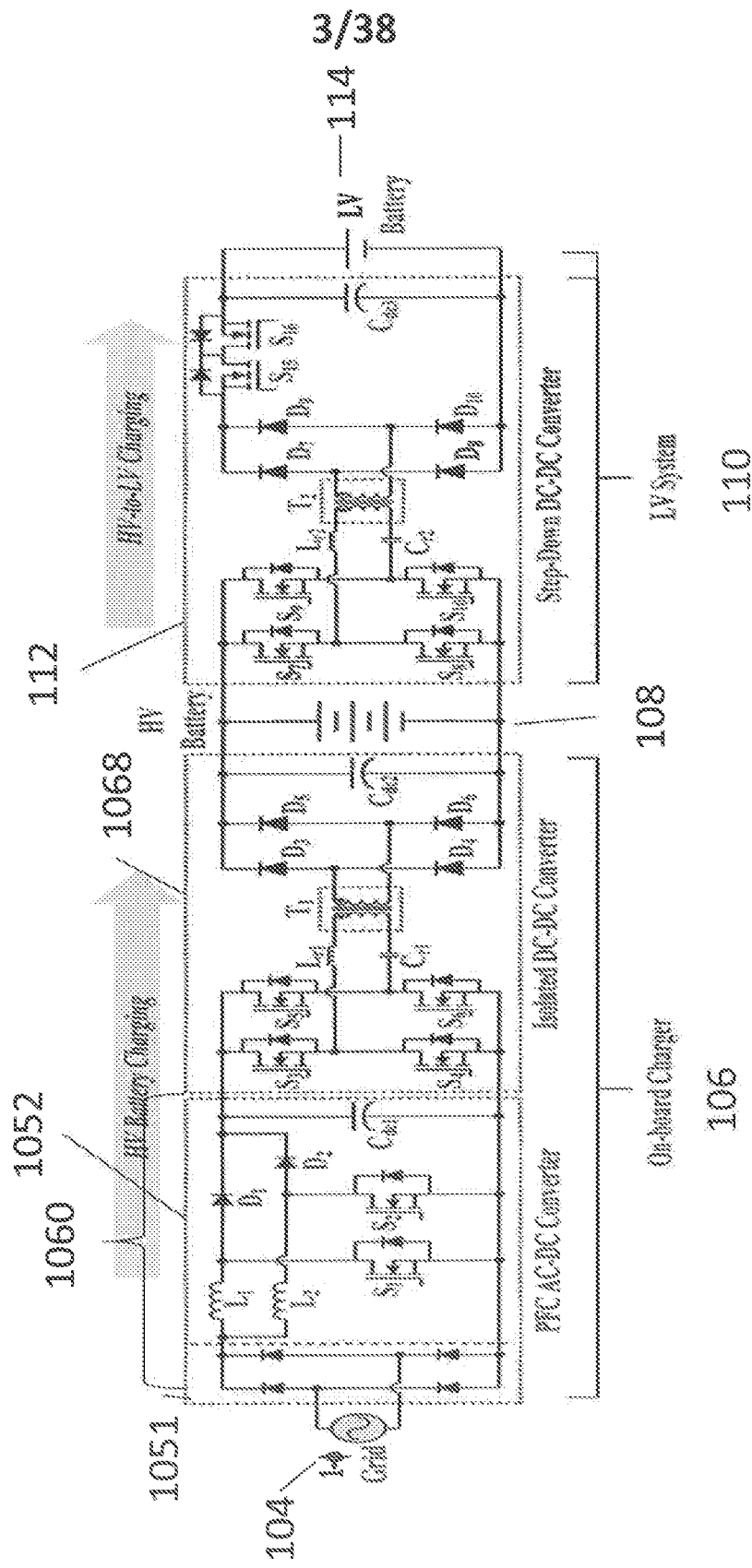
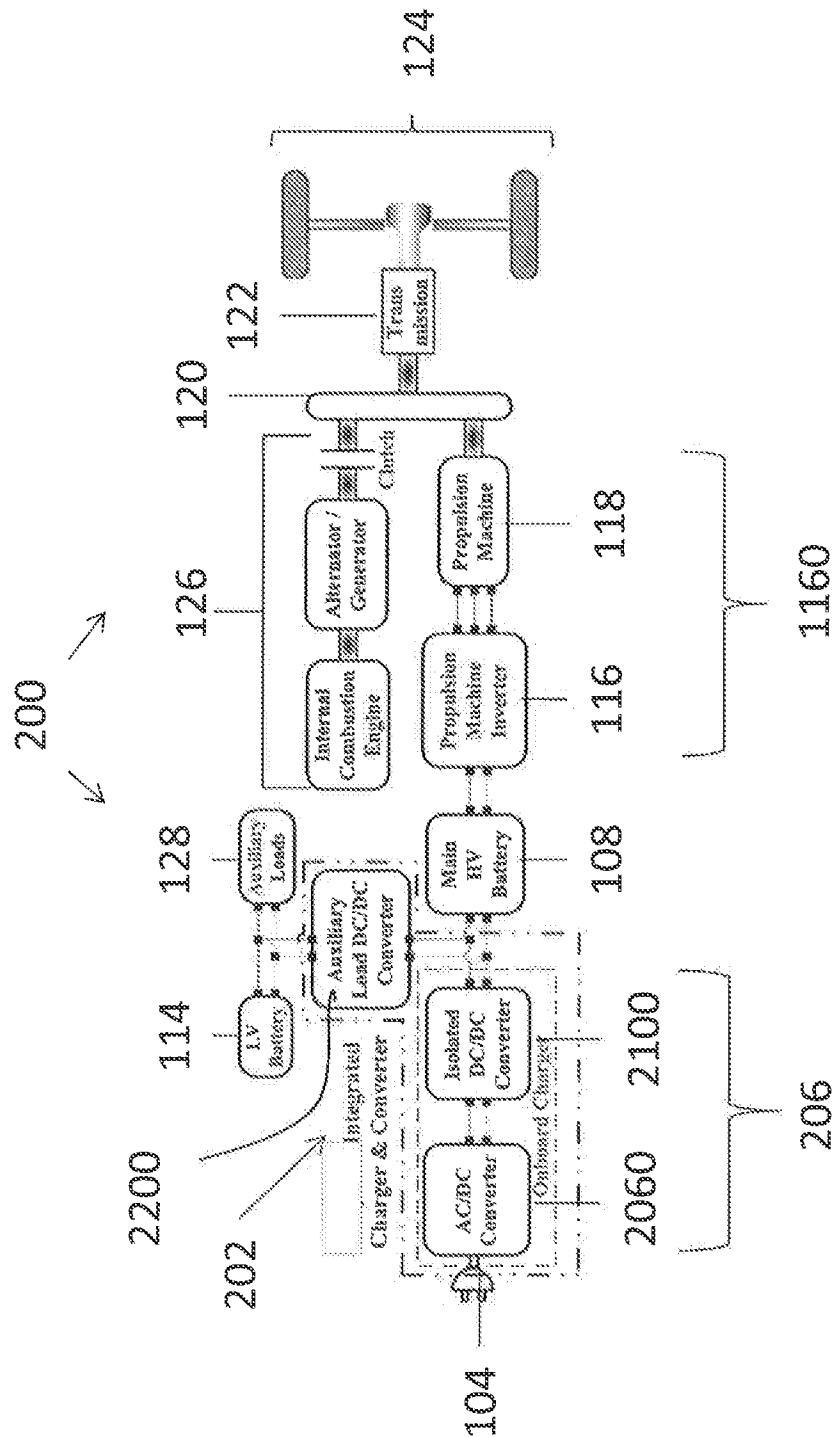
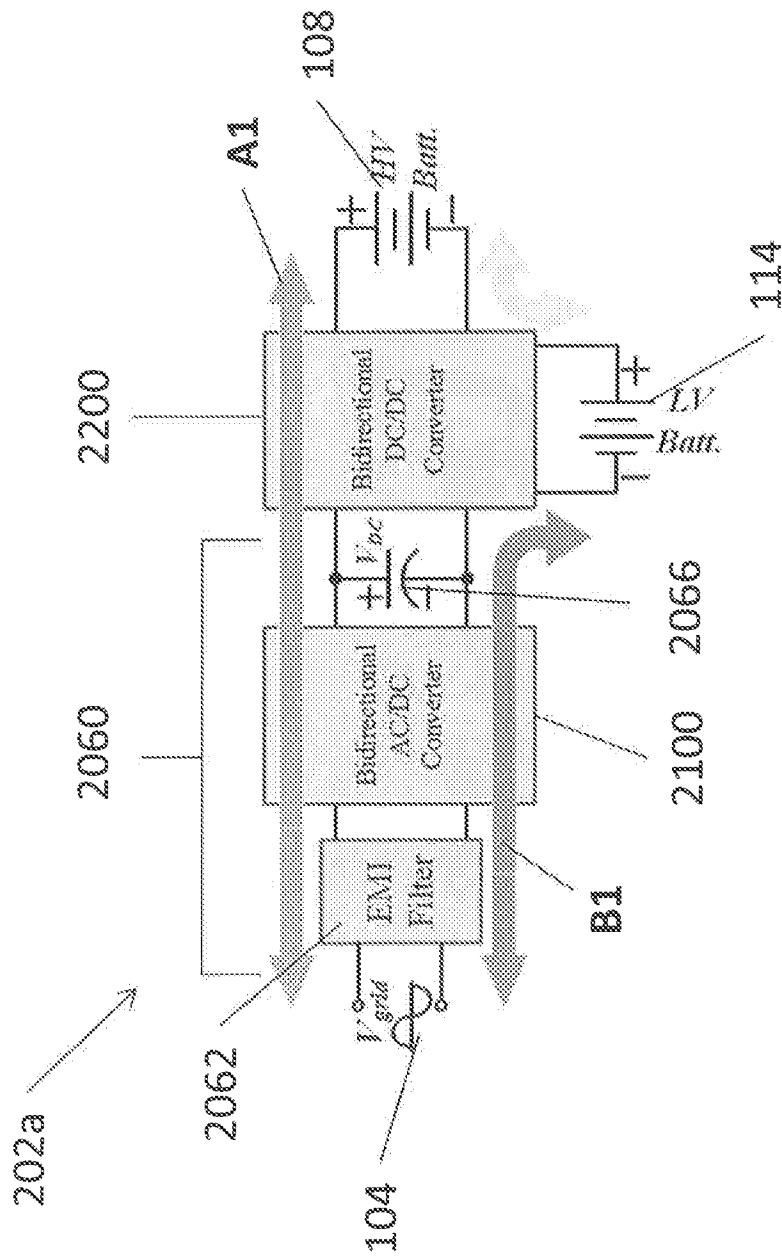


FIG. 3
PRIOR ART



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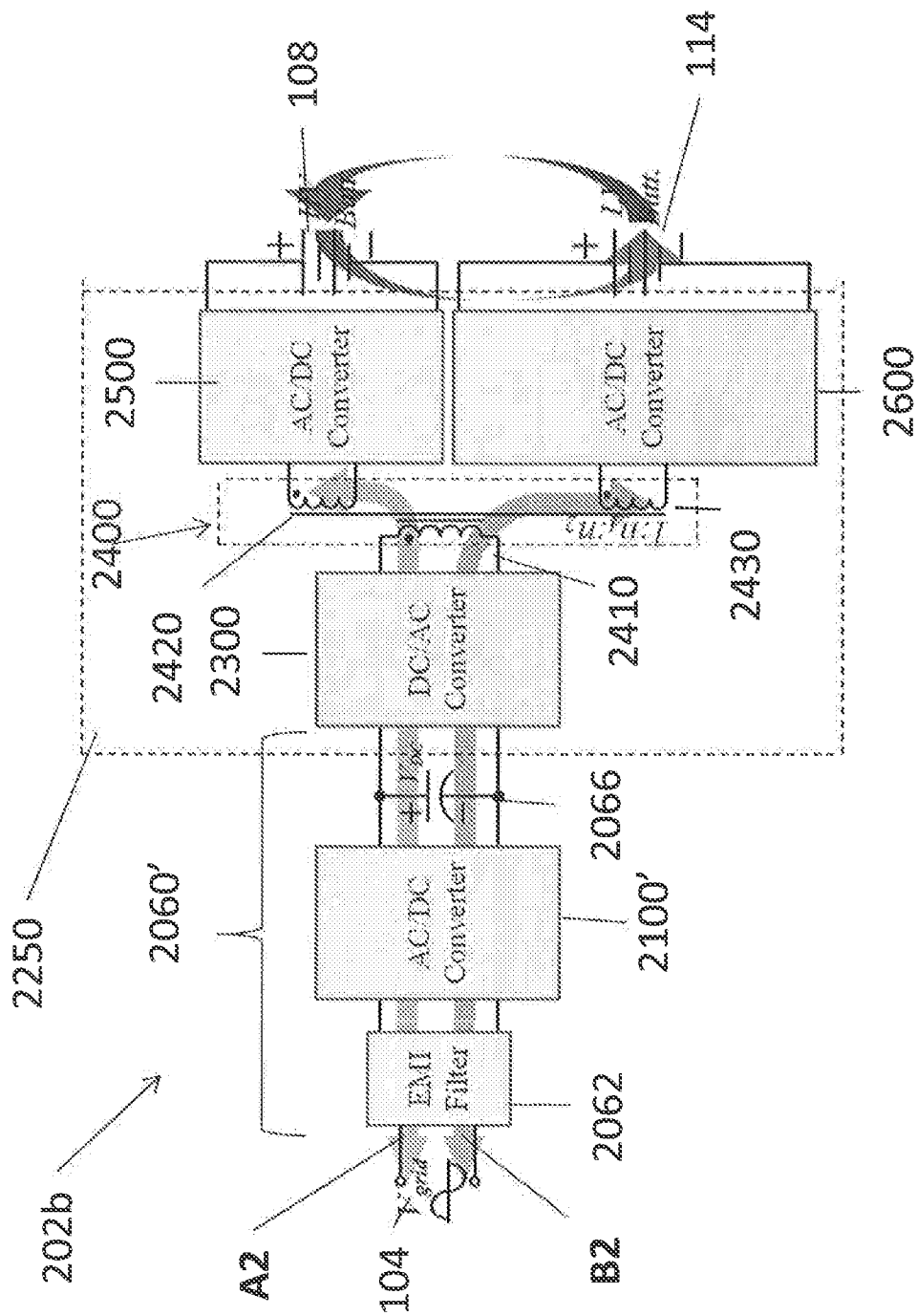
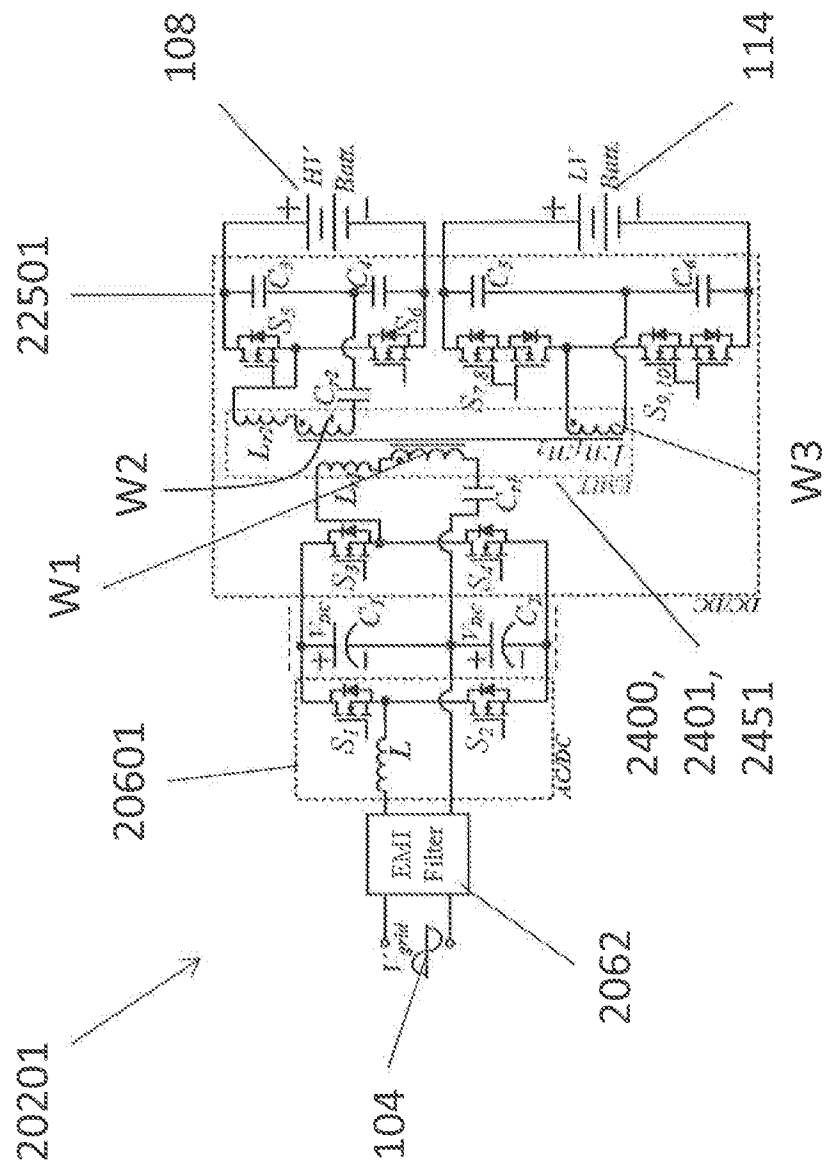


