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(54) **Title:** MODULAR MULTILEVEL INERTIAL-LESS MV TO DC (MV2DC) TRANSFORMERS

(57) **Abstract:** A power converter, comprising a DC bridge, a first transformer, a plurality of AC bridges, and a controller. The DC bridge can be electrically coupled to a DC power source. The first transformer can comprise a primary winding electrically interfacing with the DC bridge and a plurality of secondary windings. The plurality of AC bridges can be electrically coupled in series, wherein each of the plurality of AC bridges electrically interfaces with a respective secondary winding of the plurality of secondary windings. The controller can be configured to control the DC bridge and the plurality of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to DC or AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the plurality of AC bridges.

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MODULAR MULTILEVEL INERTIAL-LESS MV TO DC (MV2DC) TRANSFORMERS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 63/526,770, filed on 14 July 2024, which is incorporated herein by reference in its entirety as if fully set forth below.

FIELD OF THE DISCLOSURE

[0002] The various embodiments of the present disclosure relate generally to transformers, and more particularly, to modular multilevel inertia-less MV to DC transformers.

BACKGROUND

[0003] We are in the midst of a global energy transition towards a decarbonized energy system, driven in large part by continued advances and price declines in technologies such as PV solar, batteries, digital electronics, and power semiconductors. Growth of PV solar in the US is expected to reach 1050 GW by 2035, exceeding the total connected generation capacity in the US. Similarly, electric vehicles are growing at a 60% year-over-year rate and are expected to reach 125 million EVs over the next 15 years. At the same time, the growth of wind energy, energy storage, and hydrogen electrolyzer systems is continuing at a similar breakneck pace. The lower costs are making the transition towards decarbonization even easier, driving a move towards electrification of everything. All this is creating enormous demand for new electricity infrastructure, including wires, transformers, motors, batteries, solar panels, etc., which in turn is driving up demand for basic materials such as copper, aluminum, steel, Lithium, and rare earth metals. In the case of power transformers, this has already driven a severe shortage and extended supply times from 3 months to more than 3 years (and growing), all at a time when demand is exploding.

[0004] Hundreds of gigawatts of new sources and loads are looking to connect to the grid and exchange energy with it. This includes PV solar, battery energy storage, EV charging, and hydrogen electrolysis – in many cases showing a ‘cellular’ structure that operates at its core with a DC voltage that is typically in the range of 400 VDC to 1500 VDC, with individual subgroups or modules rated at 100 kW to 2-3 MW. In some applications, e.g., in energy storage or vehicleto-grid (V2G), power flow may need to be bidirectional. To interconnect with the grid, this voltage has to be converted to AC and is then coupled to the grid with a 60 Hz transformer. Power levels for individual facilities range from 100 kW for a DC fast charger or small industrial-scale PV or storage system, to as much as 1000 MW for utility-scale PV, storage, fuel cells, and hydrogen electrolysis. Additional applications such as locomotive traction are also important, consuming 3-5 MW of power with a 25 kV single-phase voltage catenary. In most of these cases, the AC grid is at a distribution level, ranging from 13 kV to 34 kV, with each connected ‘module’ rated at 100 kW to a few megawatts. Many modules are then paralleled to achieve the overall system rating. This architecture is almost universal and requires both the DC/AC converter, the MV transformer, and associated sensing and protection devices. Even a small 100 kW DC fast charger, including transformer and switchgear, can weigh over 1500 kg and cost >$50,000. Integrating all this functionality into a simple, low-cost scalable single-stage device can have a significant impact on this rapidly growing sector.

[0005] The use of power converters to replace transformers and realize a solid-state transformer or SST, has been proposed for many decades, but the ability to realize robust, efficient, and cost-effective solutions has eluded us, and the idea has remained an aspiration. The concept has typically built on the use of a modular multilevel converter (MMC) to convert the high or medium-voltage (MV) AC line to a DC voltage. This topology has been widely used in high-power HVDC systems. For use in medium voltage distribution grids, especially where conversion to DC is also required, a dual active bridge (DAB) converter is often used. FIG. 1 shows a typical MV AC to LV DC converter schematic. Voltage sharing between the series stacked stages of the MMC, under static and dynamic conditions, is a major challenge, requiring complex control and protection strategies. Such an approach, including many intermediate energy storage elements, results in high volume and cost, slow dynamic response, as well as complexity in terms of control. Finally, the SST has to be able to manage major faults and transients on the grid, including lightning strikes, resulting in ‘basic insulation level’ or BIL requirements of >90 kV. While this is relatively easy to achieve in passive transformers, ensuring that semiconductor devices are safe in the presence of such transients is more challenging.

[0006] Another approach, called the soft switching solid-state transformer (S4T), proposed the use of low-inertia current-source type converters, with stacked converters on the medium voltage side, where the voltage sharing was ensured through the use of model predictive control. This also proved to be very challenging to control, especially under dynamic, transient, and overload conditions. Further, the size and cost goals could not be met. As a result, it is seen that while there are several technically viable solutions, none of them, thus far, have shown that they can meet the requirements of robustness, controllability, and cost.

BRIEF SUMMARY

[0007] An exemplary embodiment of the present disclosure provides a power converter, comprising a DC bridge, a first transformer, a plurality of AC bridges, and a controller. The DC bridge can be electrically coupled to a DC power source. The first transformer can comprise a primary winding electrically interfacing with the DC bridge and a plurality of secondary windings. The plurality of AC bridges can be electrically coupled in series, wherein each of the plurality of AC bridges electrically interfaces with a respective secondary winding of the plurality of secondary windings. The controller can be configured to control the DC bridge and the plurality of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to DC or AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the plurality of AC bridges.

[0008] In any of the embodiments disclosed herein, each of the plurality of AC bridges can be not connected in shunt with an energy storage capacitor.

[0009] In any of the embodiments disclosed herein, the DC bridge can comprise four switches, and the controller can be configured to control the four switches.

[0010] In any of the embodiments disclosed herein, each of the plurality of AC bridges can comprise four bidirectional switches, and the controller can be configured to control the four bidirectional switches.

[0011] In any of the embodiments disclosed herein, each of the plurality of AC bridges can comprise a filter inductor, and the plurality of AC bridges can be electrically coupled in series via the filter inductors.

[0012] In any of the embodiments disclosed herein, each of the plurality of AC bridges can comprise a first clamping circuit electrically coupled in shunt across the respective secondary winding for the AC bridge and a second clamping circuit electrically coupled in shunt to the respective AC bridge.

[0013] In any of the embodiments disclosed herein, the first and second clamping circuits can be configured to limit voltage spikes across switches of the AC bridges.

[0014] In any of the embodiments disclosed herein, the controller can be configured to operate at least one AC bridge in the plurality of AC bridges via a pulse width modulation control signal.

[0015] In any of the embodiments disclosed herein, the pulse width modulation control signal can be a sigma-delta modulation control signal.

[0016] In any of the embodiments disclosed herein, the controller can be configured to selectively control each of the plurality of AC bridges to alter the second magnitude of the voltage level at the output of the plurality of AC bridges.

[0017] Another embodiment of the present disclosure provides a power converter comprising a DC bridge, a plurality of AC bridges, a plurality of transformers, and a controller. The DC bridge can be electrically coupled to a DC power source. The plurality of AC bridges can be electrically coupled in series. Each of the plurality of transformers can comprise a primary winding electrically interfacing with the DC bridge and a secondary winding electrically interfacing with a respective AC bridge in the plurality of AC bridges. The controller can be configured to control the DC bridge and the plurality of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to DC or AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the plurality of AC bridges.

[0018] Another embodiment of the present disclosure provides a power converter, comprising a DC bridge, a plurality of transformer, a first plurality of AC bridges, a second plurality of AC bridges, a third plurality of AC bridges, and a controller. The DC bridge can be electrically coupled to a DC power source. Each transformer in the plurality of transformers can comprise a primary winding electrically interfacing with the DC bridge, a first secondary winding, a second secondary winding, and a third secondary winding. The first plurality of AC bridges can be electrically coupled in series and configured to output an AC power signal at a first phase. Each of the first plurality of AC bridges can be electrically interfacing with a respective first secondary winding of the plurality of transformer. The second plurality of AC bridges can be electrically coupled in series and configured to output an AC power signal at a second phase. Each of the second plurality of AC bridges can be electrically interfacing with a respective second secondary winding of the plurality of transformers. The third plurality of AC bridges can be electrically coupled in series and configured to output an AC power signal at a third phase. Each of the third plurality of AC bridges can be electrically interfacing with a respective third secondary winding of the plurality of transformers. The controller can be configured to control the DC bridge and the first, second, and third pluralities of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to three-phase AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the first, second, and third pluralities of AC bridges.

[0019] In any of the embodiments disclosed herein, each AC bridge in the first, second, and third pluralities of AC bridges can comprise a filter inductor, the first plurality of AC bridges can be electrically coupled in series via the respective filter inductors, the second plurality of AC bridges can be electrically coupled in series via the respective filter inductors, and the third plurality of AC bridges can be electrically coupled in series via the respective filter inductors.

[0020] Another embodiment of the present disclosure provides a power converter comprising a DC power source, a plurality of converter units, and a controller. Each converter unit in the plurality of converter units can comprise a DC bridge coupled to the DC power source, a first AC bridge, a second AC bridge, a third AC bridge, a first transformer comprising a primary winding interfacing with the DC bridge and a secondary winding interfacing with the first AC bridge, a second transformer comprising a primary winding interfacing with the DC bridge and a secondary winding interfacing with the second AC bridge, and a third transformer comprising a primary winding interfacing with the DC bridge and a secondary winding interfacing with the third AC bridge. Outputs of each of the first AC bridges can be connected in electrical series to generate a first phase AC bridge output, outputs of each of the second AC bridges can be connected in electrical series to generate a second phase AC bridge output, and outputs of each of the third AC bridges can be connected in electrical series to generate a third phase AC bridge output. The controller can be configured to control the DC bridges and AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to the first phase, second phase, and third phase AC bridge outputs having a voltage level at a second magnitude greater than the first magnitude.

[0021] In any of the embodiments disclosed herein, each of the first AC bridges, second AC bridges, and third AC bridges can comprise a filter inductor, the first AC bridges can be electrically coupled in series via the respective filter inductors, the second AC bridges can be electrically coupled in series via the respective filter inductors, and the third AC bridges can be electrically coupled in series via the respective filter inductors.

[0022] In any of the embodiments disclosed herein, the controller can be configured to selectively control each of the first AC bridges, second AC bridges, and third AC bridges to alter the second magnitude of the voltage level at the first phase, second phase, and third phase AC bridge outputs.

[0023] These and other aspects of the present disclosure are described in the Detailed Description below and the accompanying drawings. Other aspects and features of embodiments will become apparent to those of ordinary skill in the art upon reviewing the following description of specific, exemplary embodiments in concert with the drawings. While features of the present disclosure may be discussed relative to certain embodiments and figures, all embodiments of the present disclosure can include one or more of the features discussed herein. Further, while one or more embodiments may be discussed as having certain advantageous features, one or more of such features may also be used with the various embodiments discussed herein. In similar fashion, while exemplary embodiments may be discussed below as device, system, or method embodiments, it is to be understood that such exemplary embodiments can be implemented in various devices, systems, and methods of the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The following detailed description of specific embodiments of the disclosure will be better understood when read in conjunction with the appended drawings. For the purpose of illustrating the disclosure, specific embodiments are shown in the drawings. It should be understood, however, that the disclosure is not limited to the precise arrangements and instrumentalities of the embodiments shown in the drawings.

[0025] FIG. 1 illustrates a conventional modular multilevel converter-based SST configuration.

[0026] FIGS. 2A-D provide (FIG. 2A) a circuit schematic of an exemplary isolated intertia-less converter (IIC) unit, and key waveforms of the IIC showing (FIG. 2B) positive, (FIG. 2C) zero, and (FIG. 2D) negative voltage level generation, in accordance with some embodiments of the present disclosure.

[0027] FIG. 3 provides a schematic showing detailed components of the IIC unit with locally controlled clamp configuration, in accordance with some embodiments of the present disclosure.

[0028] FIGS. 4A-C illustrate series connected AC bridges forming a converter with (FIG. 4A) independent transformer per IIC unit, (FIG. 4B) IIC units sharing a single transformer, and

(FIG. 4C) corresponding representative waveforms, respectively, in accordance with some embodiments of the present disclosure.

[0029] **FIG. 5** provides a circuit schematic of a power converter in a single-phase string implementation using IIC units for MV2DC interface, in accordance with some embodiments of the present disclosure.

[0030] **FIG. 6** provides a circuit schematic for a power converter capable of three-phase MV2DC implemented using IIC units.

[0031] **FIGS. 7A-B** provide (FIG. 7A) a circuit schematic for a MV2DC power converter with three service connected IIC comprising one ΣΔ controlled IIC unit and (FIG. 7B) its representative waveform, in accordance with some embodiments of the present disclosure.

[0032] **FIG. 8** provides exemplary controller architecture for a MV2DC power converter showing plant and core module level control layers (module control comprises staircase control for n-1 IIc units and ΣΔ control for n^{th} IIC unit, in accordance with some embodiments of the present disclosure.