FIG. 5B



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5
4
3
2
1

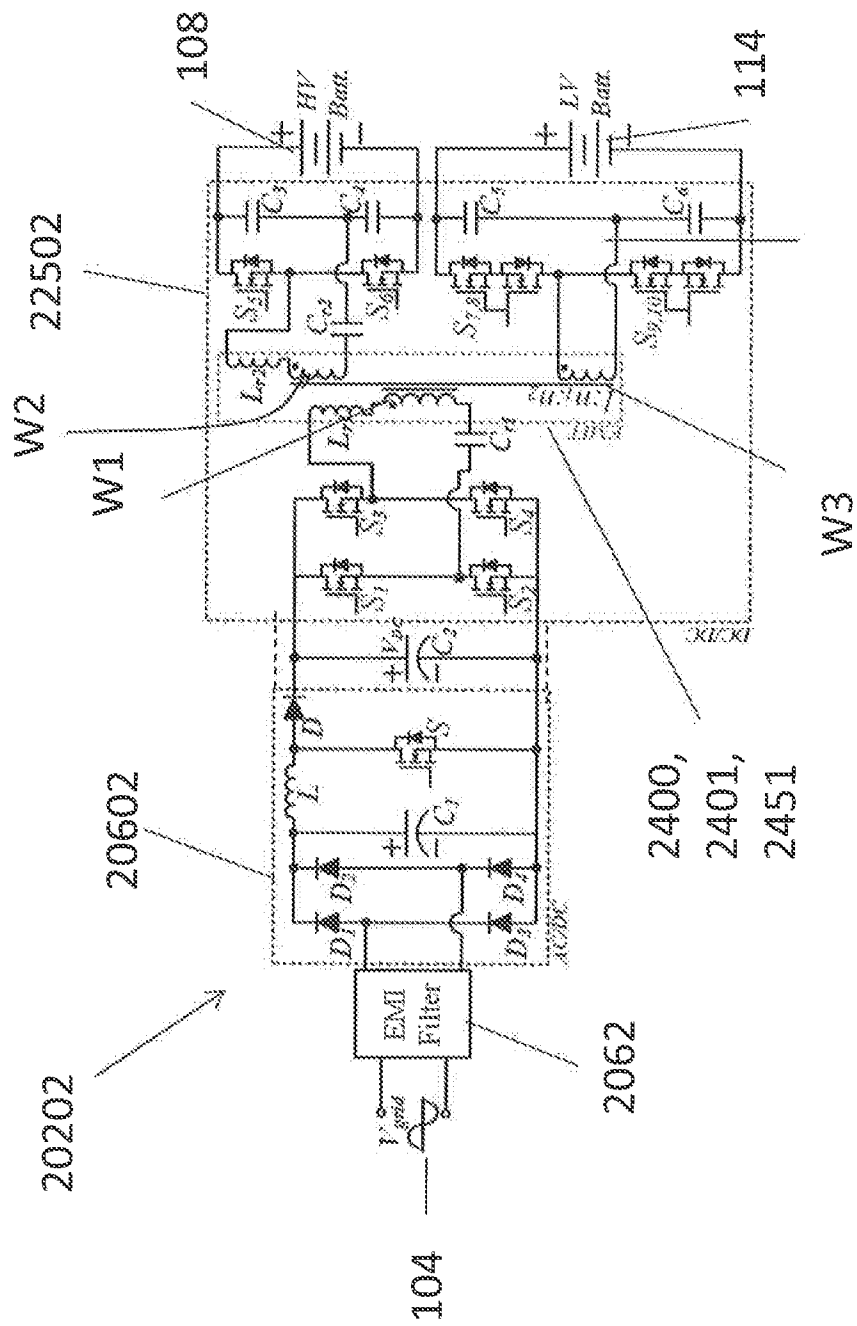


FIG. 7

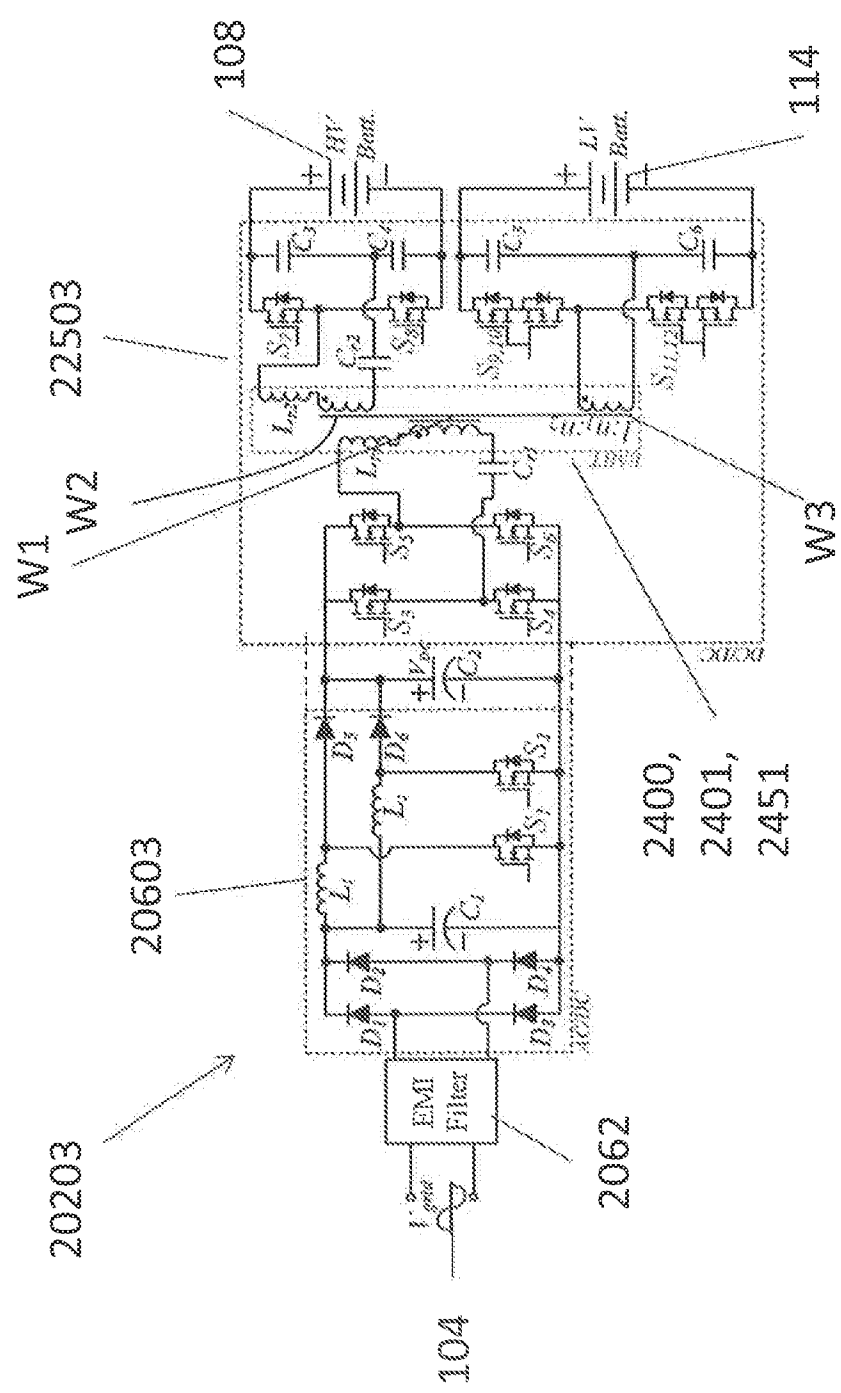


FIG. 8

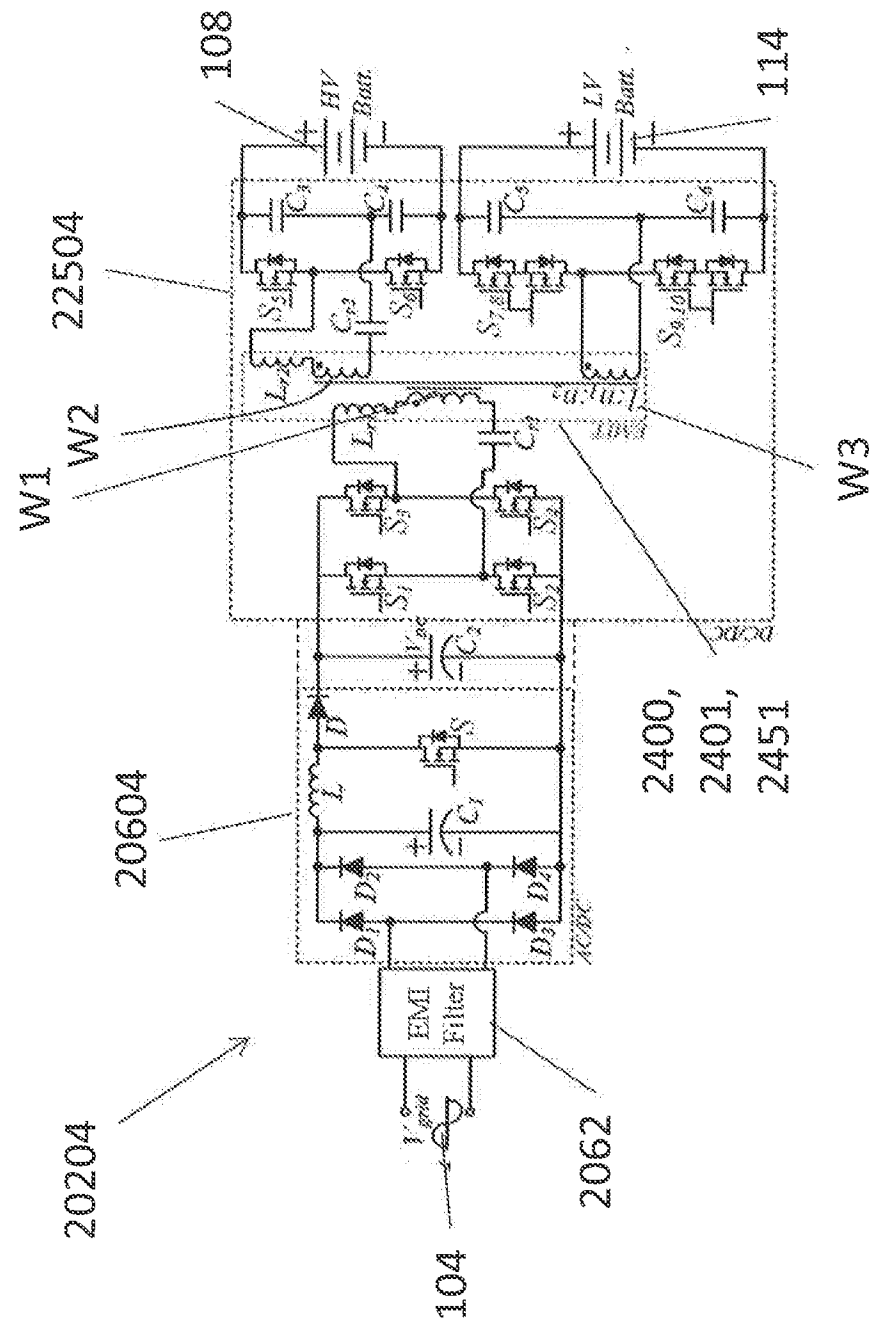
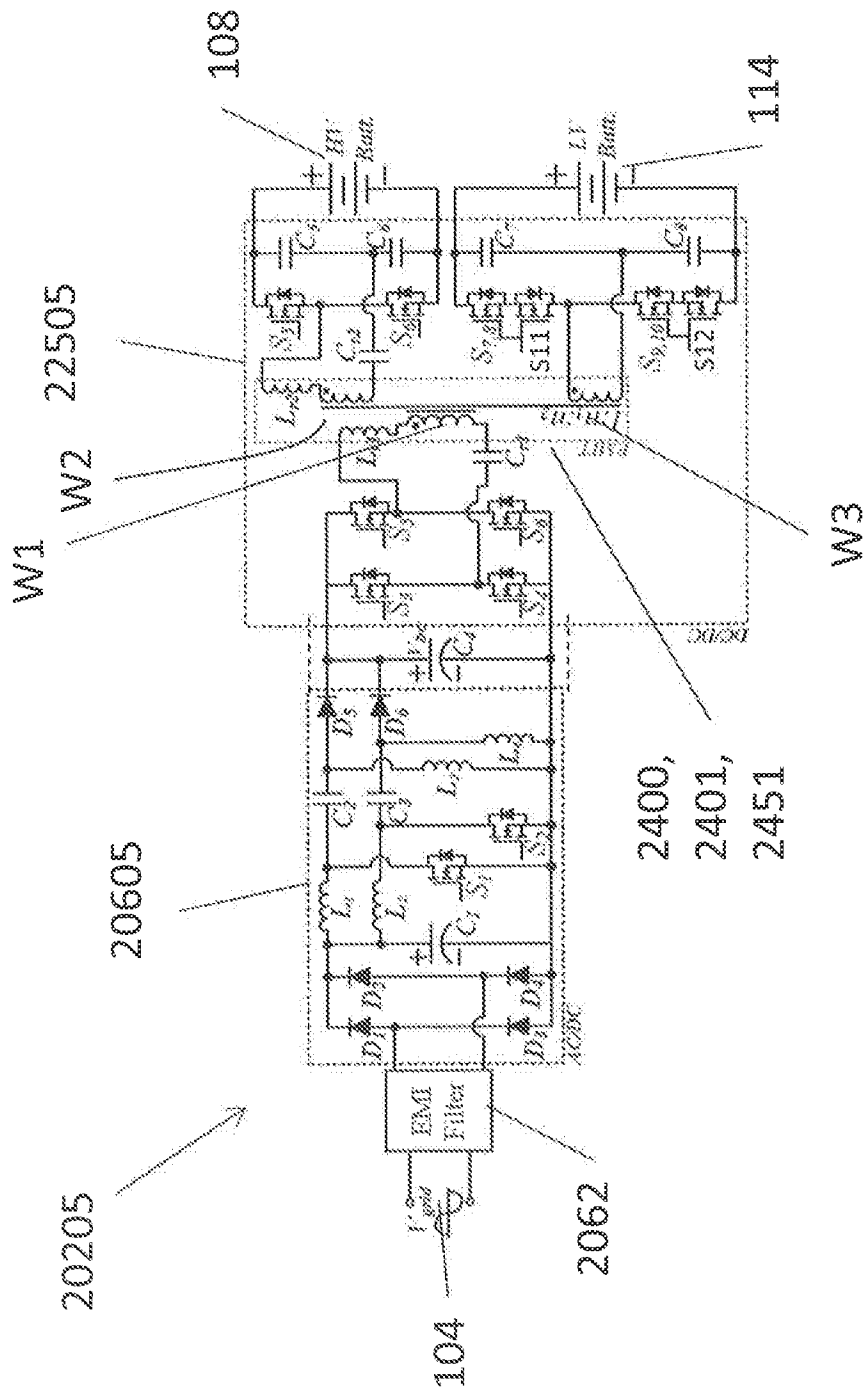


FIG. 9

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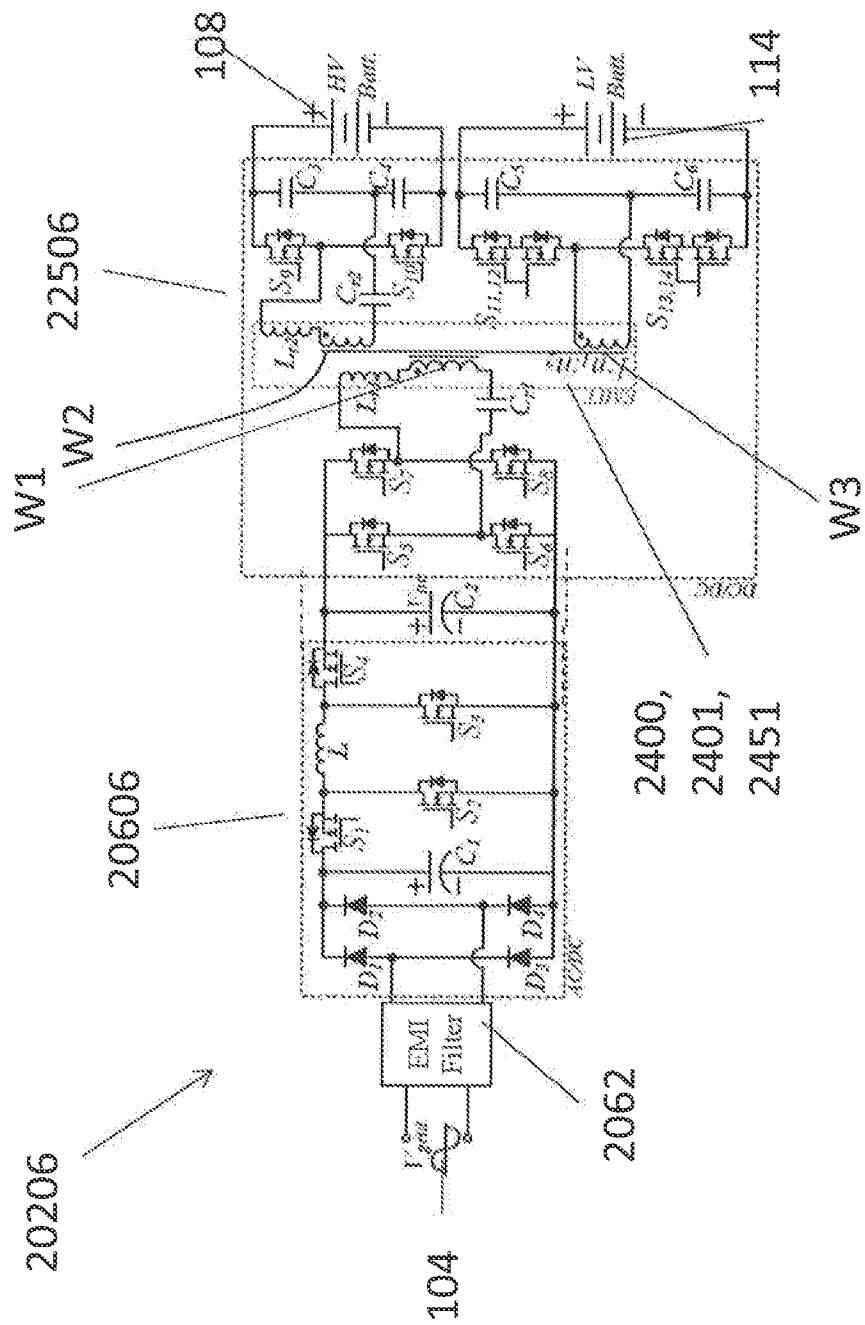