[0033] **FIG. 9**, provides a schematic for an exemplary MV2DC power converter configuration for use in a windfarm, in accordance with some embodiments of the present disclosure.

[0034] **FIGS. 10A-B** provide exemplary MV2DC power converters with (FIG. 10A) series and (FIG. 10B) parallel connected modules, in accordance with some embodiments of the present disclosure.

[0035] **FIGS. 11A-B** provide (FIG. 11A) a circuit schematic of a power converter in a three-phase implementation utilizing a plurality of AC units each having a DC bridge and three transformers, one for each phase, and (FIG. 11B) a schematic for an nth AC unit, in accordance with some embodiments of the present disclosure.

DETAILED DESCRIPTION

[0036] Although preferred exemplary embodiments of the disclosure are explained in detail, it is to be understood that other exemplary embodiments are contemplated. Accordingly, it is not intended that the disclosure is limited in its scope to the details of construction and arrangement of components set forth in the following description or illustrated in the drawings. The disclosure is capable of other exemplary embodiments and of being practiced or carried out in various ways. Also, in describing the preferred exemplary embodiments, specific terminology will be resorted to for the sake of clarity.

[0037] To facilitate an understanding of the principles and features of the present disclosure, various illustrative embodiments are explained below. The components, steps, and materials described hereinafter as making up various elements of the embodiments disclosed herein are intended to be illustrative and not restrictive. Many suitable components, steps, and materials that would perform the same or similar functions as the components, steps, and materials described herein are intended to be embraced within the scope of the disclosure. Such other components, steps, and materials not described herein can include, but are not limited to, similar components or steps that are developed after development of the embodiments disclosed herein.

[0038] As used in the specification and the appended claims, the singular forms "a," "an" and "the" include plural referents unless the context clearly dictates otherwise.

[0039] Also, in describing the preferred exemplary embodiments, terminology will be resorted to for the sake of clarity. It is intended that each term contemplates its broadest meaning as understood by those skilled in the art and includes all technical equivalents which operate in a similar manner to accomplish a similar purpose.

[0040] Ranges can be expressed herein as from "about" or "approximately" one particular value and/or to "about" or "approximately" another particular value. When such a range is expressed, another exemplary embodiment includes from the one particular value and/or to the other particular value.

[0041] Similarly, as used herein, "substantially free" of something, or "substantially pure", and like characterizations, can include both being "at least substantially free" of something, or "at least substantially pure", and being "completely free" of something, or "completely pure".

[0042] By "comprising" or "containing" or "including" is meant that at least the named compound, member, particle, or method step is present in the composition or article or method, but does not exclude the presence of other compounds, materials, particles, method steps, even if the other such compounds, material, particles, method steps have the same function as what is named.

[0043] Mention of one or more method steps does not preclude the presence of additional method steps or intervening method steps between those steps expressly identified. Similarly, it is also to be understood that the mention of one or more components in a device or system does not preclude the presence of additional components or intervening components between those components expressly identified.

[0044] The materials described as making up the various members of the invention are intended to be illustrative and not restrictive. Many suitable materials that would perform the same or a similar function as the materials described herein are intended to be embraced within the scope of the invention. Such other materials not described herein can include, but are not limited to, for example, materials that are developed after the time of the development of the invention.

[0045] Reference will now be made in detail to exemplary embodiments of the disclosed technology, examples of which are illustrated in the accompanying drawings and disclosed herein. Wherever convenient, the same references numbers will be used throughout the drawings to refer to the same or like parts.

[0046] Isolated Inertia-less Converters (IIC)

[0047] The present disclosure provides novel systems and methods for converting a low-voltage DC source, e.g, 400-3,000 VDC, to a medium or high-voltage AC source, e.g., 12-35 kVAC. At the heart of the system is a building block comprising a fully bidirectional DC/HF-AC/LF-AC cell that includes high-frequency isolation, and which can be controlled in a simple open-loop manner, while still providing safety and controllability at low-cost. Such a cell is the subject of U.S. Provisional Application No. 63/526,796 and PCT Application No. PCT/US2024/037964, both of which are entitled “Control of Inertia-less High Frequency Isolated Converters” and are incorporated herein by reference in their entireties as if fully set forth below. FIG. 2A shows a circuit schematic for an exemplary Isolated Inertia-less Converter (IIC). The IIC can use a full bridge converter to convert the available DC voltage to a square wave or quasi-square wave. It can then be connected to a high-frequency transformer with very low leakage inductance, typically realized with a coaxial winding transformer (CWT) or with coaxial Litz wire windings. Exemplary transformers are disclosed in U.S. Provisional Application No. 63/655,493, entitled “Coaxial Winding Structures for Modular MV Converters,” which is incorporated herein by reference in its entirety as if fully set forth below. As used herein, “high-frequency transformer” refers to a galvanically isolated power transformer operated above 10 kHz, and typically between 20-40 kHz depending on the rated current and voltage for the transformer. The ultra-low leakage inductance, which could be in the range of 100-500 nH, can be important for optimal operation of the IIC converter. The transformer is typically implemented with a 1:1 or 1:2 turns ratio, depending on the voltages, though other winding ratios are contemplated by the present disclosure. An exemplary design could be based on an 800 VDC building block with a 1:1 turns ratio, though this disclosure is not so limited. In some applications, such as utility-scale PV solar, one could use a 3-level inverter pole configuration to connect to 1500 VDC collection systems.

[0048] Assuming that a 800 V square wave at, e.g., 20 kHz is applied to a 1:1 transformer, FIGS. 2B-D show that the same voltage is then applied to a full bridge made with bidirectional switches (realized with two SiC MOSFETs connected in anti-series). Using an "unfolding" technique that is well known, a DC or lower frequency AC waveform can be realized on the "output" of this converter. The two converter bridges can be operated without any phase shift control or intended gate delays, with typical targeted operation at zero phase shift. FIG. 3 shows a detailed structure of an IIC embodiment for practical implementation. Given real gate delays and deviations in control that may occur, it can be important that voltage clamps be included on both sides of the bidirectional bridge, as shown in FIG. 3. The voltage on the clamps can be controlled via local elements (as shown in FIG. 3) to be around the reflected DC side voltage. The current on the low-frequency (LF) AC side of the bidirectional full bridge converter can be the output current. This can be reflected back into the high-frequency (HF) transformer as a high-frequency current to prevent saturation of the core. This can be achieved by "flipping" the bridge devices so that the desired voltage can be realized at the output while the transformer current flips between $\pm Io$. This is again well known to one skilled in the art. Lastly, it is interesting to note that the magnitude of voltage on the output of the LF AC bridge can be maintained at Vs (assuming a 1:1 transformer), independent of the load current. This can be true if the leakage inductance is very low.

[0049] In U.S. Provisional Application No. 63/526,796 and PCT Application No. PCT/US2024/037964, both of which are entitled "Control of Inertia-less High Frequency Isolated Converters" and are incorporated herein by reference in their entireties as if fully set forth below, we have shown that using an integral pulse control strategy such as sigma-delta modulation (ΣΔM), one can realize a controlled AC output with the circuit shown in FIG. 3. This can be extended to three phase-controlled output, if a three-phase bidirectional bridge is used. This can be achieved using the "flipping" logic discussed above, which can allow the high-frequency transformer to be used without saturation. It should also be noted that switching the bridge devices in a PWM fashion can create voltage spikes and additional stress due to energy trapped in the transformer leakage inductance and may not be a viable solution.

[0050] For the basic IIC converter, it can be seen that the output voltage can be reflected to the LF AC output with virtually no attenuation and in every switching cycle with no delays and no transients. That can be because the voltage drop across the transformer leakage inductance is minimal. As such, the transfer function between the DC source voltage and the LF AC output bridge over a switching cycle can be unity, with virtually no energy storage – an inertia-less converter. The voltage stresses are well managed, and the energy dissipated in the clamp is minimal (because of low leakage inductance). The currents in the IIC are well controlled to I_0 by the output. Finally, using wide bandgap devices such as SiC MOSFETs would also ensure fast switching and elimination of any stored charge and reverse recovery effects and would give low switching losses.

[0051] Modular Multilevel MV2DC Transformers

[0052] To achieve the objective of medium voltage AC to DC (MV2DC) conversion from a common DC stage, the IIC converter can be split into two components — a DC module comprising a DC bridge with four swithes/devices and a DC supply, as shown in FIG. 2A, and an AC module comprising the high-frequency transformer and AC bridge, along with an output filter inductor *Lac*. A preferred approach is to have a common DC module feed multiple AC modules with a common square wave, with the AC modules/bridges connected in series to achieve higher voltage, as shown in FIG. 4A.

[0053] In particular, as shown in FIG. 4A, an exemplary power converter comprises a DC bridge 405, a plurality of AC bridges 410A-C, and a plurality of transformers. The DC bridge 405 comprises four switches. The DC bridge is electrically coupled to a DC power source 406. Each of the plurality of AC bridges 410A-C comprises four bidirectional switches. The plurality of AC 410A-C bridges 410A-C are electrically coupled in series via filter inductors 415A-C. Each of the plurality of AC bridges 410A-C can further comprise a first clamping circuit 430A-C electrically coupled in shunt across the respective secondary winding 425A-C for the AC bridge 410A-C. Each of the plurality of AC bridges 410A-C also comprise a second clamping circuit 435A-C electrically coupled in shunt to the respective AC bridge. Each of the transformers comprise a primary winding 420A-C and a secondary winding 425A-C. The primary winding 420A-C electrically interfaces with the DC bridge 405. The secondary winding 425A-C electrically interfaces with a respective AC bridge 410A-C in the plurality of AC bridges. A controller (not shown in FIG. 4A) controls the switches of the AC 410A-C and DC 405 bridges to convert DC power from the DC power source 406 having a voltage level at a first magnitude to DC or AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the plurality of AC bridges 407. As used herein, magnitude of an AC voltage means the RMS value of the AC signal. For example, if the DC power source has a voltage level of 10 VDC and the output of the AC bridges has a voltage level of 100

VAC, then the magnitude of the DC power source is 10V and the magnitude of the AC bridge output is 100V.

[0054] It can be seen that to achieve typical distribution voltage levels of 13 kV(or 34 kV) with low-cost 1.7 kV devices operating at a voltage stress of <800 V can be between 14 (or 42) AC modules/bridges stacked together in series for each phase, i.e., 3x42 for a three-phase system. With a 1 kV peak stress, the number of modules would reduce to 11 (13 kV) or 33 (34 kV). Further, with 3.3 kV devices, the number of modules would reduce to 6 (13 kV) or 17 (34 kV), with a big reduction in system cost and complexity. As of today, 3.3 kV devices are too expensive and may not be economically viable, a situation that can change in the future.

[0055] Controlling these modules by coordinating switching mode transitions of so many bidirectional devices based on local voltage and current measurements, as would be ideal for four-quadrant AC operation, would add tremendous cost and complexity, and it could degrade converter reliability. One way to simplify control is to drive all device gates in each AC module and the DC module with an autonomously derived or open-loop gating signal from a controller (not shown) that is acted upon locally by each of the modules. Any small deviations in switching instants and current flows during the switching transitions can be managed by enforcing common overlap times from the DC bridge, as well as with clamp circuits (cm_1 and cm_2) on both sides of the AC bridge using well-known techniques. The low leakage inductance can ensure low trapped energy and, thus, reduced power loss. A DC blocking capacitor (Cb) can be added on both sides of the module transformer winding (as shown in FIG. 3) to ensure that core saturation does not occur due to voltage offsets or circulating currents, even with small deviations in switching times. Further, FIG. 3 depicts an RC balancing circuit, which can be connected across each IIC unit cell to balance the voltages on the series-connected cells of the MV2DC module, particularly under conditions when the AC side bridge is off.

[0056] Given the small leakage inductance in each transformer, the voltage on the HF AC bridge input can be essentially the same voltage generated by the DC bridge (with small differences at the edges due to time to ramp up and down current in the leakage inductance). The AC bridge switches can be controlled in synchronism with the square wave to provide either a positive, zero or negative voltage on the LF AC side, as shown in FIGS. 2B-D. The series cascaded AC bridge voltages can be summed over each cycle to realize the desired stepped output voltage. At the same time, the AC bridge operation can maintain high-frequency operation on the transformer side to allow the transfer of power using the flipping logic described above. The AC bridges can utilize independent transformer as in FIG. 4A or a plurality of AC bridges can share the transformer core as in FIG. 4B, depending on the targeted performance parameters such as resulting core size, cost, and loss.