FIG. 11

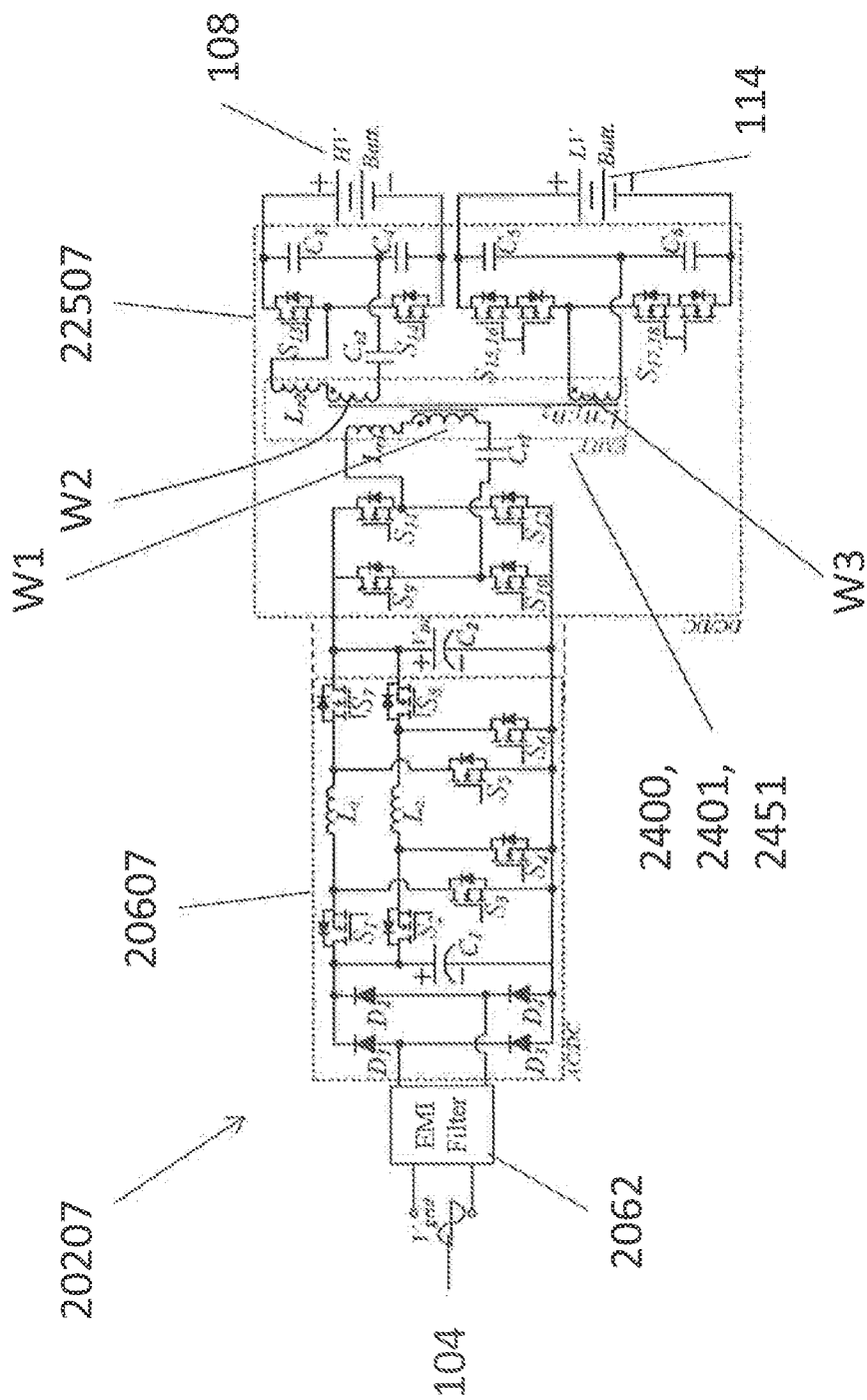


FIG. 12

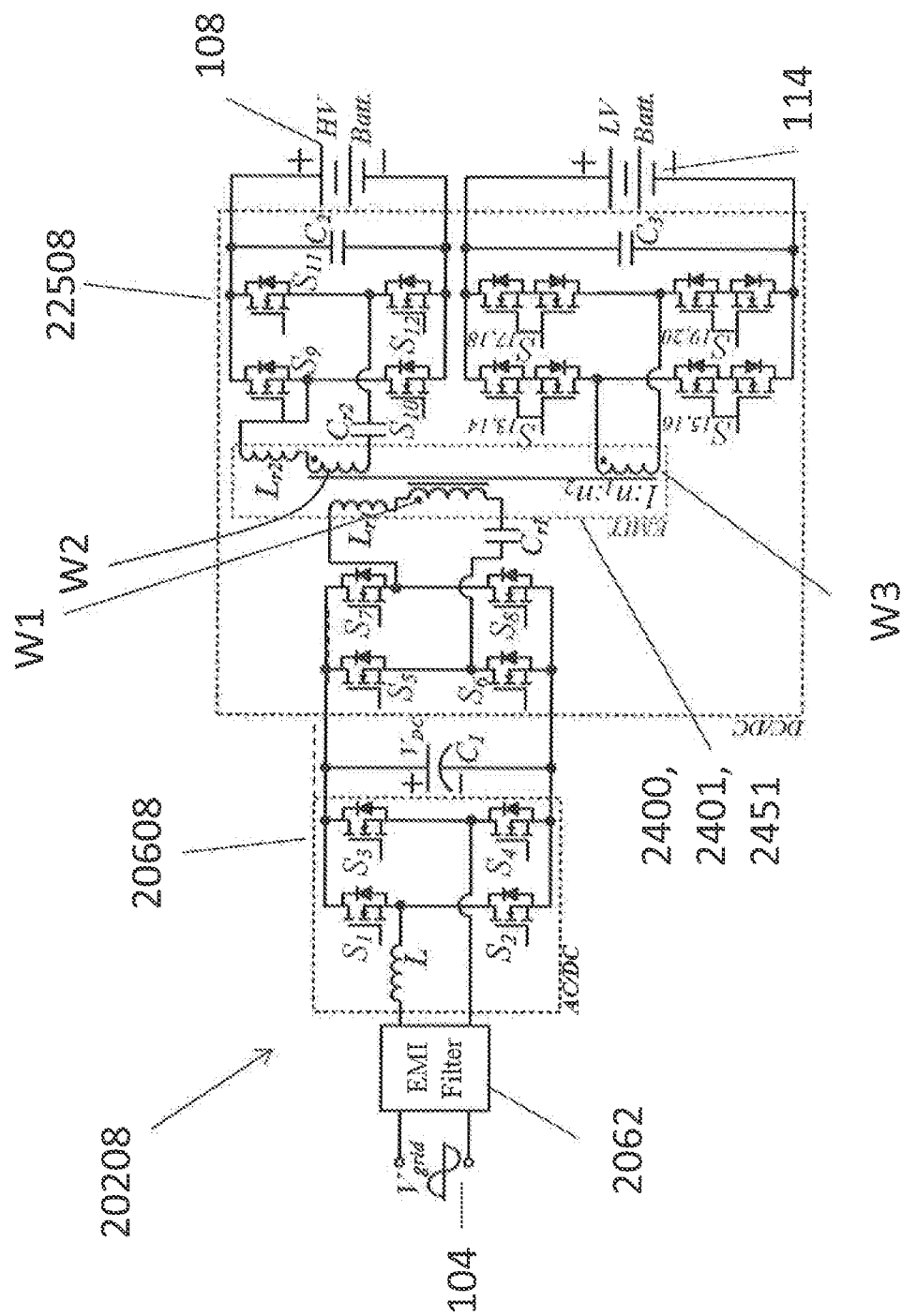


FIG. 13

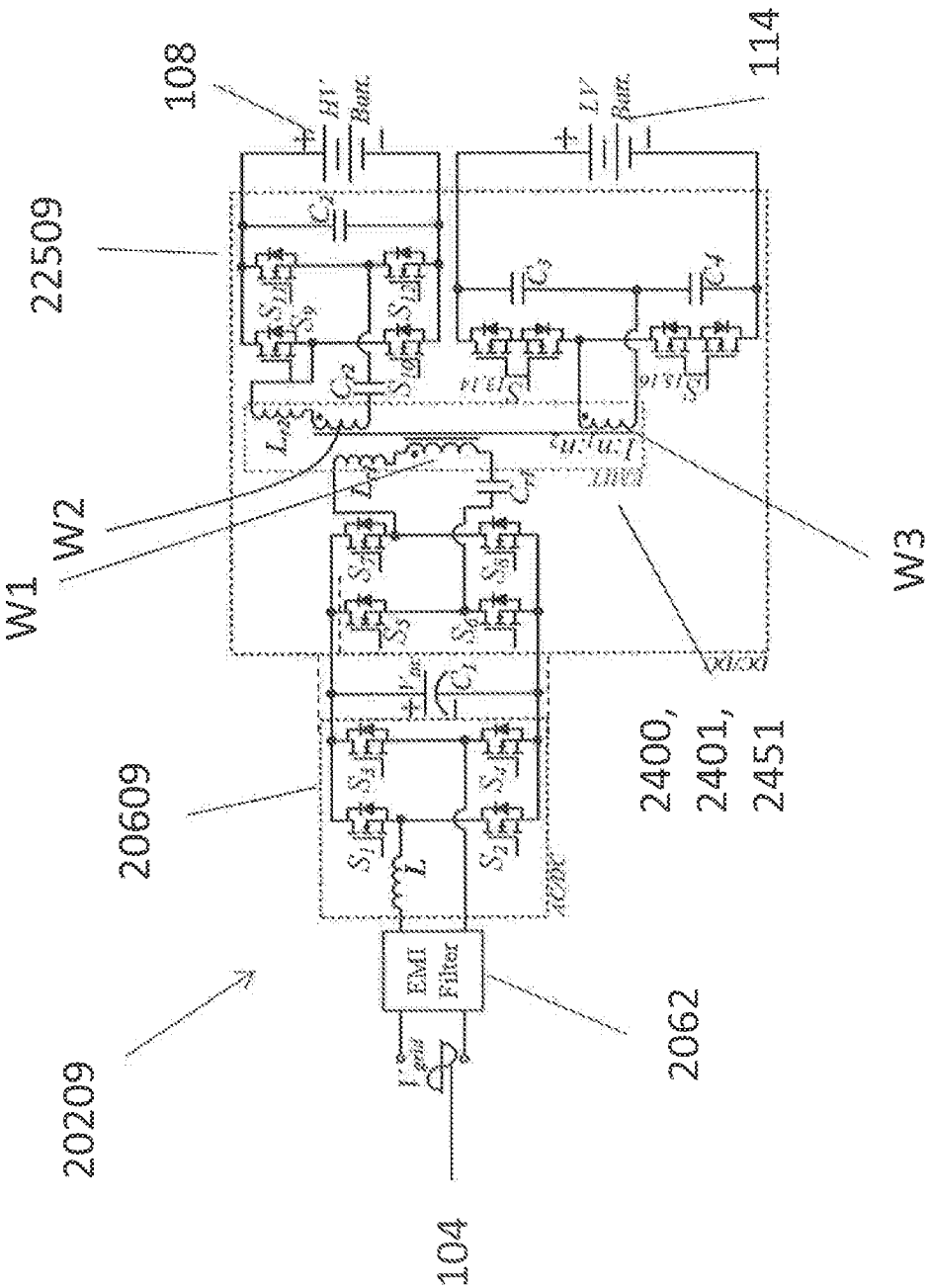


FIG. 14

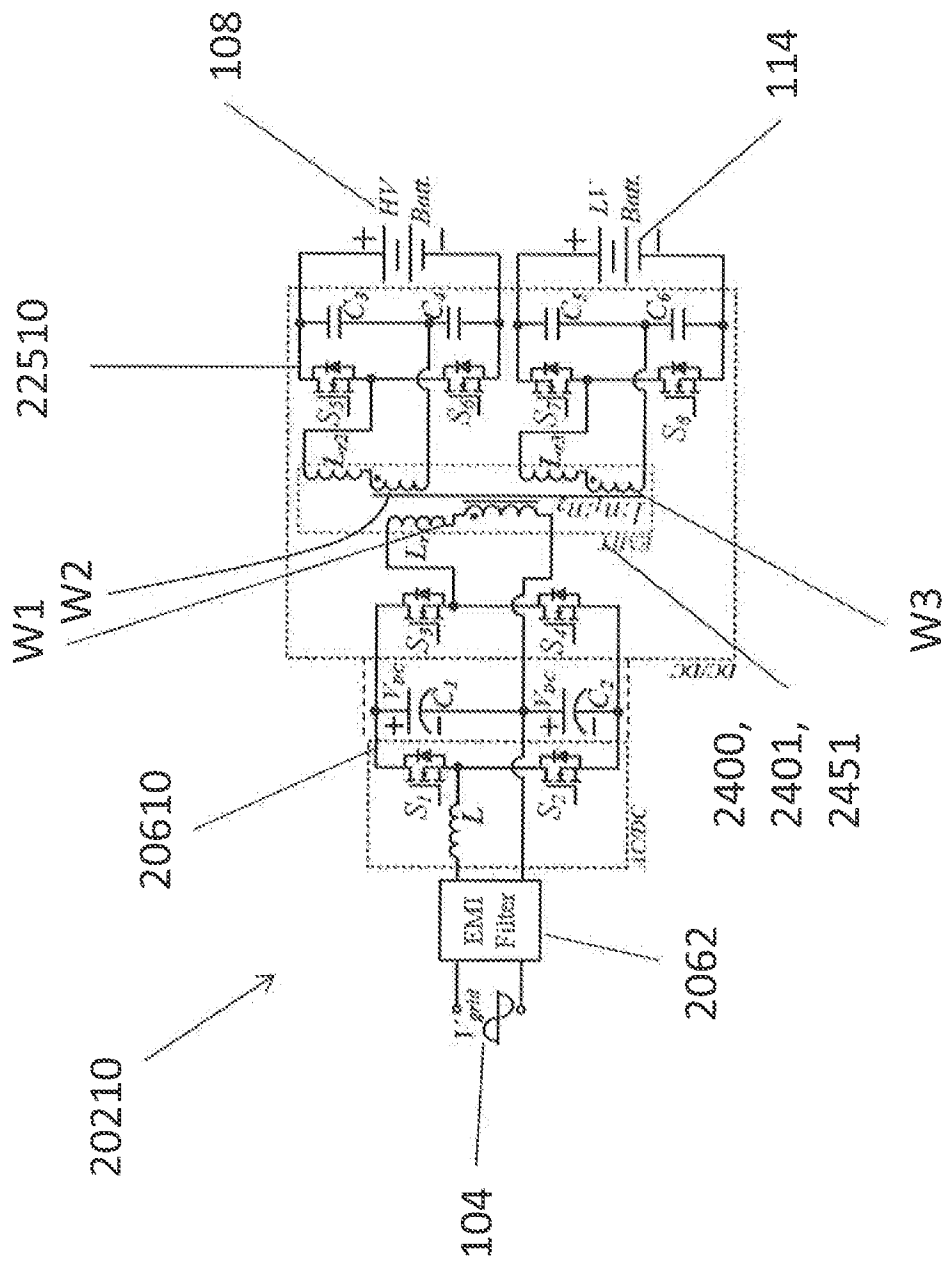


FIG. 15

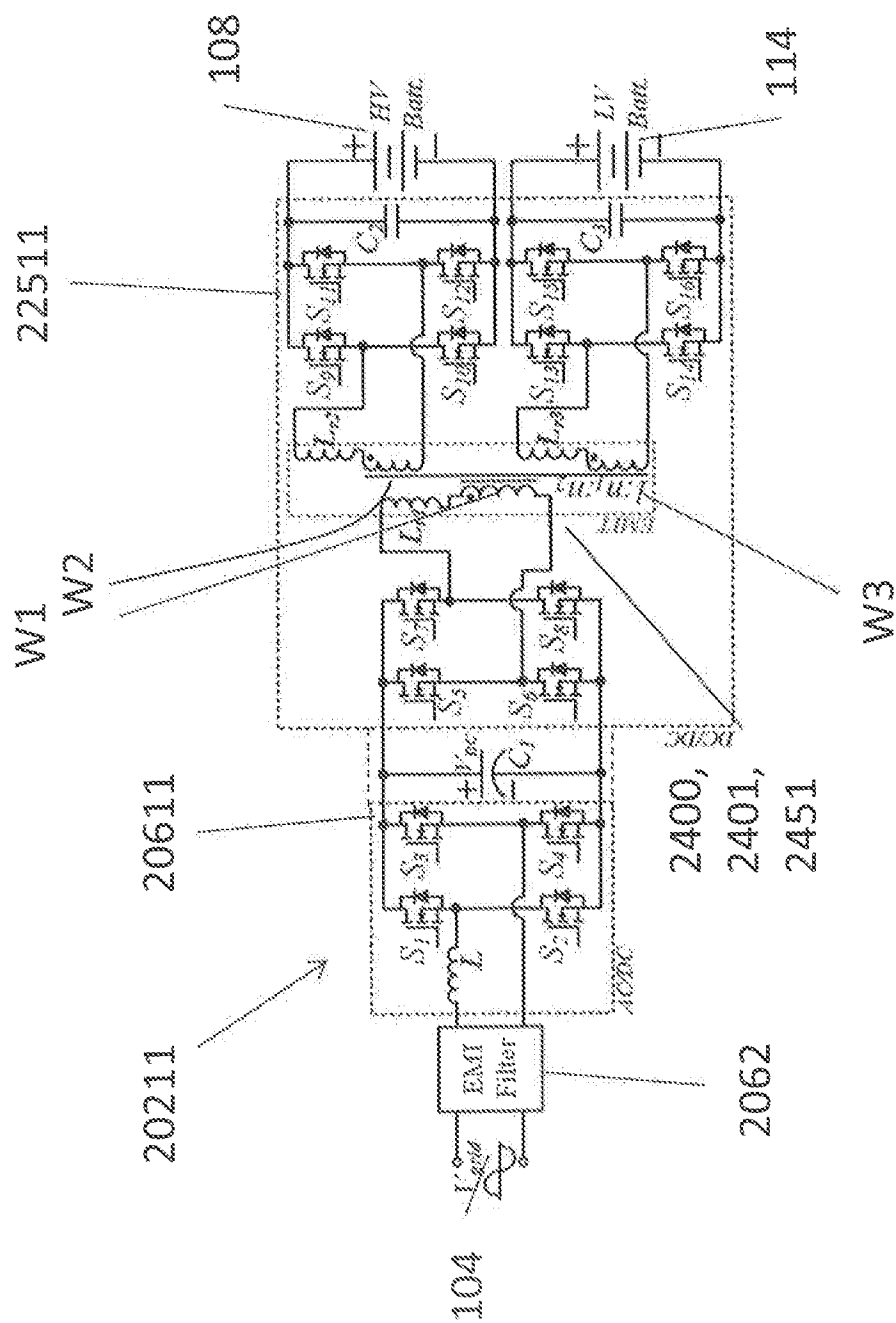


FIG. 16