[0057] For example, FIG. 4B provides a schematic circuit for an exemplary power converter comprises a DC bridge 405, a plurality of AC bridges 410A-C, and a transformer with single primary winding 440 and a plurality of secondary windings 445A-C (as opposed to a plurality of transformers each with a single primary winding and single secondary winding, as shown in FIG. 4A). The DC bridge 405 comprises four switches. The DC bridge 405 is electrically coupled to a DC power source 406. Each of the plurality of AC bridges 410A-C comprises four bidirectional switches. The plurality of AC 410A-C bridges 410A-C are electrically coupled in series via filter inductors 415A-C. Each of the plurality of AC bridges 410A-C can further comprise a first clamping circuit 430A-C electrically coupled in shunt across a respective secondary winding 445A-C of the transformer for the AC bridge 410A-C. Each of the plurality of AC bridges 410A-C also comprise a second clamping circuit 435A-C electrically coupled in shunt to the respective AC bridge. The primary winding 440A electrically interfaces with the DC bridge 405. The secondary windings 445A-C electrically interfaces with a respective AC bridge 410A-C in the plurality of AC bridges. A controller (not shown in FIG. 4B) controls the switches of the AC 410A-C and DC 405 bridges to convert DC power from the DC power source 406 having a voltage level at a first magnitude to DC or AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the plurality of AC bridges 407.

[0058] FIG. 4C shows a representative waveform of three AC bridges connected in series that achieve the stepped output waveform, while achieving the desired high-frequency current in each of the transformers. The voltage stress across each device in the AC bridge can be limited by the HF square wave, and by the clamp voltages, while the current in each device can be limited by the current in the low-frequency output side. It can be noted that the low-frequency side can provide DC outputs, allowing scaling to MVDC also.

[0059] FIG. 5 shows a exemplary embodiment of a single-phase string that can be supported from a single DC bridge switching from a 800 V DC source. As an example, 14 IIC cells generating +/- 800 V on the LF AC output side can be stacked in series to generate a “stepped waveform” at 7.2 kV rms, the line-neutral voltage in a 13 kV distribution system. All IIC stages switch simultaneously with a single square wave that is generated by the DC stage. An output inductor is integrated with the IIC module to improve modularity and scalability and to provide local filtering against high-frequency notches and transients that can be generated. It should be noted that all 14 inductors in the IIC modules are series connected and together realize the filter inductor utilized at the grid interface. It is also possible to add an extra AC module, which could provide redundancy and the ability to reach the target output voltage, even in case of a single AC module failure. If all 14 IIC modules are turned off, the stack has a voltage withstand capability of 47.6 kV (with 1.7 kV devices), 4.6 times the peak normal voltage on the grid side. This allows for robust protection strategies and ensures safe operation and shutdown.

[0060] FIG. 6 shows an exemplary embodiment in which three such strings are used to realize a three-phase MV2DC Transformer core module, including a single DC stage and ‘N’ number of IIC modules. The converter shown in FIG. 6 comprises a DC bridge 605. The converter further comprises a plurality of transformers each having a primary winding 620A-C, a first secondary winding 625A-C, a second secondary winding 626A-C, and a third secondary winding 627A-C. A first plurality of AC bridges 630A-C are electrically coupled in series and configured to output an AC power signal at a first phase of a three-phase signal. Each of the first plurality of AC bridges 630A-C electrically interface with a respective first secondary winding 625A-C of the plurality of transformers. A second plurality of AC bridges 631A-C are electrically coupled in series and configured to output an AC power signal at a second phase of a three-phase signal. Each of the second plurality of AC bridges 631A-C electrically interface with a respective second secondary winding 626A-C of the plurality of transformers. A third plurality of AC bridges 632A-C are electrically coupled in series and configured to output an AC power signal at a third phase of a three-phase signal. Each of the third plurality of AC bridges 632A-C electrically interface with a respective third secondary winding 627A-C of the plurality of transformers.

[0061] For instance, with 42 such modules, each rated at 8 kW, one can realize a 13.2 kV MV2DC Transformer rated at 333 kW. One can then take three such MV2DC core modules (with their individual DC modules) and reconnect the output phases in series to realize a 1 MW system at 34 kV or connect the phases in parallel to realize a 1 MW system at 13 kV. These core modules can be further paralleled to increase the overall power rating at the plant level. In many cases, the DC system itself is “modular” in structure (e.g., batteries, PV strings, or electrolyzers), allowing the DC side to be scaled as needed without requiring enormous DC side currents. This provides high modularity and flexibility in addressing a wide variety of applications and grid specifications that can be found today, all using the same modules.

[0062] The stepped waveform is similar to conventional MMC converters. For example, to realize 150 kV DC with 1.5 kV granularity, 100 steps are utilized. Here, at 13 kV, we see only 14 steps, which can result in undesirable transients and harmonics on the AC side. To address this issue, one of the series stacked IIC cells can employ sigma-delta modulation (ΣΔM) control, as discussed earlier. This approach can use a discrete pulse modulation control strategy to reduce the impact of the steps and achieve low THD currents in the grid. FIGS. 7A-B show an exemplary embodiment of an IIC cell operating under sigma-delta control, along with representative waveforms. This shows switching at a much faster rate than the stepped waveform, allowing finer control of the fundamental and mitigation of harmonics, without in any way compromising the basic premise of the IIC cell or the MV2DC Transformer. With the ΣΔM stage implemented in one or more cells, we essentially see a very high-performance arbitrary voltage source with high bandwidth that can provide grid support, including grid forming and black start capability for grid-connected DER resources.

[0063] There can be virtually no energy storage in the entire MV2DC Transformer, except at the DC source. The entire converter can look like an arbitrary voltage source behind the filter inductor with no dynamics or coupling, making the grid-connected plant easier to control. Unlike an MMC, there are no dynamics associated with balancing capacitor voltages, or dynamic issues with handling fault currents. In case of a grid side fault, the MV2DC system can, within one switching cycle, reduce its voltage to match the grid and to control the current, or can present a desired level of inertia as needed. An exemplary controller that can be utilized to control the various embodiments disclosed herein is shown in FIG. 8. The controller can comprise a master controller at the plant level, another layer of control at the core module level, and local control at each IIC cell level, as well as communications between modules and the cloud. Thus, as used herein, the term “controller” can refer to a single controller or multiple controllers that operate together to achieve functionality of the various converters disclosed herein.

[0064] FIGS. 11A-B provide another embodiment of a three-phase power converter. The converter comprises a DC power source 1105, a plurality of converter units 1110A-C, and a controller (not shown in FIGS. 11A-B). FIG. 11B provides a schematic of a converter unit, while FIG. 11A shows a collection of three converter units 1110A-C in which only the first phase AC bridges are shown. Each converter unit comprises a DC bridge 1115A-C coupled to the DC power source 1105, a first AC bridge 1120A-C, a second AC bridge 1121, a third AC bridge 1122, a first transformer 1125A-C, a second transformer 1126, and a third transformer 1127. The first transformer comprises a primary winding interfacing with the DC bridge and a secondary winding interfacing with the first AC bridge. The second transformer comprises a primary winding interfacing with the DC bridge and a secondary winding interfacing with the second AC bridge. The third transformer comprises a primary winding interfacing with the DC bridge and a secondary winding interfacing with the third AC bridge. The outputs of each of the first AC bridges are connected in electrical series to generate a first phase AC bridge output. The outputs of each of the second AC bridges are connected in electrical series to generate a second phase AC bridge output. The outputs of each of the third AC bridges are connected in electrical series to generate a third phase AC bridge output. The controller is configured to control the DC bridges and AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to the first phase, second phase, and third phase AC bridge outputs having a voltage level at a second magnitude greater than the first magnitude. Thus, for example, the converter can receive DC power at a first voltage level and generate three-phase AC power as a higher voltage level.

[0065] MV2DC Transformer Applications and Impact

[0066] The MV2DC embodiments disclosed herein show novel approaches to realizing a flexible, robust, and scalable grid connection for a wide variety of high-power applications, including energy storage, hydrogen electrolyzers, PV solar farms, EV fast charging, and traction locomotives. It can also be used to implement distribution-level grid-forming STATCOMs, including energy storage. It can also be utilized with the windfarm applications, wherein windfarm can have direct connect to medium voltage three-phase AC on land (see FIG. 9). For offshore windfarms, collector field can be a MVDC (e.g., 50kV) with the presented modular MV2DC stage can essentially be used as DC/DC interface to level-up the voltage if needed or can be connected to the three-phase AC grid.

[0067] The heart of the system can be the IIC cell, which can be split into a common DC module and multiple AC modules. The AC modules can be stacked in series to realize a variety of typical distribution voltages ranging from 13 kV to 34 kV AC. While the number of AC modules connected in series can be arbitrarily defined, standard modules that address the 13 kV applications can be connected in series (see FIG. 10A) and parallel (see FIG. 10B) to address other voltage classes – e.g., 20 kV/34 kV.

[0068] The IIC AC module represents a building block, one which can be manufactured at scale. A 1 MW system can utilze ~42 modules, and a 500 MW hydrogen electrolyzer could utilize 21,000 modules, and 42 million modules at 1 GW scale. A 1 MW MV2DC subsystem that can operate over 13-34 kV AC can utilize an IIC module rated at 8 kW at ~800 VDC. It is possible to extend the AC module concept further to say 80 kW for a 10 MW MV2DC subsystem, or down to 2.8 kW for a 100 kW system. An optimization can be done to analyze which rating is the most optimal for which application, and to fit the widest range of applications with a minimal number of high-volume AC modules. The IIC AC module can be designed with parts that are commonly available in high volume and can be manufactured very economically using standard automated power electronics manufacturing techniques. An estimate of cost and weight for an application such as EV fast charging suggests that the cost can be reduced by 2X and weight by 10X. Similar benefits are possible in other applications.

[0069] It is to be understood that the embodiments and claims disclosed herein are not limited in their application to the details of construction and arrangement of the components set forth in the description and illustrated in the drawings. Rather, the description and the drawings provide examples of the embodiments envisioned. The embodiments and claims disclosed herein are further capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purposes of description and should not be regarded as limiting the claims.

[0070] Accordingly, those skilled in the art will appreciate that the conception upon which the application and claims are based may be readily utilized as a basis for the design of other structures, methods, and systems for carrying out the several purposes of the embodiments and claims presented in this application. It is important, therefore, that the claims be regarded as including such equivalent constructions.

[0071] Furthermore, the purpose of the foregoing Abstract is to enable the United States Patent and Trademark Office and the public generally, and especially including the practitioners in the art who are not familiar with patent and legal terms or phraseology, to determine quickly from a cursory inspection the nature and essence of the technical disclosure of the application. The Abstract is neither intended to define the claims of the application, nor is it intended to be limiting to the scope of the claims in any way.

CLAIMS

What is claimed is:

1. A power converter, comprising:

a DC bridge electrically coupled to a DC power source;

a first transformer comprising:

a primary winding electrically interfacing with the DC bridge; and

a plurality of secondary windings;

a plurality of AC bridges electrically coupled in series, each of the plurality of AC bridges electrically interfacing with a respective secondary winding of the plurality of secondary windings; and

a controller configured to control the DC bridge and the plurality of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to DC or AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the plurality of AC bridges.

2. The power converter of claim 1, wherein each of the plurality of AC bridges is not connected in shunt with an energy storage capacitor.

3. The power converter of claim 1, wherein the DC bridge comprises four switches, and wherein the controller is configured to control the four switches.

4. The power converter of claim 1, wherein each of the plurality of AC bridges comprises four bidirectional switches, and wherein the controller is configured to control the four bidirectional switches.

5. The power converter of claim 1, wherein each of the plurality of AC bridges comprises a filter inductor, wherein the plurality of AC bridges are electrically coupled in series via the filter inductors.

6. The power converter of claim 1, wherein each of the plurality of AC bridges comprises:

a first clamping circuit electrically coupled in shunt across the respective secondary winding for the AC bridge; and

a second clamping circuit electrically coupled in shunt to the respective AC bridge.

7. The power converter of claim 6, wherein the first and second clamping circuits are configured to limit voltage spikes across switches of the AC bridges.

8. The power converter of claim 1, wherein the controller is configured to operate at least one AC bridge in the plurality of AC bridges via a pulse width modulation control signal.

9. The power converter of claim 8, wherein the pulse width modulation control signal is a sigma-delta modulation control signal.

10. The power converter of claim 1, wherein the controller is configured to selectively control each of the plurality of AC bridges to alter the second magnitude of the voltage level at the output of the plurality of AC bridges.

11. A power converter, comprising:

a DC bridge electrically coupled to a DC power source;

a plurality of AC bridges electrically coupled in series;

a plurality of transformers, each transformer comprising:

a primary winding electrically interfacing with the DC bridge; and

a secondary winding electrically interfacing with a respective AC bridge in the plurality of AC bridges; and

a controller configured to control the DC bridge and the plurality of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to DC or AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the plurality of AC bridges.

12. The power converter of claim 11, wherein each of the plurality of AC bridges is not connected in shunt with an energy storage capacitor.

13. The power converter of claim 11, wherein the DC bridge comprises four switches, and wherein the controller is configured to control the four switches.

14. The power converter of claim 11, wherein each of the plurality of AC bridges comprises four bidirectional switches, and wherein the controller is configured to control the four bidirectional switches.

15. The power converter of claim 11, wherein each of the plurality of AC bridges comprises a filter inductor, wherein the plurality of AC bridges are electrically coupled in series via the filter inductors.

16. The power converter of claim 11, wherein each of the plurality of AC bridges comprises:

a first clamping circuit electrically coupled in shunt across the respective secondary winding for the AC bridge; and

a second clamping circuit electrically coupled in shunt to the respective AC bridge.

17. The power converter of claim 16, wherein the first and second clamping circuits are configured to limit voltage spikes across switches of the AC bridges.

18. The power converter of claim 11, wherein the controller is configured to operate at least one AC bridge in the plurality of AC bridges via a pulse width modulation control signal.

19. The power converter of claim 18, wherein the pulse width modulation control signal is a sigma-delta modulation control signal.

20. The power converter of claim 11, wherein the controller is configured to selectively control each of the plurality of AC bridges to alter the second magnitude of the voltage level at the output of the plurality of AC bridges.

21. A power converter, comprising:

a DC bridge electrically coupled to a DC power source;

a plurality of transformers, each transformer in the plurality of transformers comprising:

a primary winding electrically interfacing with the DC bridge; and

a first secondary winding;

a second secondary winding; and

a third secondary winding;

a first plurality of AC bridges electrically coupled in series and configured to output an AC power signal at a first phase, each of the first plurality of AC bridges electrically interfacing with a respective first secondary winding of the plurality of transformer;

a second plurality of AC bridges electrically coupled in series and configured to output an AC power signal at a second phase, each of the second plurality of AC bridges electrically interfacing with a respective second secondary winding of the plurality of transformers;

a third plurality of AC bridges electrically coupled in series and configured to output an AC power signal at a third phase, each of the third plurality of AC bridges electrically interfacing with a respective third secondary winding of the plurality of transformers; and

a controller configured to control the DC bridge and the first, second, and third pluralities of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to three-phase AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the first, second, and third pluralities of AC bridges.

22. The power converter of claim 21, wherein each AC bridge in the first, second, and third pluralities of AC bridges is not connected in shunt with an energy storage capacitor.

23. The power converter of claim 21, wherein the DC bridge comprises four switches, and wherein the controller is configured to control the four switches.

24. The power converter of claim 21, wherein each AC bridge in the first, second, and third pluralities of AC bridges comprises four bidirectional switches, and wherein the controller is configured to control the four bidirectional switches.

25. The power converter of claim 21, wherein each AC bridge in the first, second, and third pluralities of AC bridges comprises a filter inductor, wherein the first plurality of AC bridges are electrically coupled in series via the respective filter inductors, the second plurality of AC bridges are electrically coupled in series via the respective filter inductors, and the third plurality of AC bridges are electrically coupled in series via the respective filter inductors.

26. The power converter of claim 21, wherein each AC bridge in the first, second, and third pluralities of AC bridges comprises:

a first clamping circuit electrically coupled in shunt across the respective secondary winding for the AC bridge; and

a second clamping circuit electrically coupled in shunt to the respective AC bridge.

27. The power converter of claim 26, wherein the first and second clamping circuits are configured to limit voltage spikes across switches of the respective AC bridge.

28. The power converter of claim 21, wherein the controller is configured to operate at least one AC bridge in the first, second, and third pluralities of AC bridges via a pulse width modulation control signal.

29. The power converter of claim 28, wherein the pulse width modulation control signal is a sigma-delta modulation control signal.

30. The power converter of claim 21, wherein the controller is configured to selectively control each AC bridge in the first, second, and third pluralities of AC bridges to alter the second magnitude of the voltage level at the output of the first, second, and third pluralities of AC bridges respectively.

31. A power converter, comprising:

a DC power source;

a plurality of converter units, each converter unit comprising:

a DC bridge coupled to the DC power source;

a first AC bridge;

a second AC bridge;

a third AC bridge;

a first transformer comprising a primary winding interfacing with the DC bridge and a secondary winding interfacing with the first AC bridge;

a second transformer comprising a primary winding interfacing with the DC bridge and a secondary winding interfacing with the second AC bridge; and

a third transformer comprising a primary winding interfacing with the DC bridge and a secondary winding interfacing with the third AC bridge;

wherein outputs of each of the first AC bridges are connected in electrical series to generate a first phase AC bridge output, outputs of each of the second AC bridges are connected in electrical series to generate a second phase AC bridge output, and outputs of each of the third AC bridges are connected in electrical series to generate a third phase AC bridge output; and

a controller configured to control the DC bridges and AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to the first phase, second phase, and third phase AC bridge outputs having a voltage level at a second magnitude greater than the first magnitude.

32. The power converter of claim 31, wherein each of the first AC bridges, second AC bridges, and third AC bridges is not connected in shunt with an energy storage capacitor.

33. The power converter of claim 31, wherein each of the DC bridges comprises four switches, and wherein the controller is configured to control the four switches.

34. The power converter of claim 31, wherein each of the first AC bridges, second AC bridges, and third AC bridges comprises four bidirectional switches, and wherein the controller is configured to control the four bidirectional switches.

35. The power converter of claim 31, wherein each of the first AC bridges, second AC bridges, and third AC bridges comprises a filter inductor, wherein the first AC bridges are electrically coupled in series via the respective filter inductors, the second AC bridges are electrically coupled in series via the respective filter inductors, and the third AC bridges are electrically coupled in series via the respective filter inductors.

36. The power converter of claim 31, wherein each of the first AC bridges, second AC bridges, and third AC bridges comprises:

a first clamping circuit electrically coupled in shunt across the respective secondary winding for the AC bridge; and

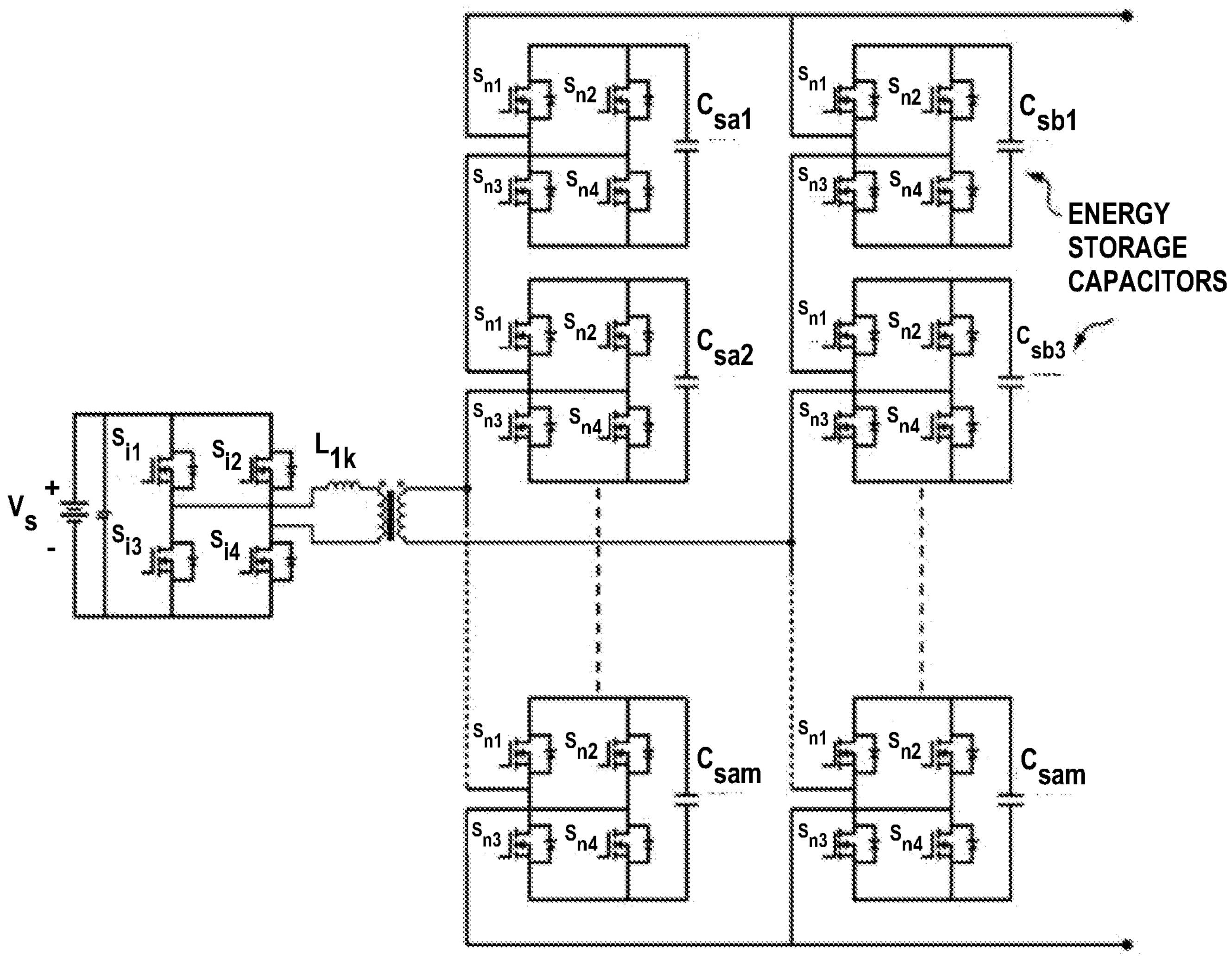
a second clamping circuit electrically coupled in shunt to the respective AC bridge.

37. The power converter of claim 36, wherein the first and second clamping circuits are configured to limit voltage spikes across switches of the respective AC bridge.

38. The power converter of claim 31, wherein the controller is configured to operate at least one of the first AC bridges, second AC bridges, and third AC bridges via a pulse width modulation control signal.

39. The power converter of claim 38, wherein the pulse width modulation control signal is a sigma-delta modulation control signal.

40. The power converter of claim 31, wherein the controller is configured to selectively control each of the first AC bridges, second AC bridges, and third AC bridges to alter the second magnitude of the voltage level at the first phase, second phase, and third phase AC bridge outputs.



V
s
+
-
S
i1
S
i2
S
i3
S
i4
L
1k
S
n1
S
n2
S
n3
S
n4
C
sa1
C
sa2
C
sam
C
sb1
C
sb3
ENERGY
STORAGE
CAPACITORS

FIG. 1

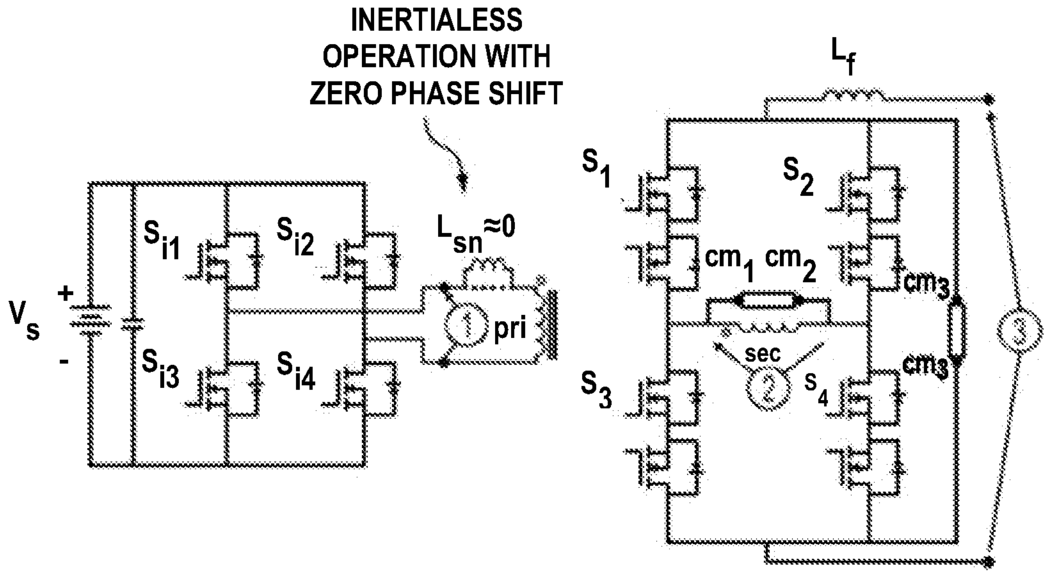

INERTIALESS
OPERATION WITH
ZERO PHASE SHIFT
L_f
S_1
S_2
S_{i1}
S_{i2}
$L_{sn} \approx 0$
V_s
+
-
S_{i3}
S_{i4}
1
pri
cm_1 cm_2
cm_3
cm_3
sec
2
S_3
S_4
3