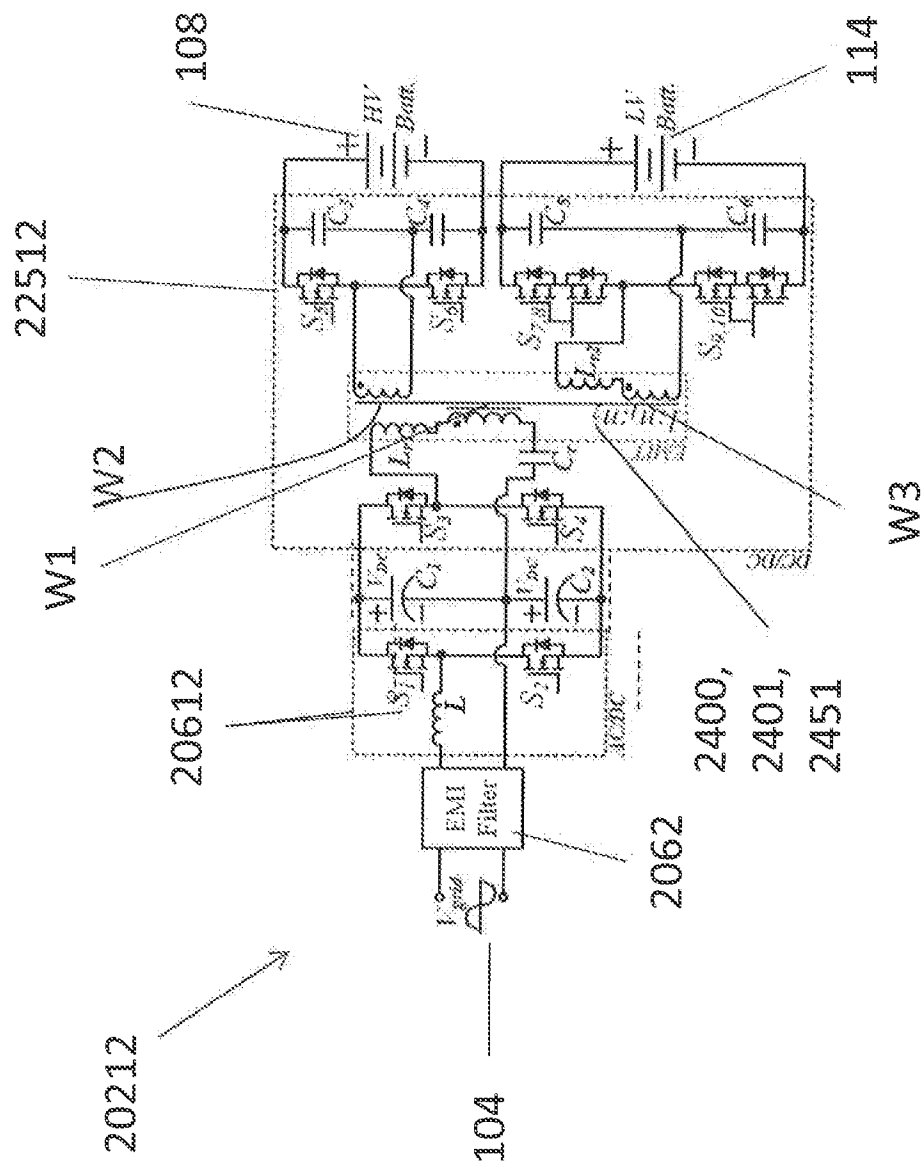
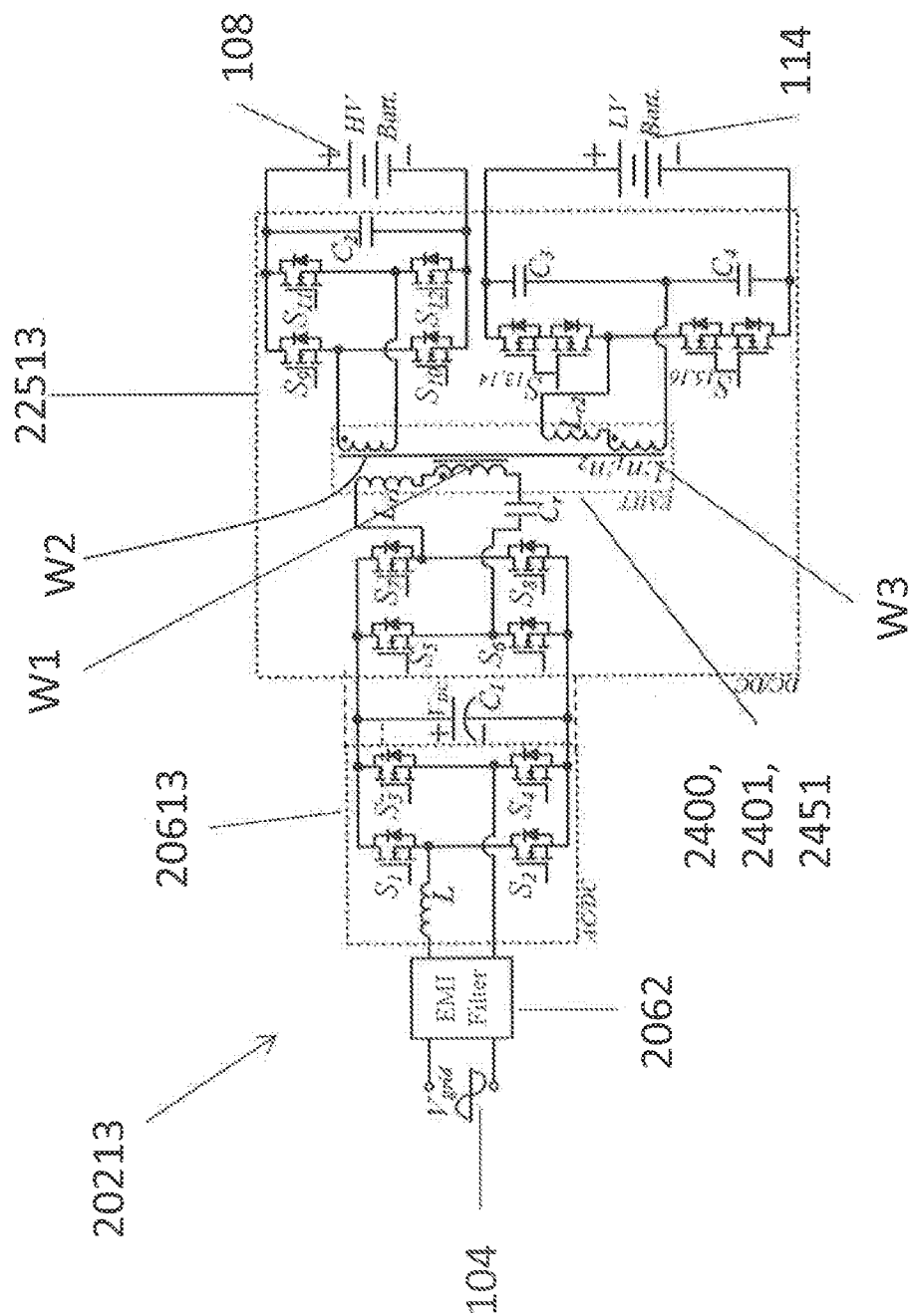


FIG. 17



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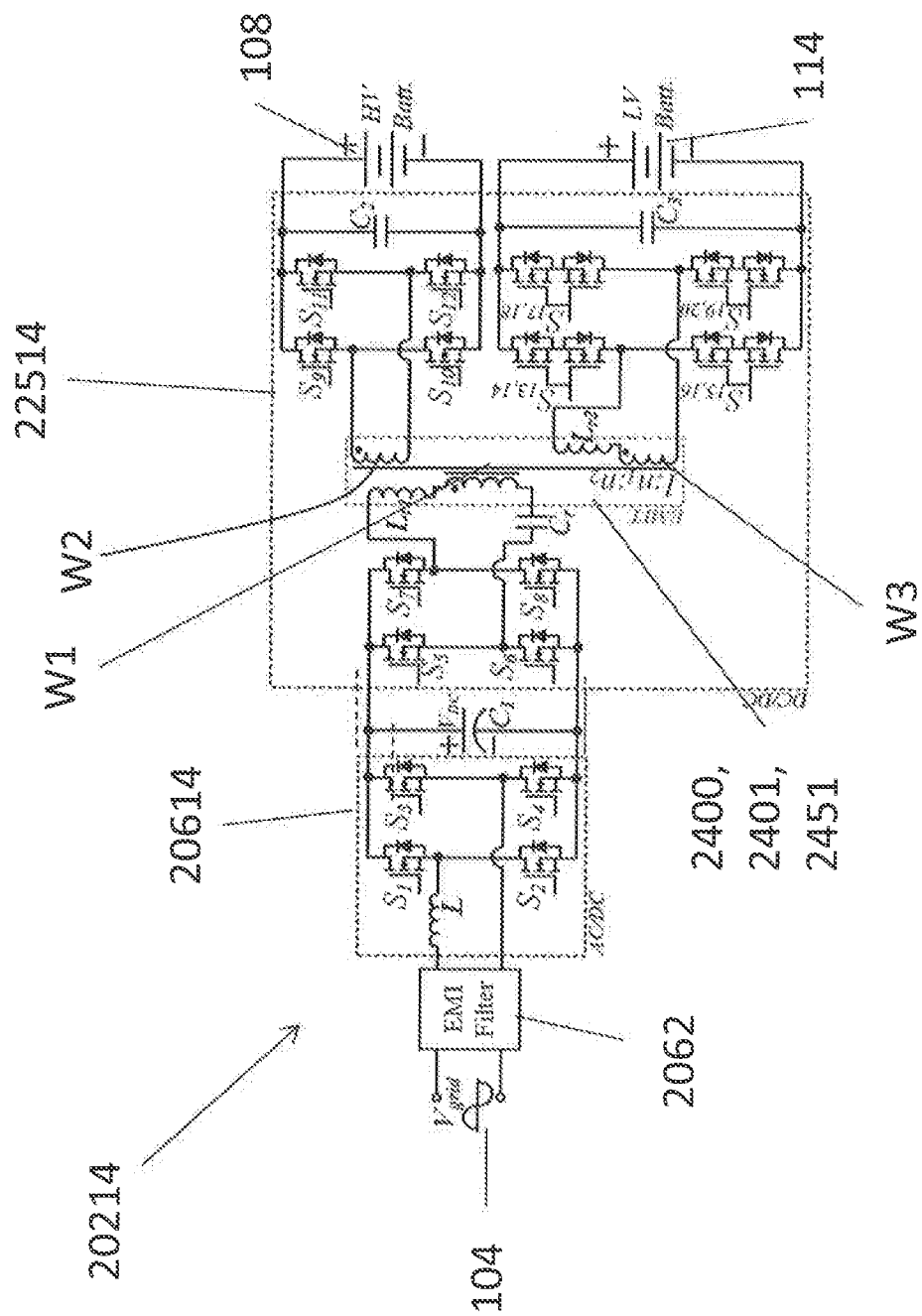


FIG. 19

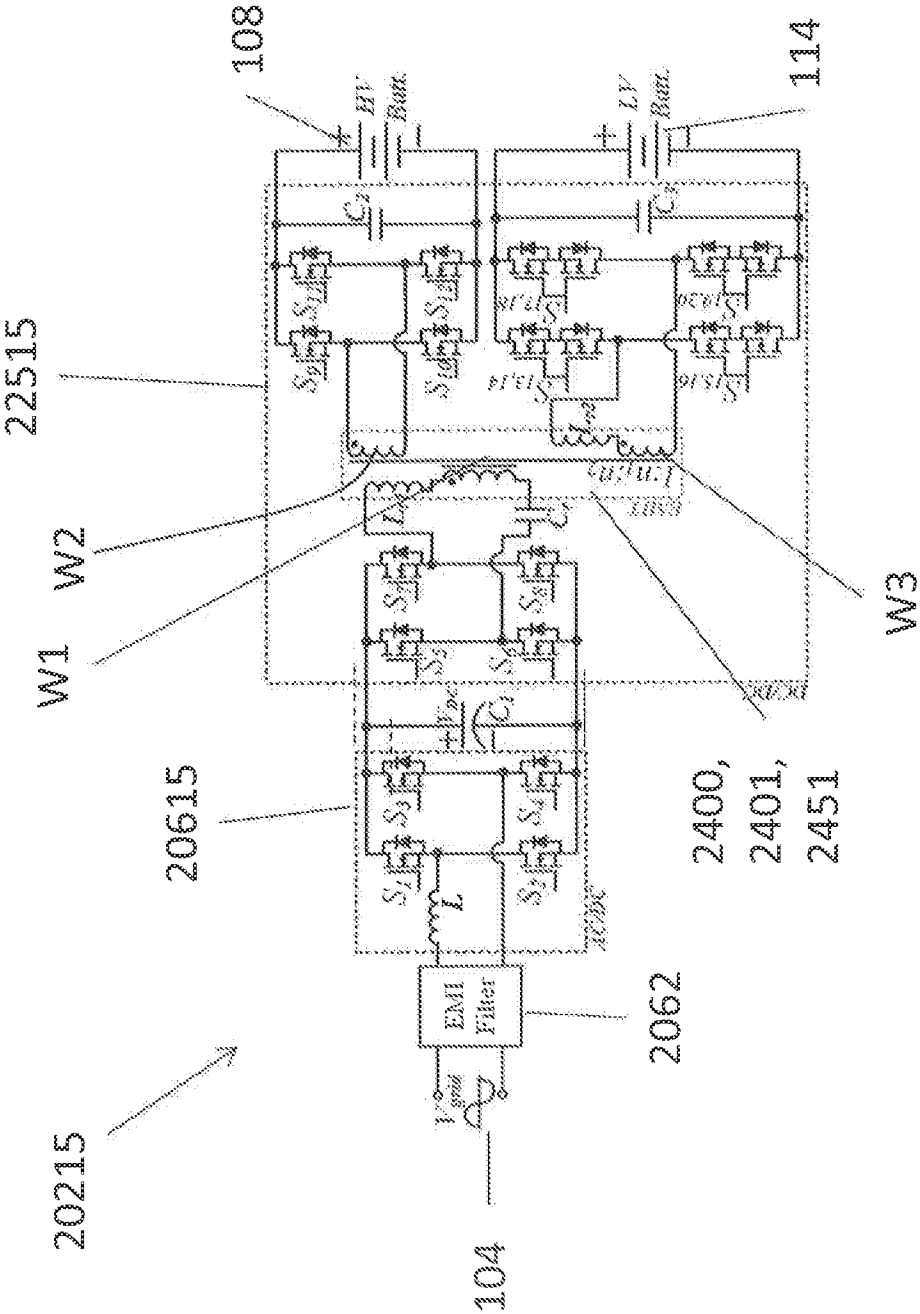
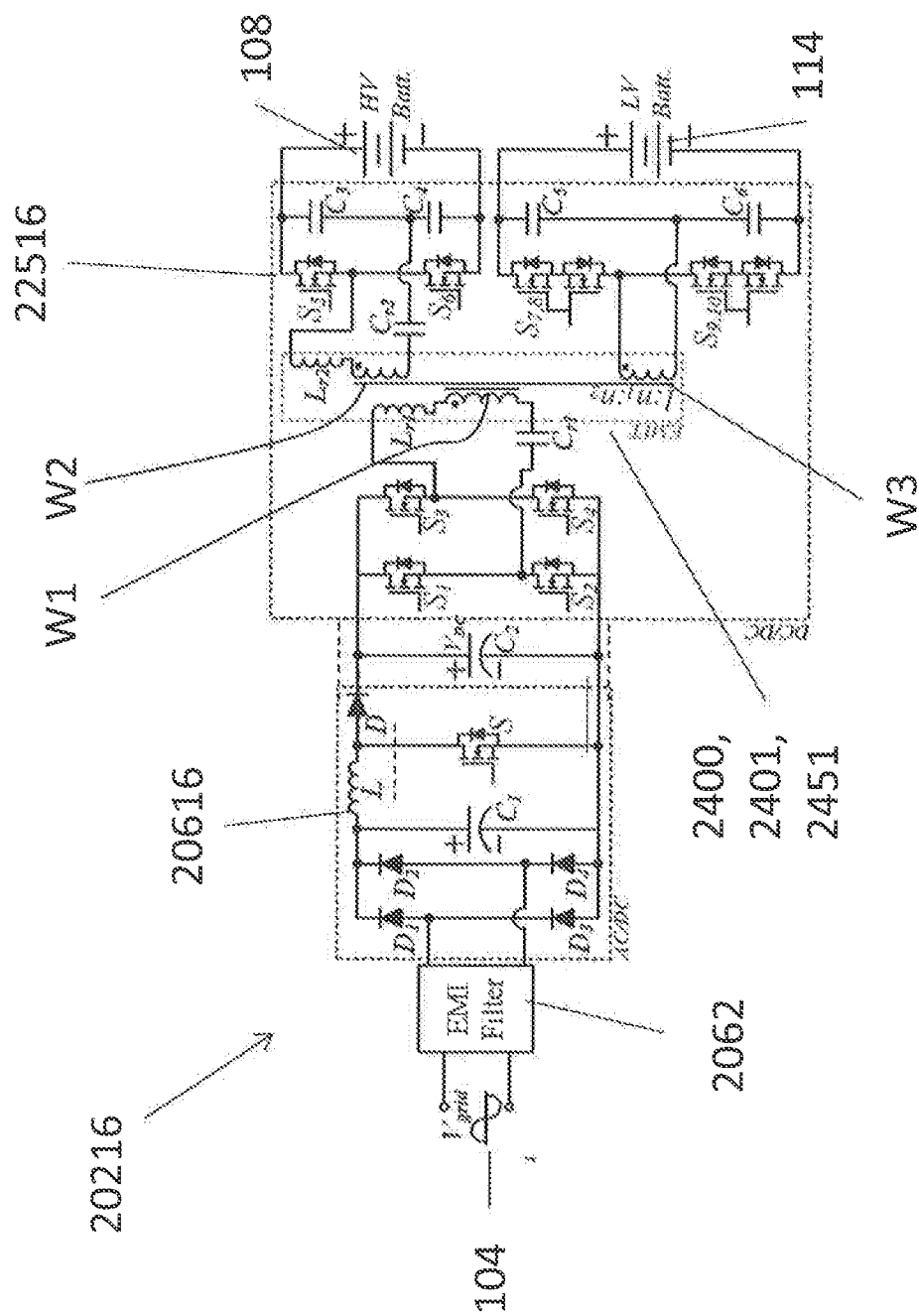


FIG. 20



ॐ नमो भगवते वासुदेवाय

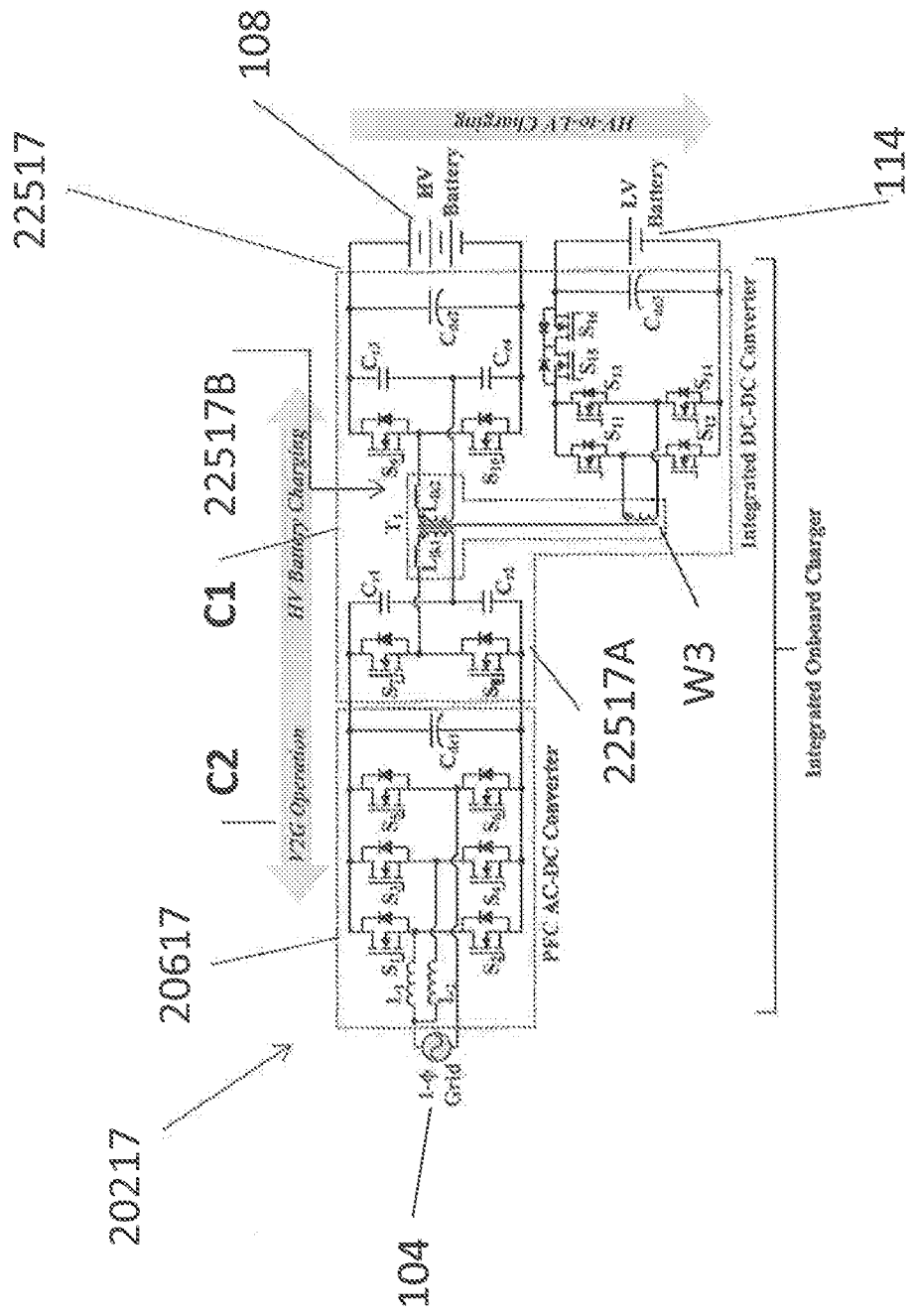


FIG. 22

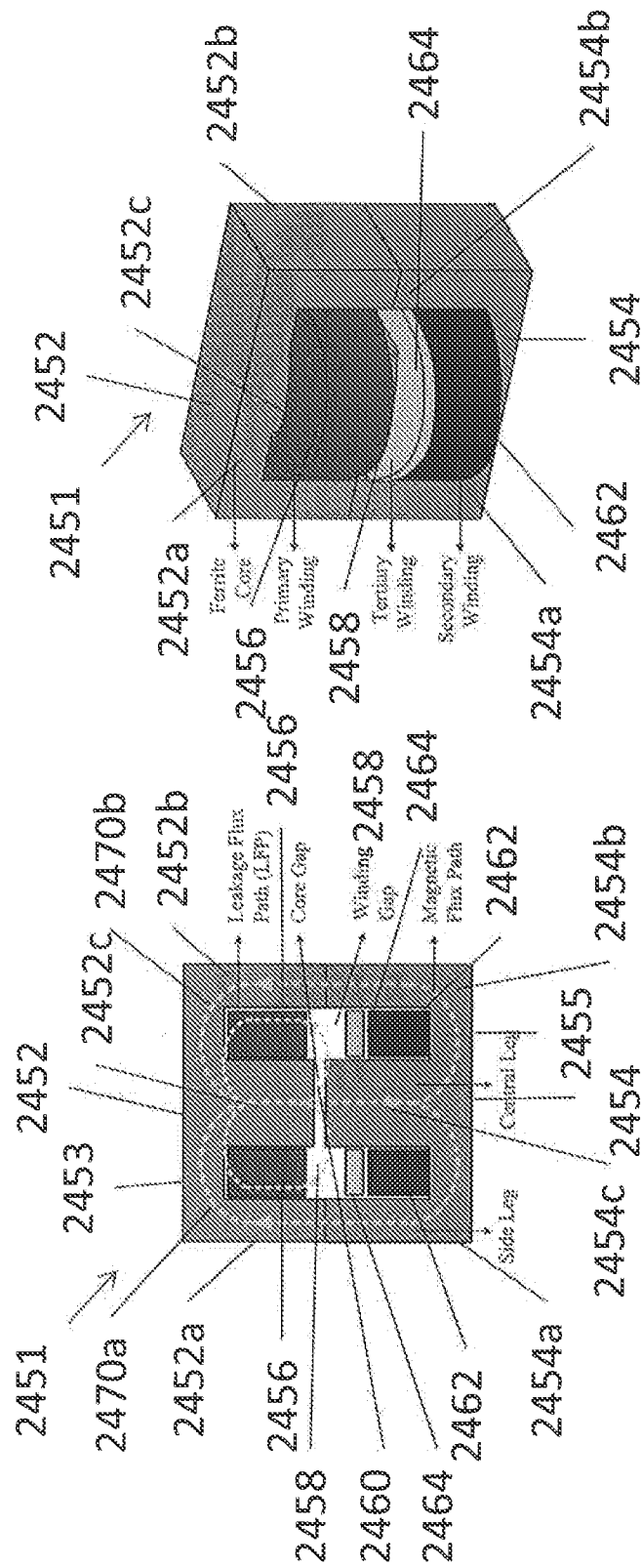
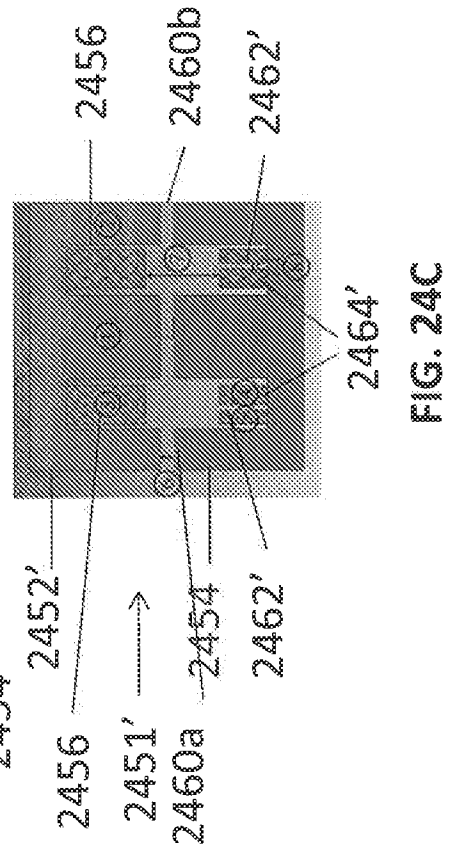
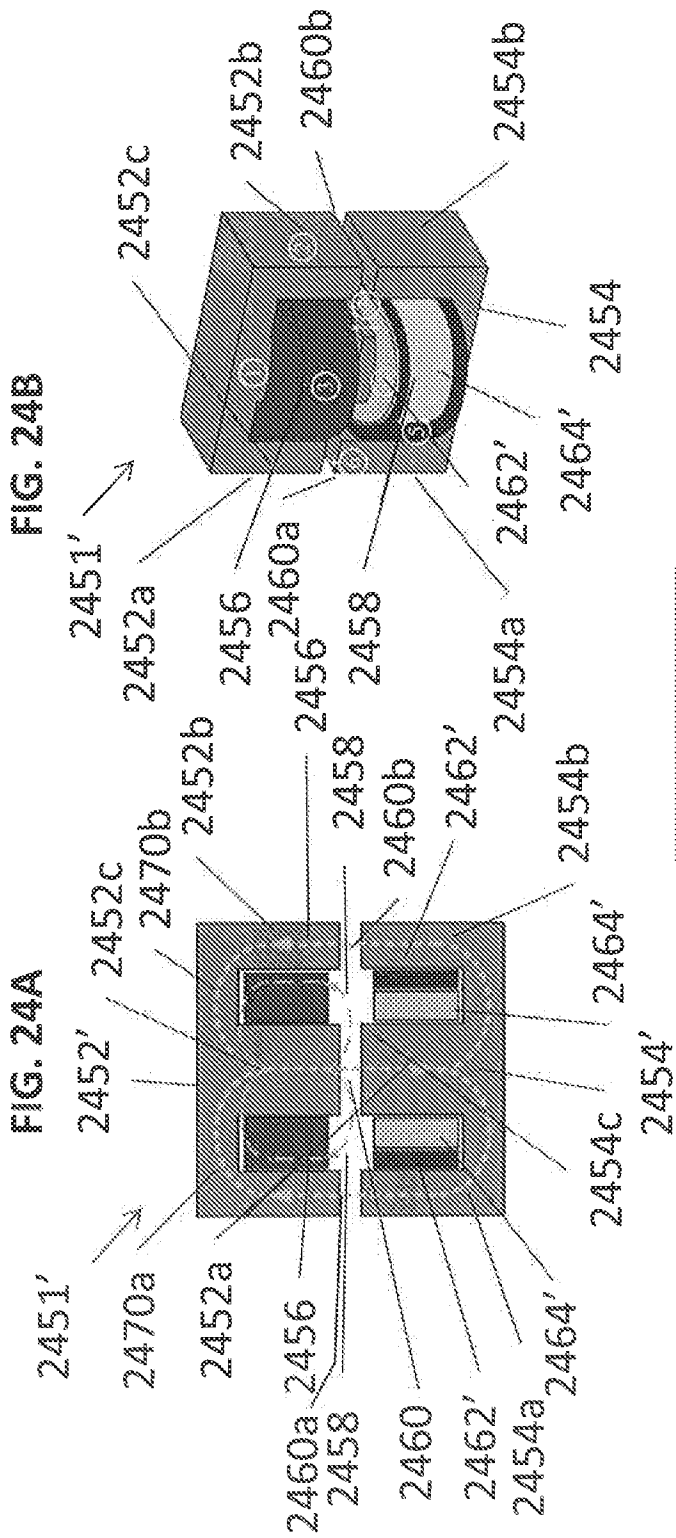