FIG. 2A

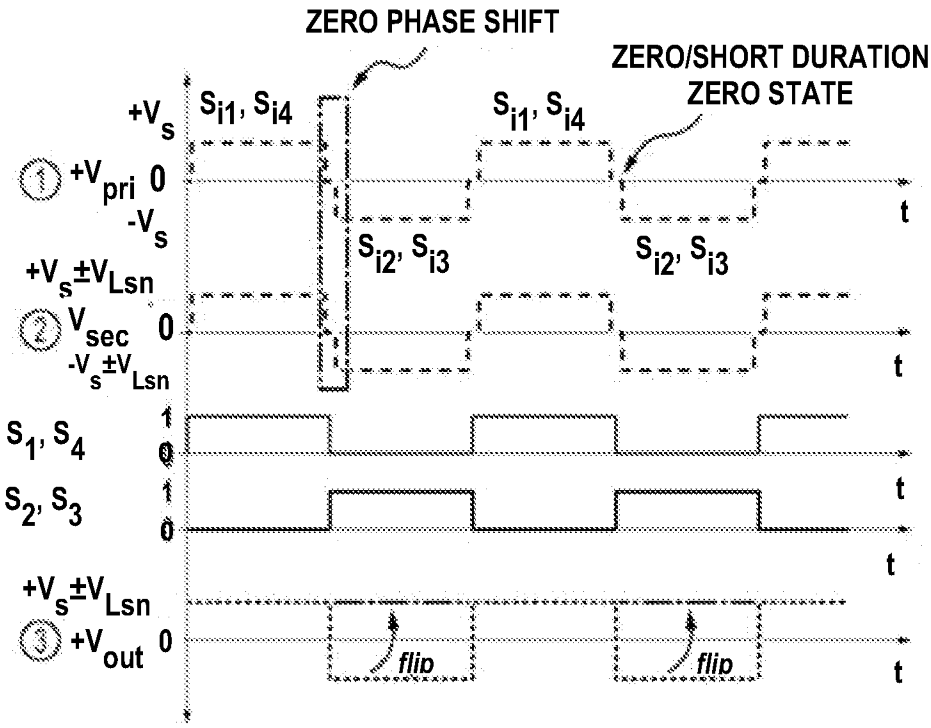

ZERO PHASE SHIFT
ZERO/SHORT DURATION
ZERO STATE
$+V_s$
S_{i1}, S_{i4}
S_{i1}, S_{i4}
1 $+V_{pri}$ 0
$-V_s$
t
S_{i2}, S_{i3}
S_{i2}, S_{i3}
$+V_s \pm V_{Lsn}$
2 V_{sec} 0
$-V_s \pm V_{Lsn}$
t
S_1, S_4
1
0
S_2, S_3
1
0
t
t
$+V_s \pm V_{Lsn}$
3 $+V_{out}$ 0
flip
flip
t

FIG. 2B

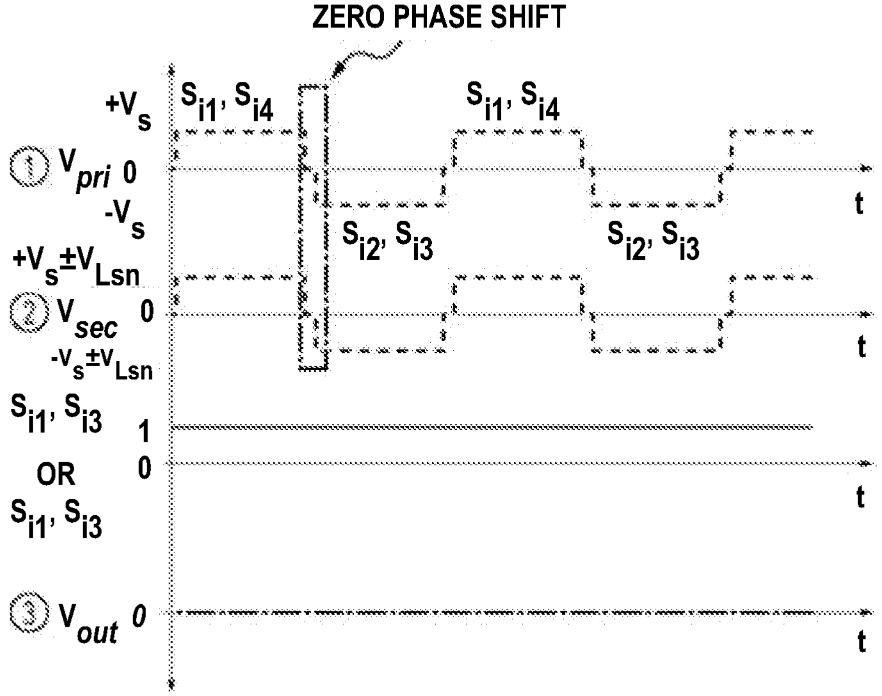

ZERO PHASE SHIFT
+Vs
Si1, Si4
① Vpri 0
-Vs
Si2, Si3
t
+Vs±VLsn
② Vsec 0
-Vs±VLsn
t
Si1, Si3
1
0
OR
Si1, Si3
t
③ Vout 0
t

FIG. 2C

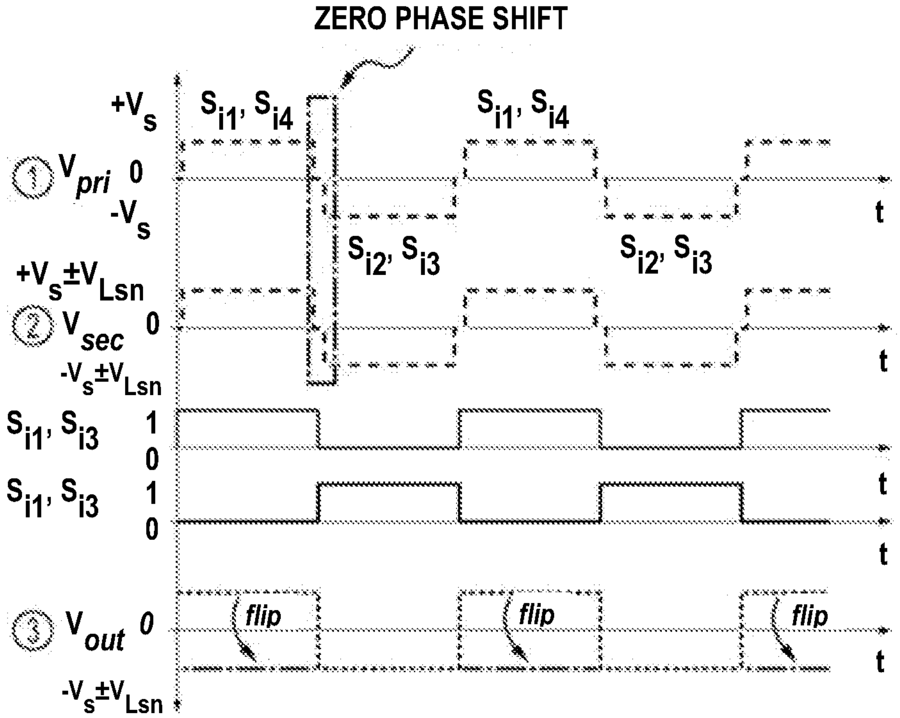

ZERO PHASE SHIFT
+Vs
Si1, Si4
① Vpri 0
-Vs
Si2, Si3
t
+Vs±VLsn
② Vsec 0
-Vs±VLsn
t
Si1, Si3
1
0
t
Si1, Si3
1
0
t
flip
③ Vout 0
-Vs±VLsn
t

FIG. 2D

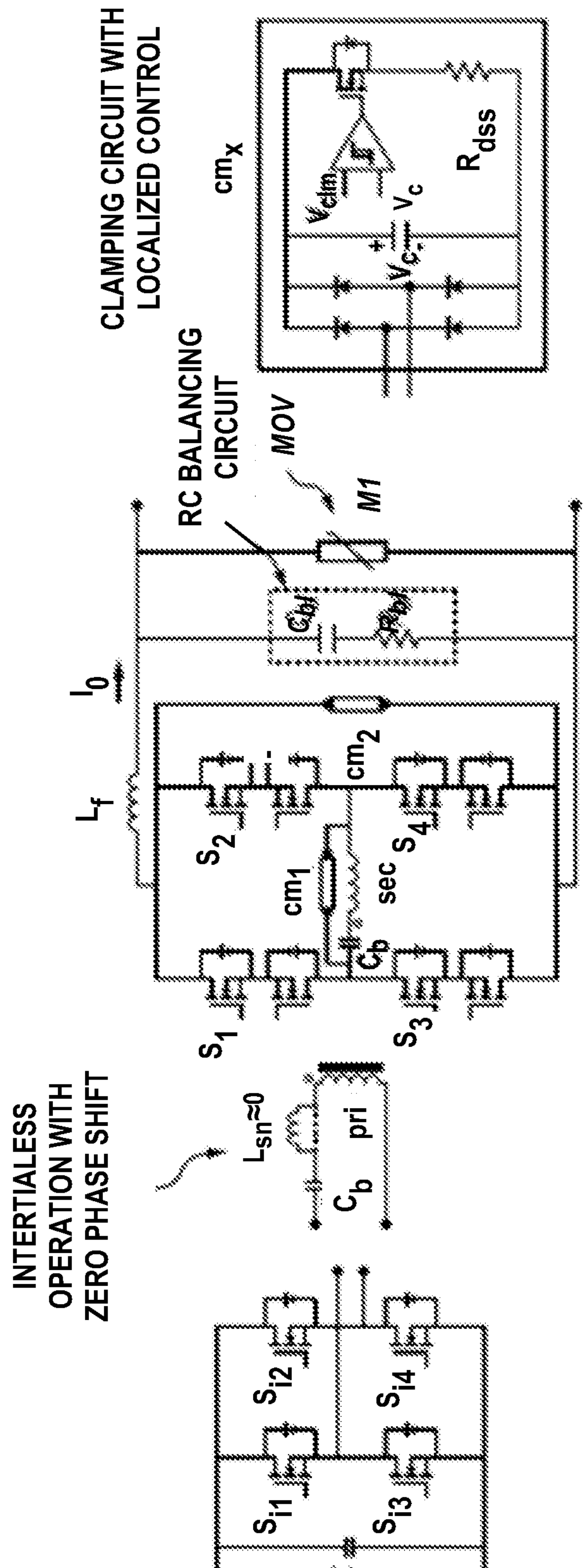
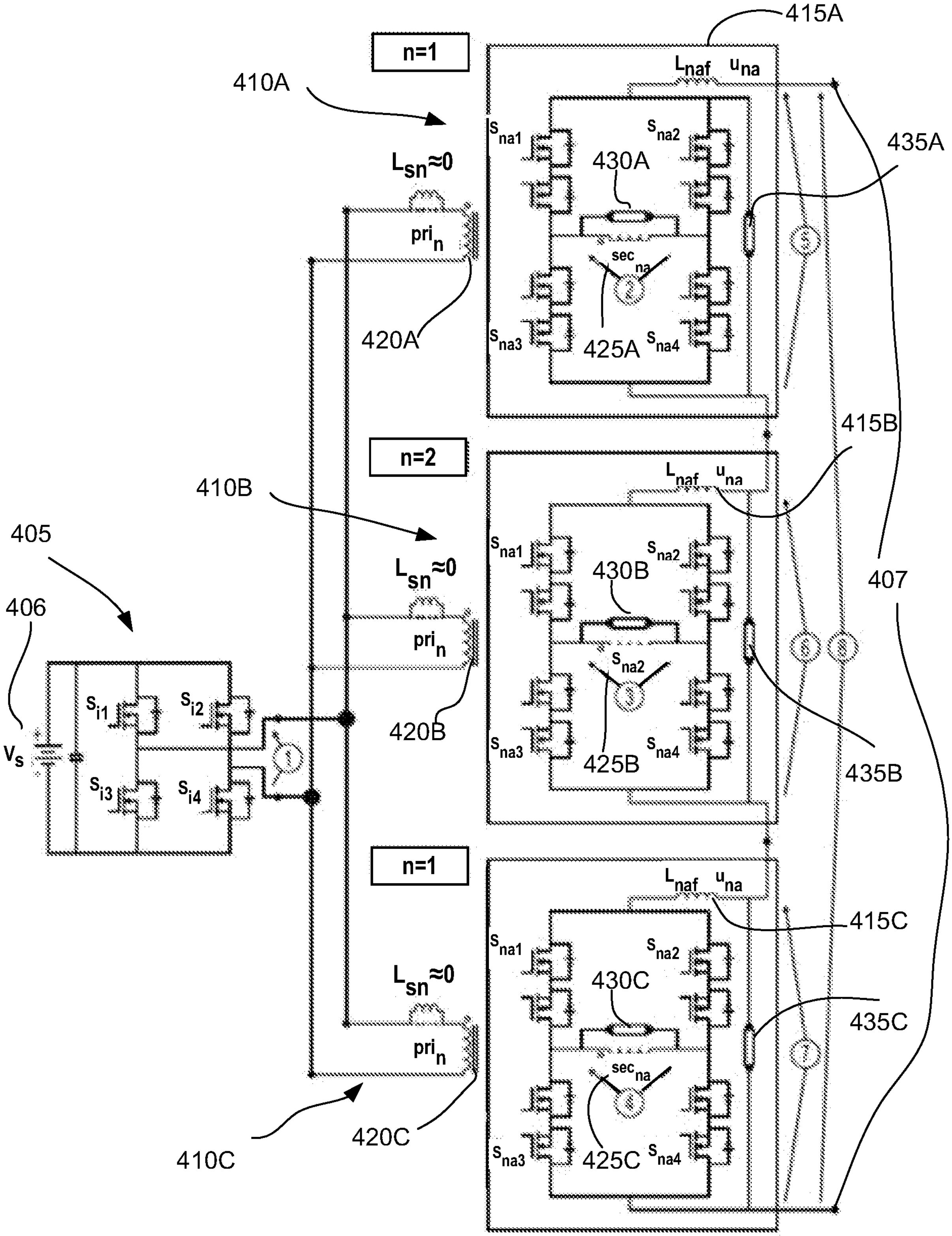
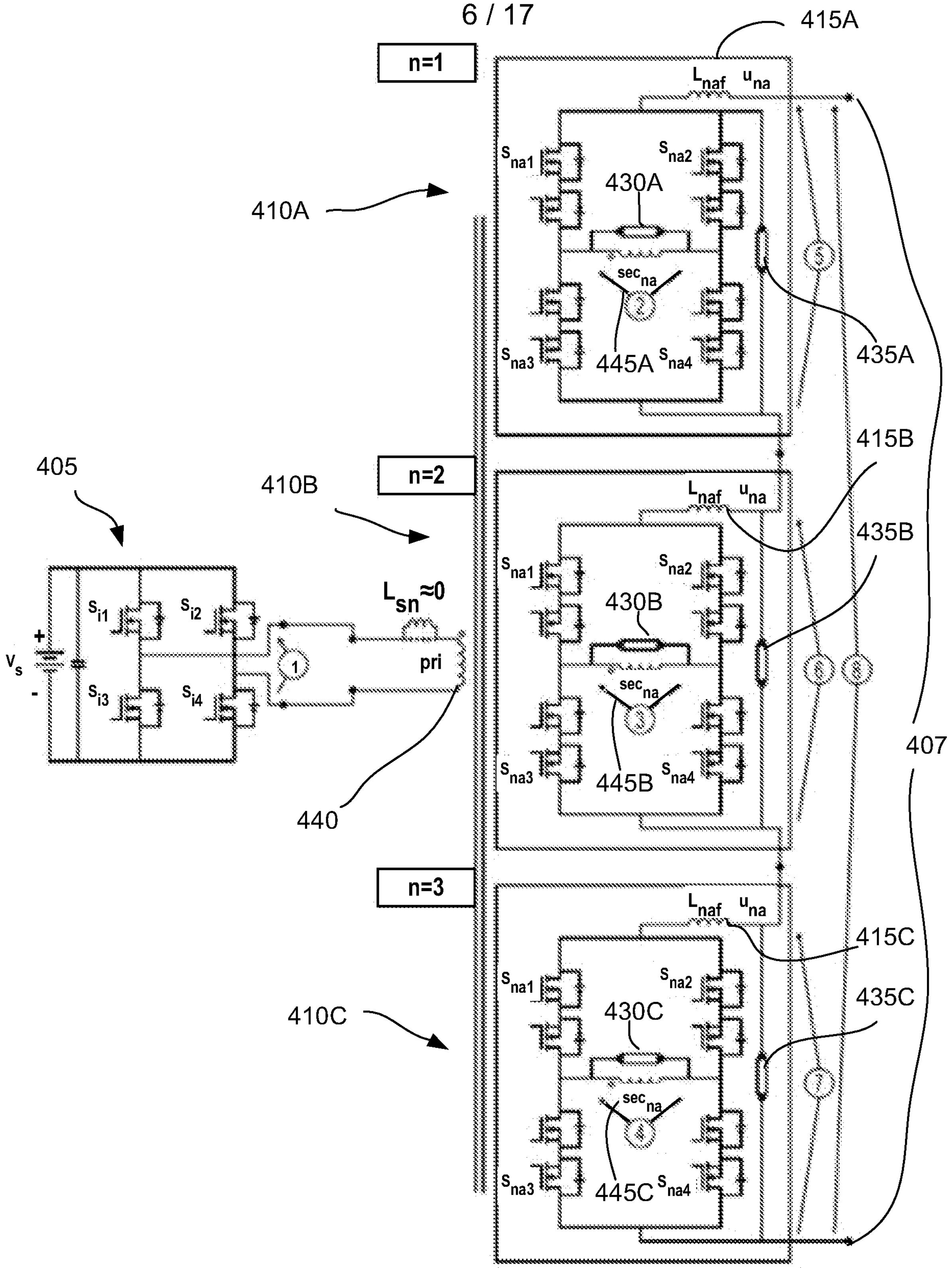

CLAMPING CIRCUIT WITH LOCALIZED CONTROL
cm_x
R_{dss}
V_{clm}
V_c
RC BALANCING CIRCUIT
MOV
M1
C_{bl}
R_{bl}
I_0
L_f
S_2
cm_2
S_4
cm_1
sec
C_b
S_1
S_3
INTERTIALESS OPERATION WITH ZERO PHASE SHIFT
L_{sn}≈0
pri
C_b
S_{i2}
S_{i4}
S_{i1}
S_{i3}
+
V_s
-

FIG. 3



415A
n=1
L_{naf} u_{na}
410A
s_{na1}
s_{na2}
435A
L_{sn}≈0
430A
pri_n
sec_{na}
420A
s_{na3}
425A
s_{na4}
n=2
415B
L_{naf} u_{na}
410B
s_{na1}
s_{na2}
405
L_{sn}≈0
430B
407
406
pri_n
s_{na2}
s_{i1}
s_{i2}
420B
V_s
s_{i3}
s_{i4}
s_{na3}
425B
s_{na4}
435B
n=1
L_{naf} u_{na}
415C
s_{na1}
s_{na2}
L_{sn}≈0
430C
435C
pri_n
sec_{na}
410C
420C
s_{na3}
425C
s_{na4}

FIG. 4A



415A
n=1
L_{naf} u_{na}
s_{na1}
s_{na2}
410A
430A
sec_{na}
2
5
435A
445A
s_{na3}
s_{na4}
405
410B
n=2
415B
435B
$L_{sn}≈0$
s_{i1}
s_{i2}
V_s
s_{i3}
s_{i4}
1
pri
430B
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410C
430C
7
4
445C

FIG. 4B

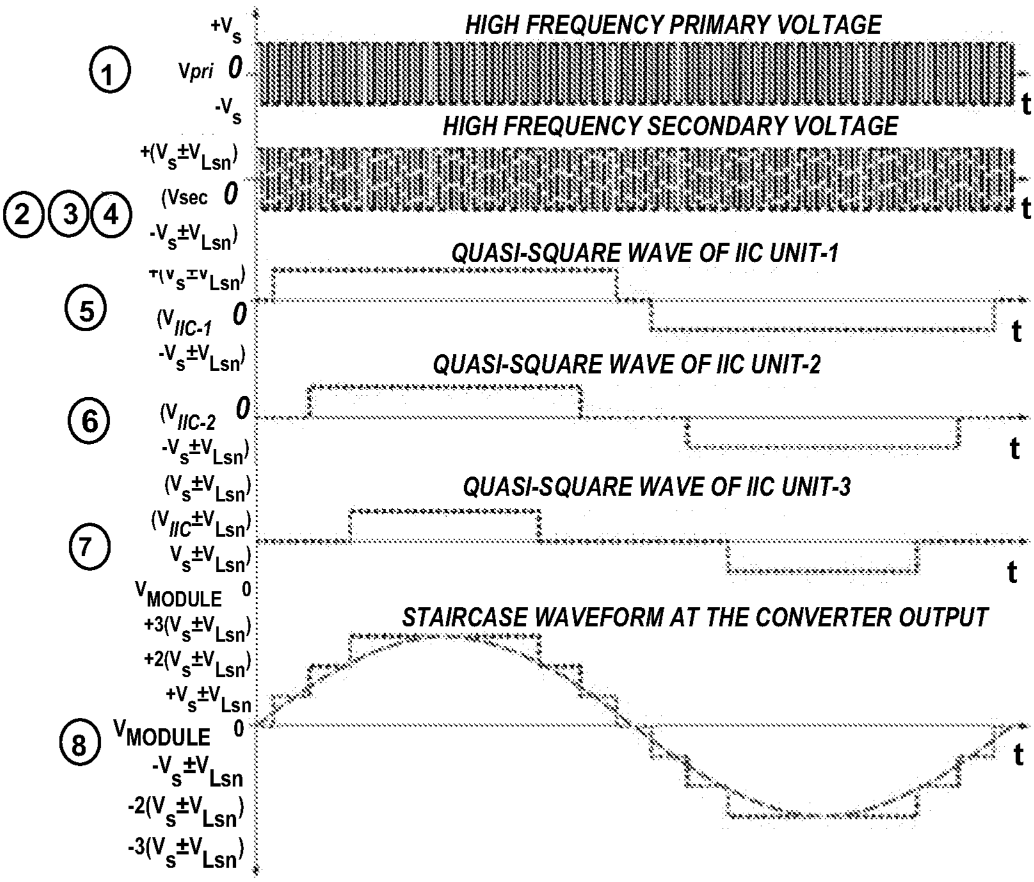

HIGH FREQUENCY PRIMARY VOLTAGE
+Vs
Vpri 0
-Vs
1
t
HIGH FREQUENCY SECONDARY VOLTAGE
+(Vs±VLsn)
(Vsec 0
-Vs±VLsn)
2 3 4
t
QUASI-SQUARE WAVE OF IIC UNIT-1
(VIIC-1 0
-Vs±VLsn)
5
t
QUASI-SQUARE WAVE OF IIC UNIT-2
(VIIC-2 0
-Vs±VLsn)
6
t
QUASI-SQUARE WAVE OF IIC UNIT-3
(Vs±VLsn)
(VIIC±VLsn)
Vs±VLsn)
7
t
VMODULE 0
STAIRCASE WAVEFORM AT THE CONVERTER OUTPUT
+3(Vs±VLsn)
+2(Vs±VLsn)
+Vs±VLsn
VMODULE 0
-Vs±VLsn
-2(Vs±VLsn)
-3(Vs±VLsn)
8
t

FIG. 4C

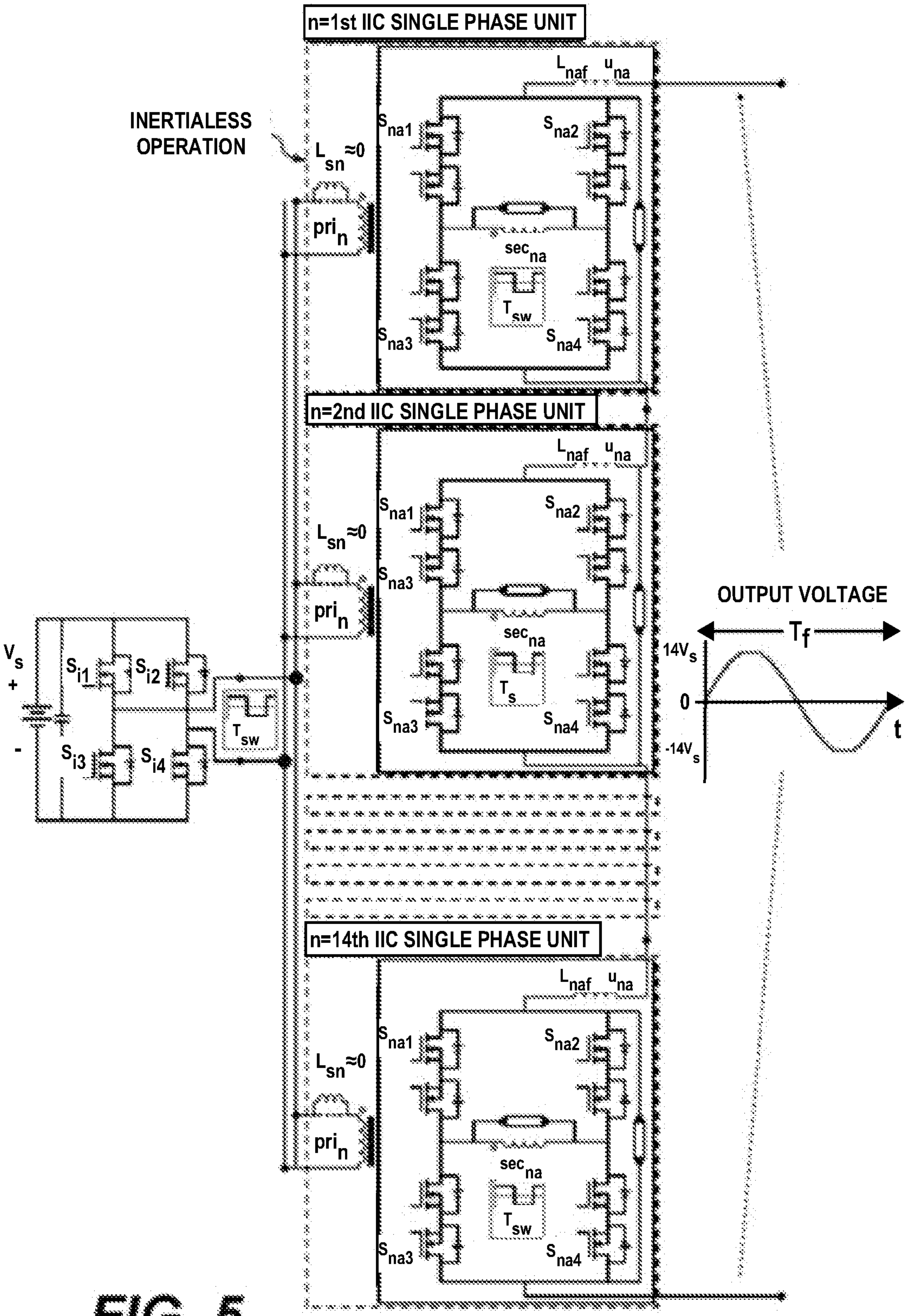

n=1st IIC SINGLE PHASE UNIT
INERTIALESS OPERATION
L_{sn}≈0
pri_n
L_{naf} u_{na}
S_{na1}
S_{na2}
sec_{na}
T_{sw}
S_{na3}
S_{na4}
n=2nd IIC SINGLE PHASE UNIT
L_{naf} u_{na}
S_{na1}
S_{na2}
S_{na3}
L_{sn}≈0
pri_n
sec_{na}
T_s
S_{na3}
S_{na4}
V_s
+
-
S_{i1}
S_{i2}
S_{i3}
S_{i4}
T_{sw}
OUTPUT VOLTAGE
T_f
$14V_s$
0
$-14V_s$
t
n=14th IIC SINGLE PHASE UNIT
L_{naf} u_{na}
S_{na1}
S_{na2}
L_{sn}≈0
pri_n
sec_{na}
T_{sw}
S_{na3}
S_{na4}