FIG. 23B

FIG. 23A



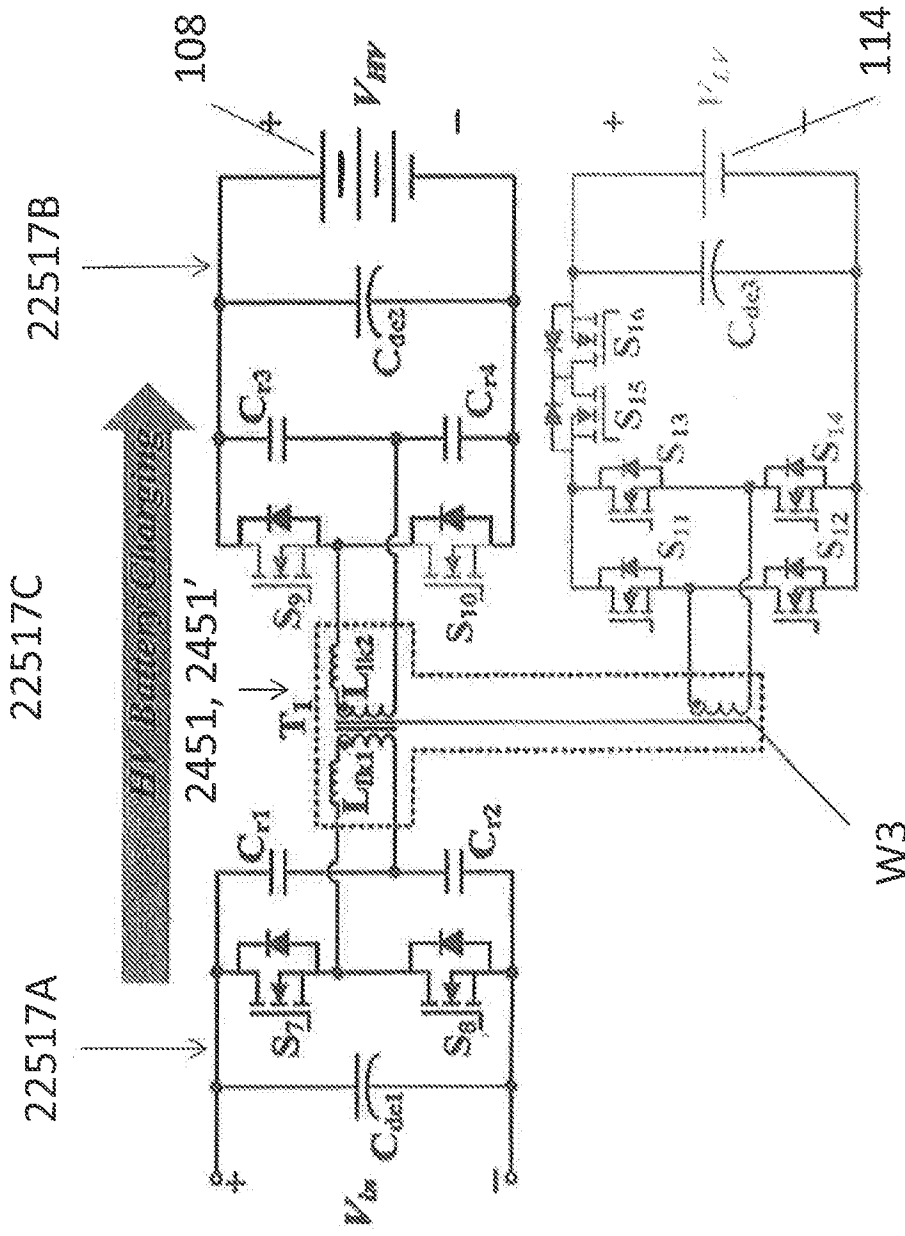


FIG. 25

22517A1

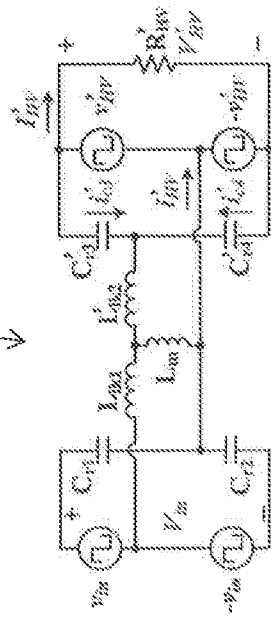
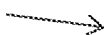


FIG. 26A

22517A2

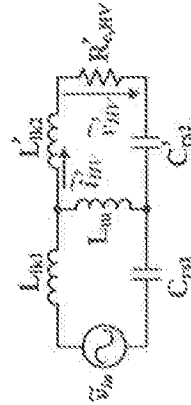
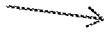


FIG. 26B

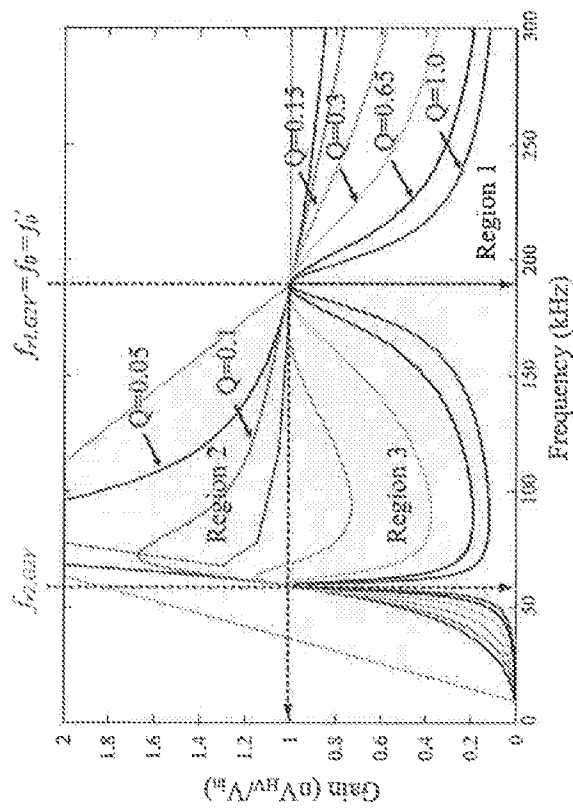


FIG. 27A

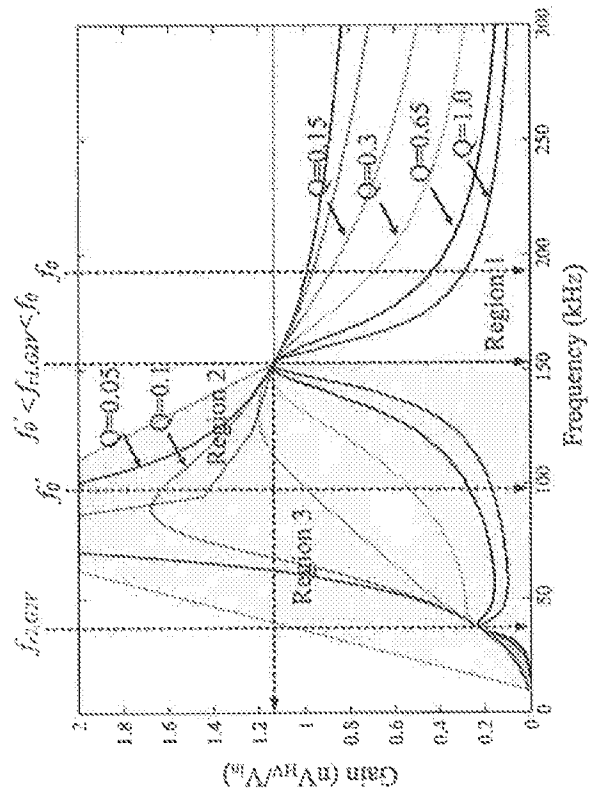


FIG. 27B

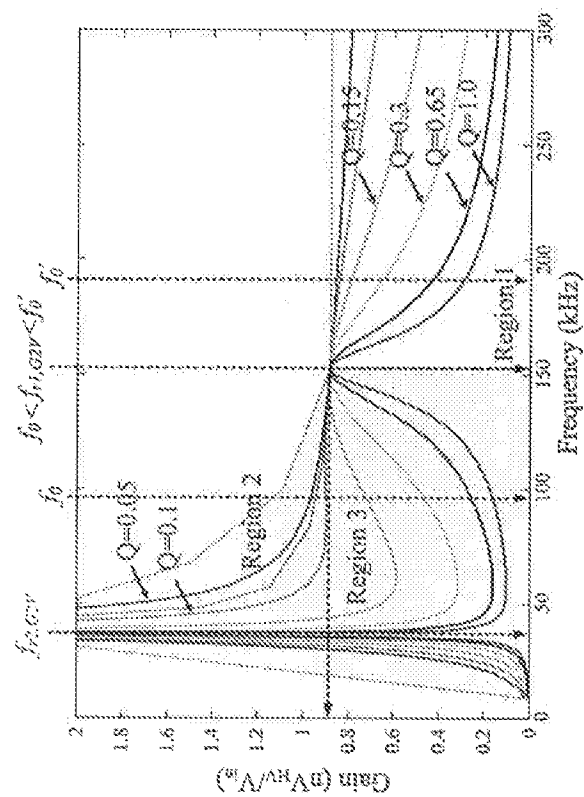


FIG. 27C

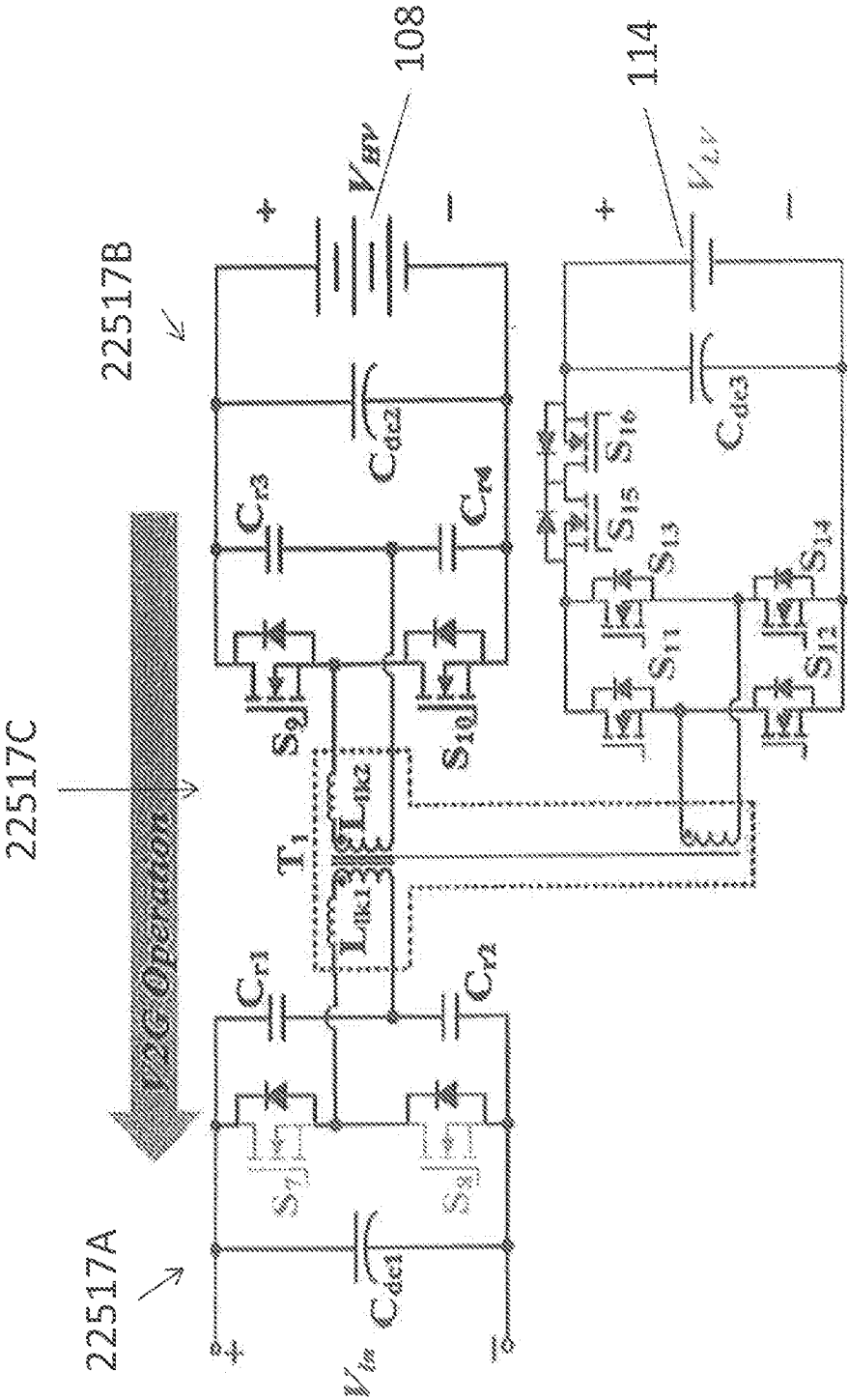


FIG. 28

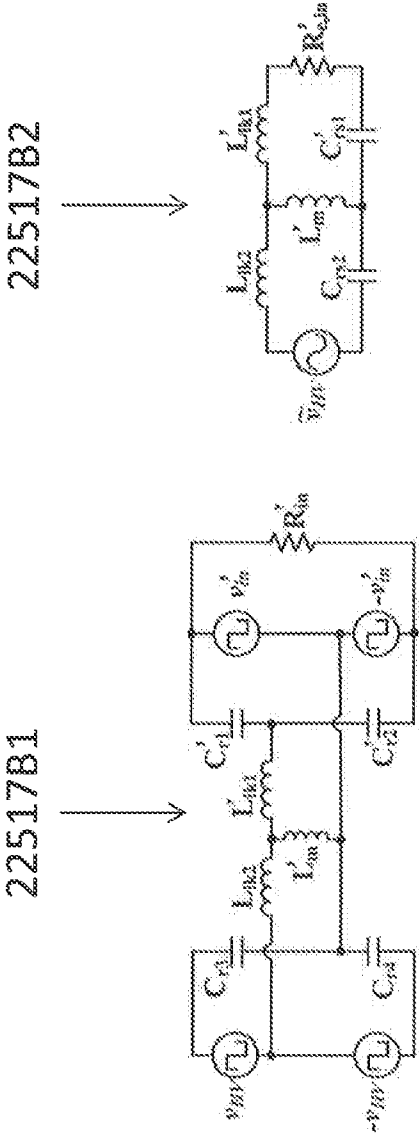


FIG. 29A

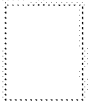


FIG. 29B

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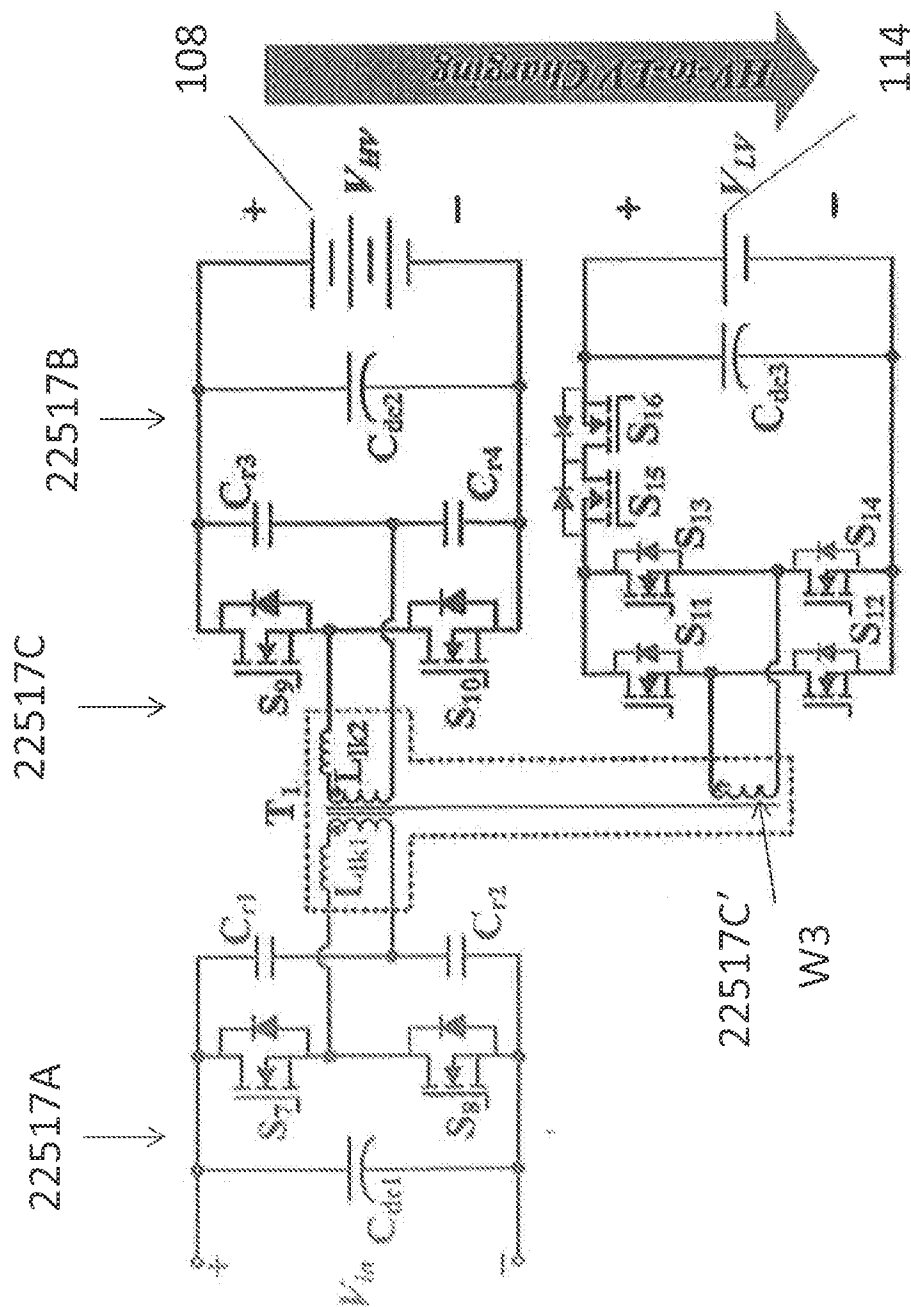