FIG. 5

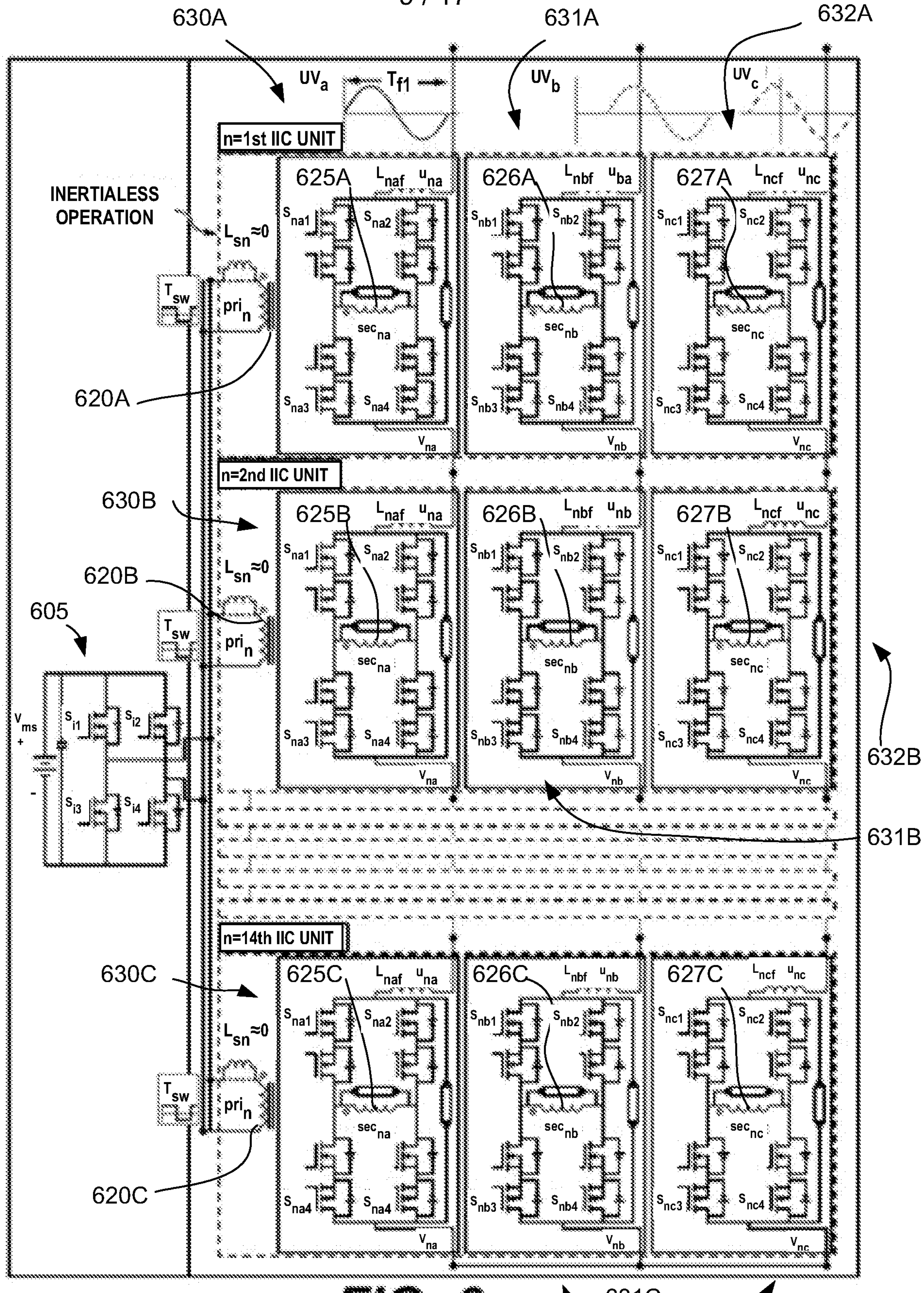

630A
631A
632A
UVa
Tf1
UVb
UVc
n=1st IIC UNIT
INERTIALESS OPERATION
Lsn≈0
Tsw
prin
620A
625A
626A
627A
secna
secnb
secnc
n=2nd IIC UNIT
630B
620B
605
625B
626B
627B
632B
631B
n=14th IIC UNIT
630C
625C
626C
627C
620C
631C
632C

FIG. 6

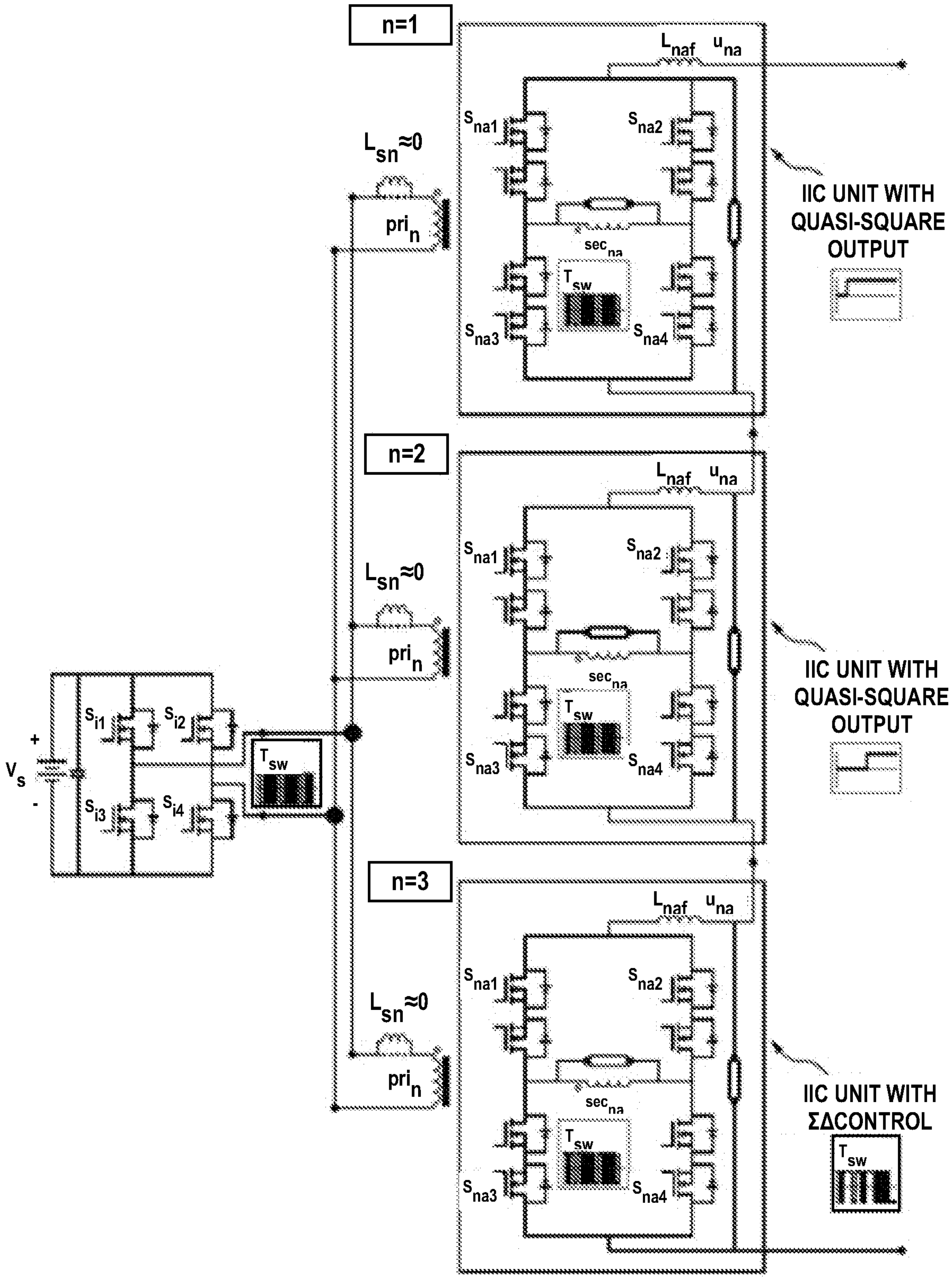
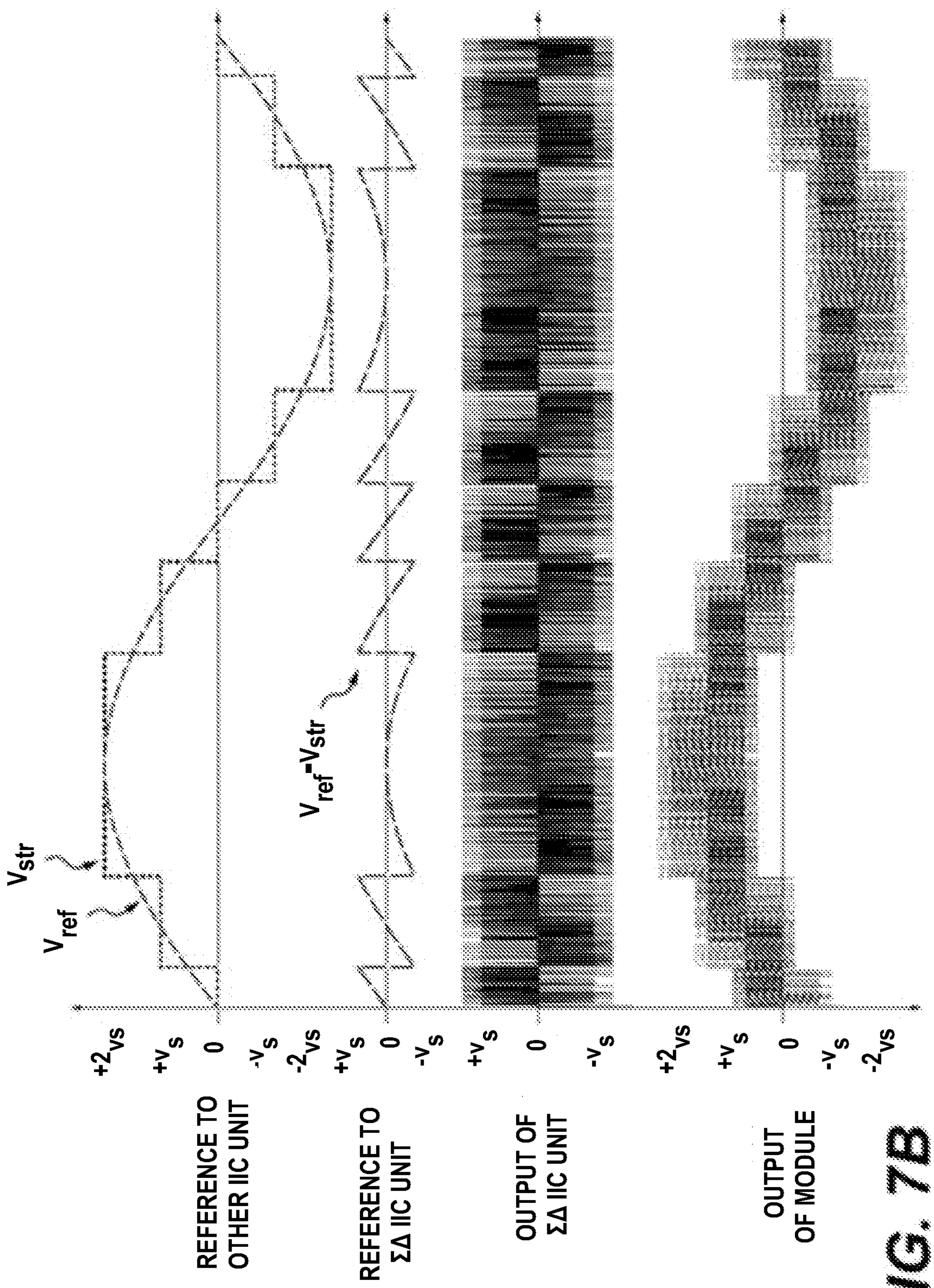

n=1
L_{naf} u_{na}
S_{na1}
S_{na2}
L_{sn}≈0
pri_n
sec_{na}
T_{sw}
S_{na3}
S_{na4}
IIC UNIT WITH QUASI-SQUARE OUTPUT
n=2
L_{naf} u_{na}
S_{na1}
S_{na2}
L_{sn}≈0
pri_n
sec_{na}
T_{sw}
S_{na3}
S_{na4}
IIC UNIT WITH QUASI-SQUARE OUTPUT
V_s
+
-
S_{i1}
S_{i2}
S_{i3}
S_{i4}
T_{sw}
n=3
L_{naf} u_{na}
S_{na1}
S_{na2}
L_{sn}≈0
pri_n
sec_{na}
T_{sw}
S_{na3}
S_{na4}
IIC UNIT WITH ΣΔCONTROL
T_{sw}