FIG. 30

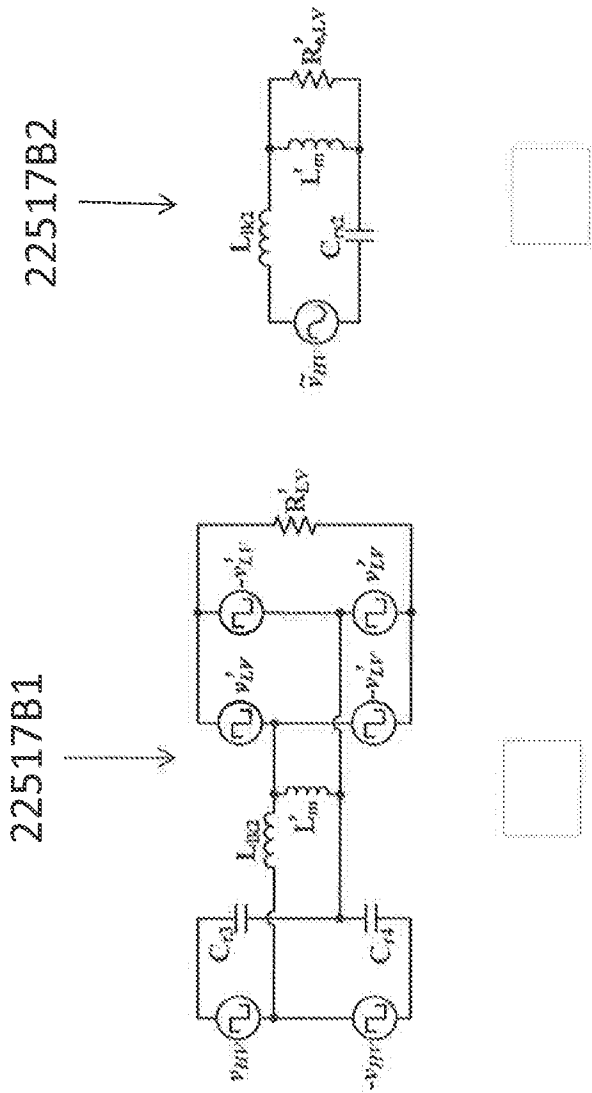
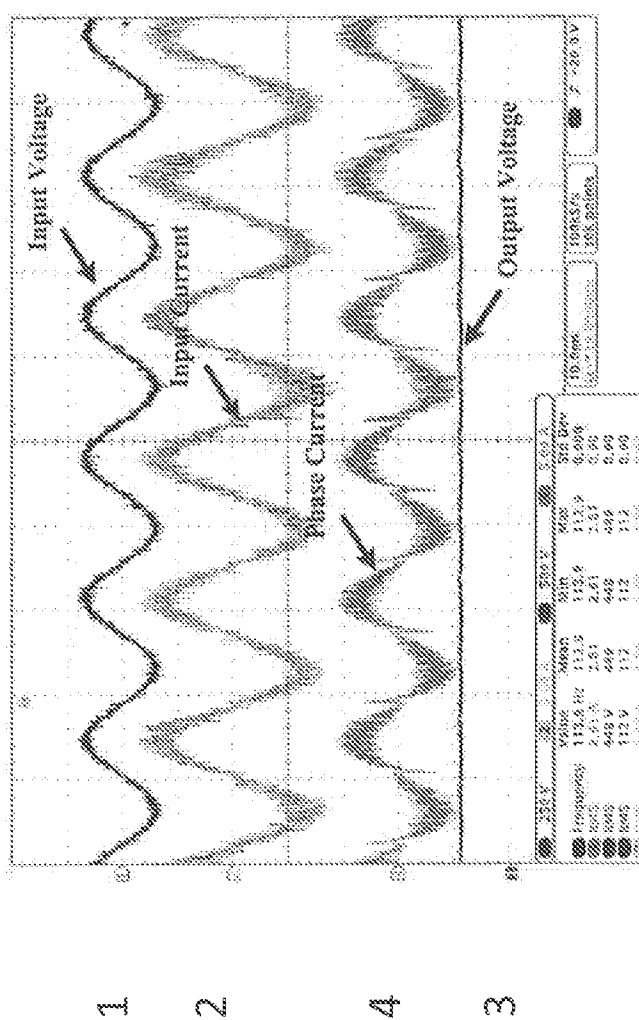
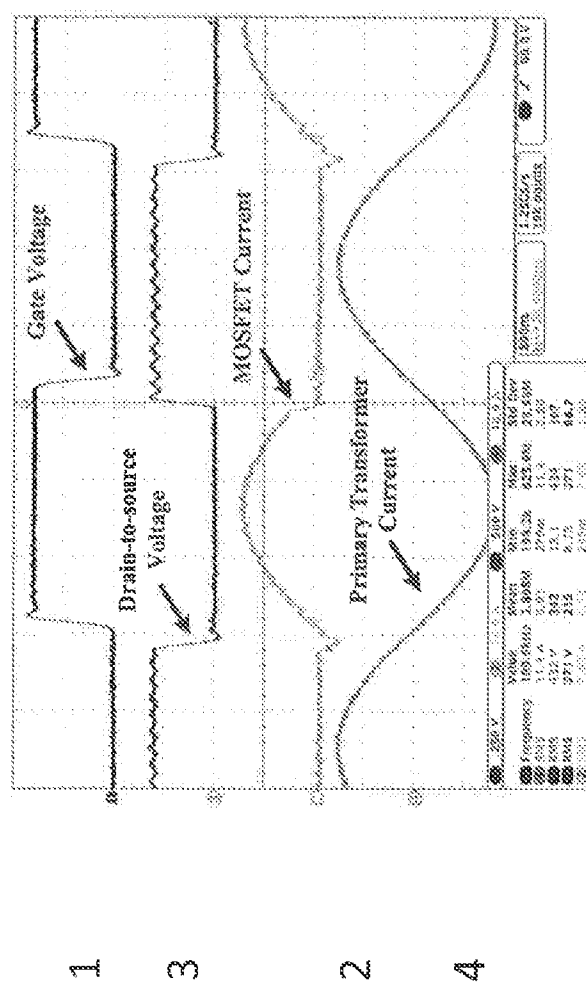


FIG. 31B

FIG. 31A



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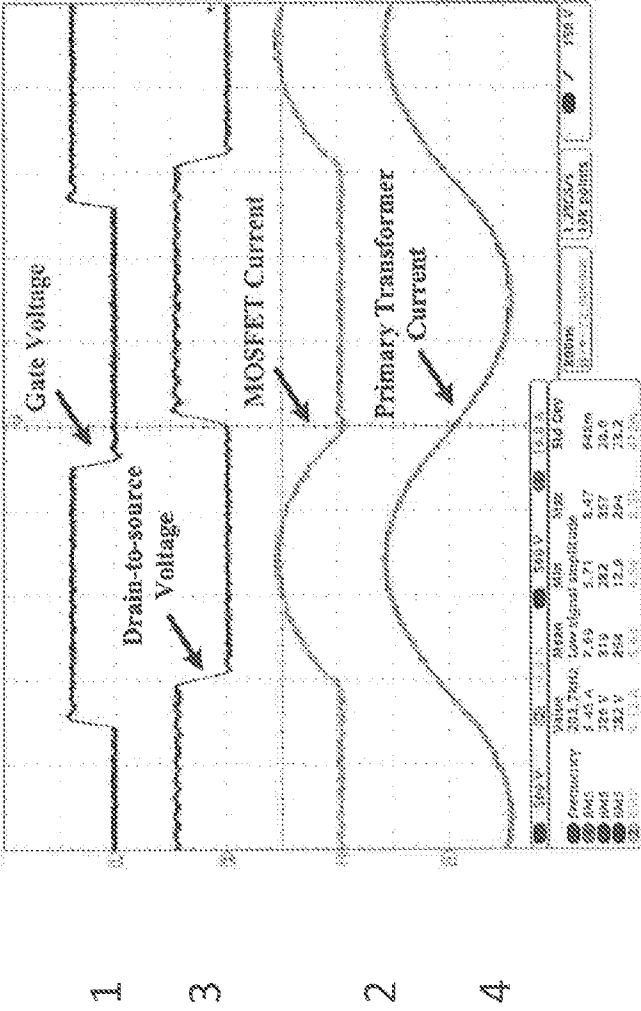
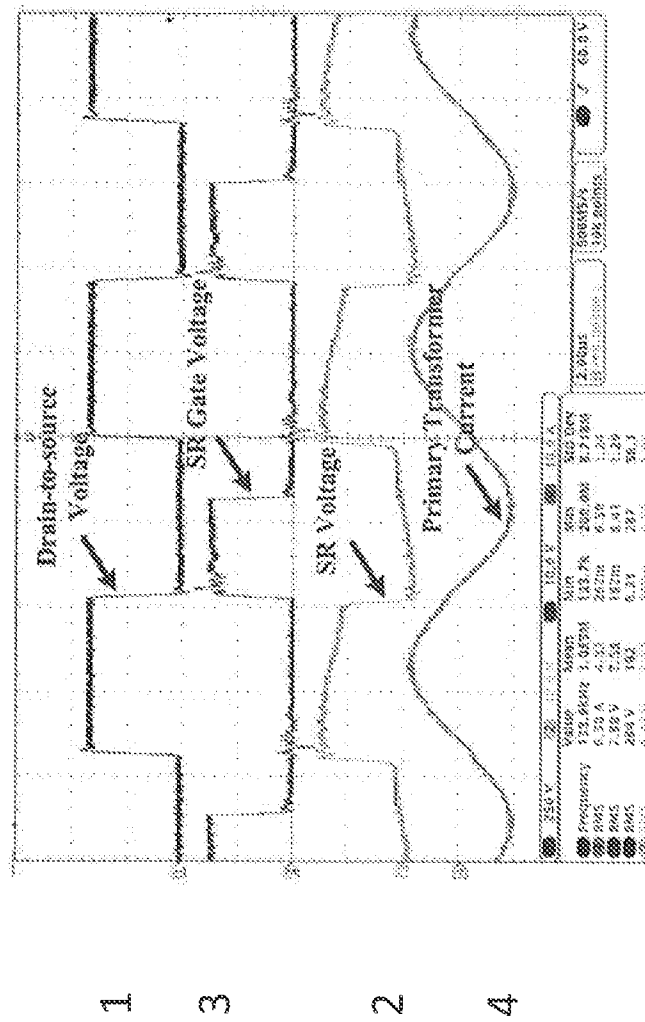


FIG. 34



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