FIG. 7A



REFERENCE TO OTHER IIC UNIT
REFERENCE TO ΣΔ IIC UNIT
OUTPUT OF ΣΔ IIC UNIT
OUTPUT OF MODULE
V_{str}
V_{ref}
$V_{ref}-V_{str}$
$+2v_s$
$+v_s$
0
$-v_s$
$-2v_s$

FIG. 7B

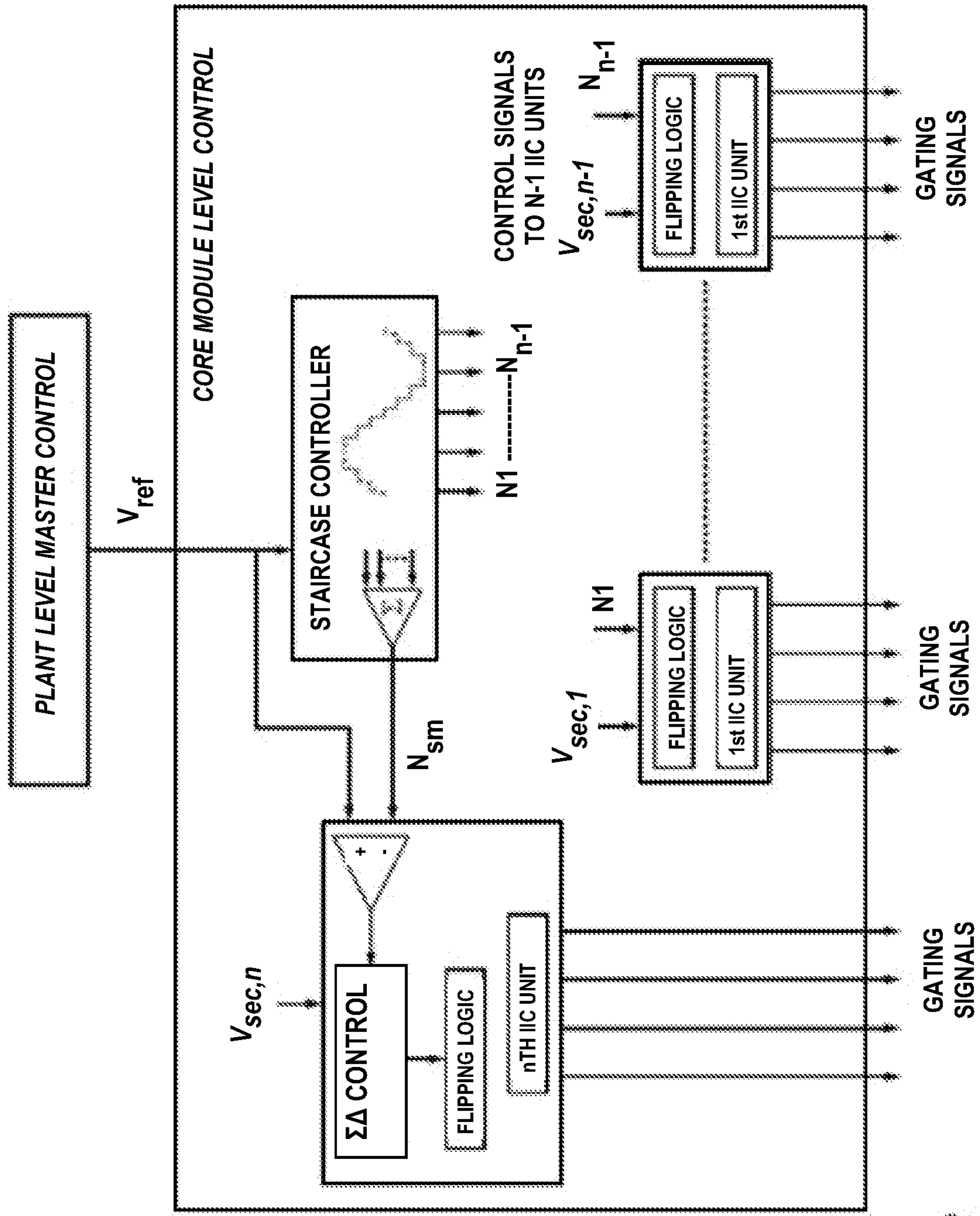

PLANT LEVEL MASTER CONTROL
V_{ref}
CORE MODULE LEVEL CONTROL
STAIRCASE CONTROLLER
N1 ---------- N_{n-1}
N_{sm}
CONTROL SIGNALS TO N-1 IIC UNITS
$V_{sec,n-1}$
N_{n-1}
FLIPPING LOGIC
1st IIC UNIT
GATING SIGNALS
$V_{sec,1}$
N1
FLIPPING LOGIC
1st IIC UNIT
GATING SIGNALS
$V_{sec,n}$
ΣΔ CONTROL
FLIPPING LOGIC
nTH IIC UNIT
GATING SIGNALS

FIG. 8

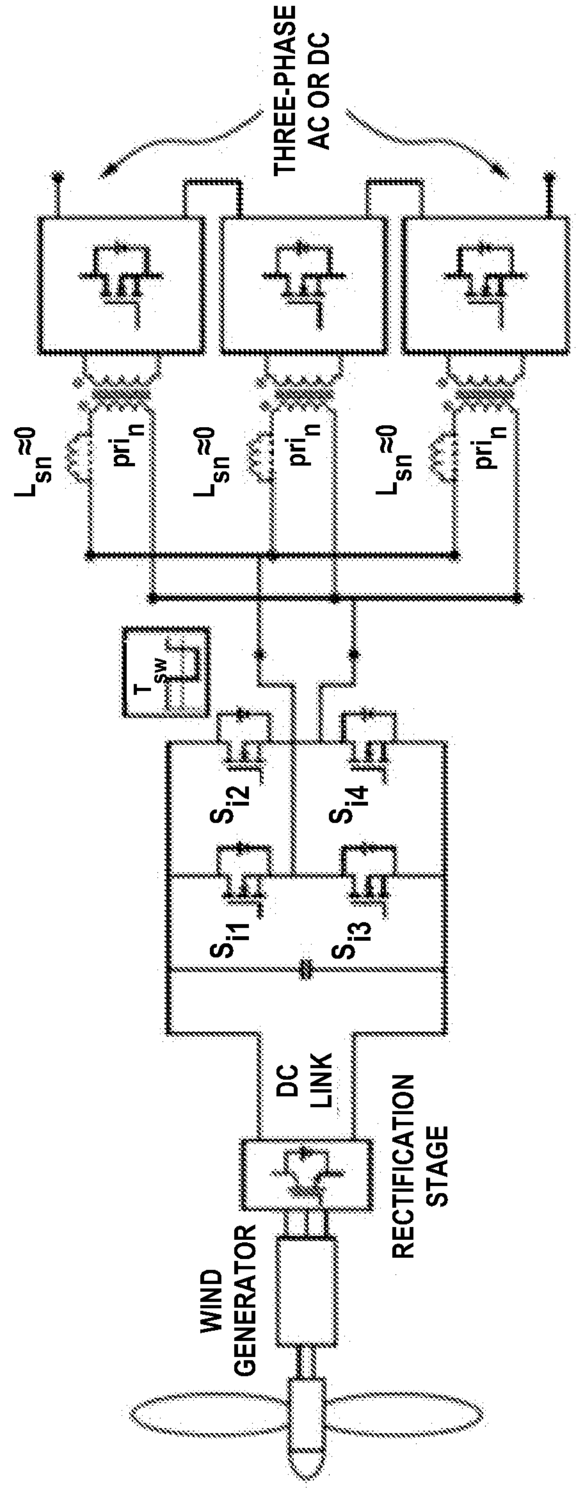

THREE-PHASE
AC OR DC
L_{sn}≈0
pri_n
L_{sn}≈0
pri_n
L_{sn}≈0
pri_n
T_{sw}
S_{i2}
S_{i4}
S_{i1}
S_{i3}
DC
LINK
RECTIFICATION
STAGE
WIND
GENERATOR

FIG. 9

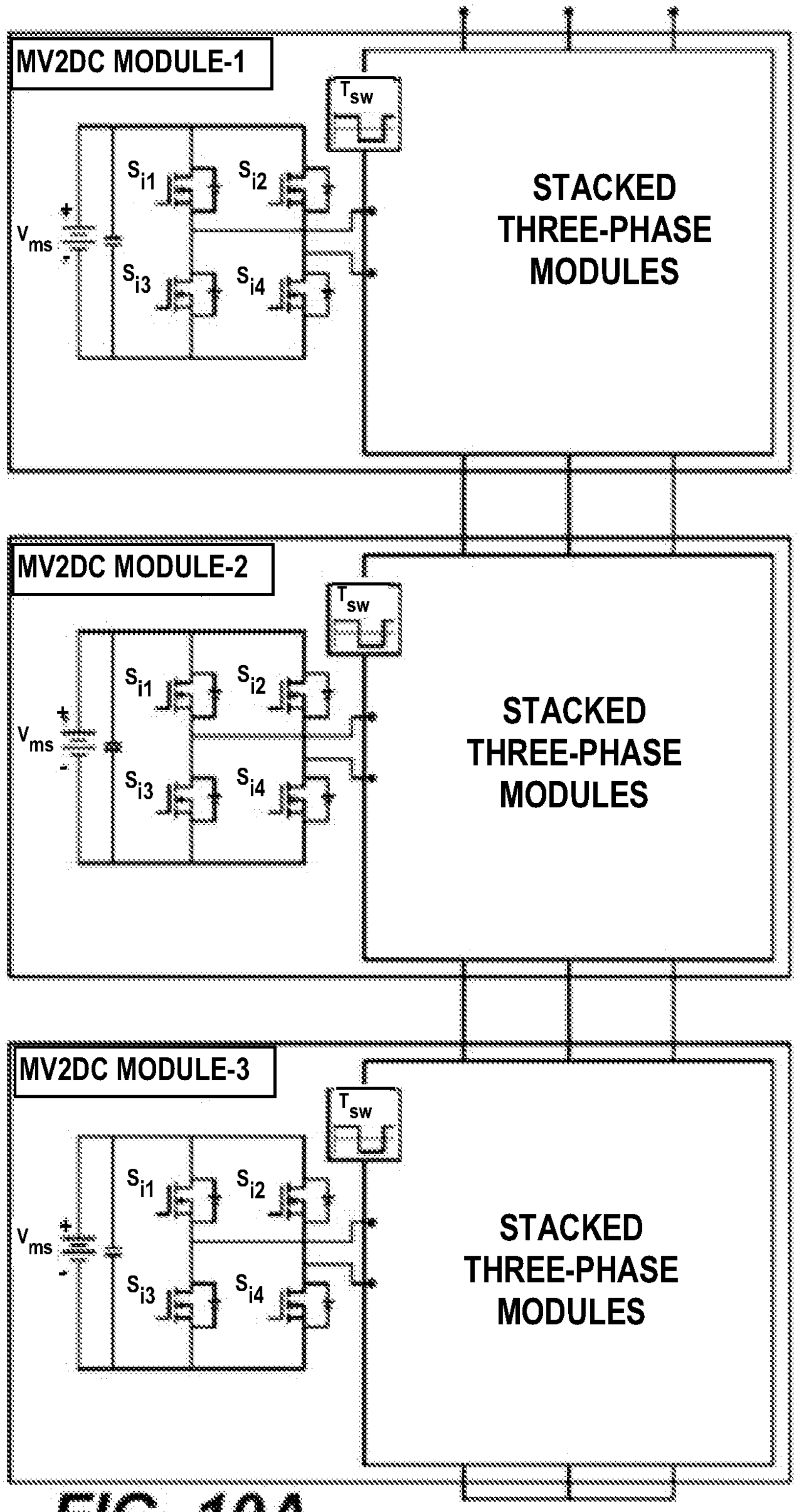

MV2DC MODULE-1
T_{sw}
S_{i1}
S_{i2}
V_{ms}
S_{i3}
S_{i4}
STACKED THREE-PHASE MODULES
MV2DC MODULE-2
T_{sw}
S_{i1}
S_{i2}
V_{ms}
S_{i3}
S_{i4}
STACKED THREE-PHASE MODULES
MV2DC MODULE-3
T_{sw}
S_{i1}
S_{i2}
V_{ms}
S_{i3}
S_{i4}
STACKED THREE-PHASE MODULES

FIG. 10A

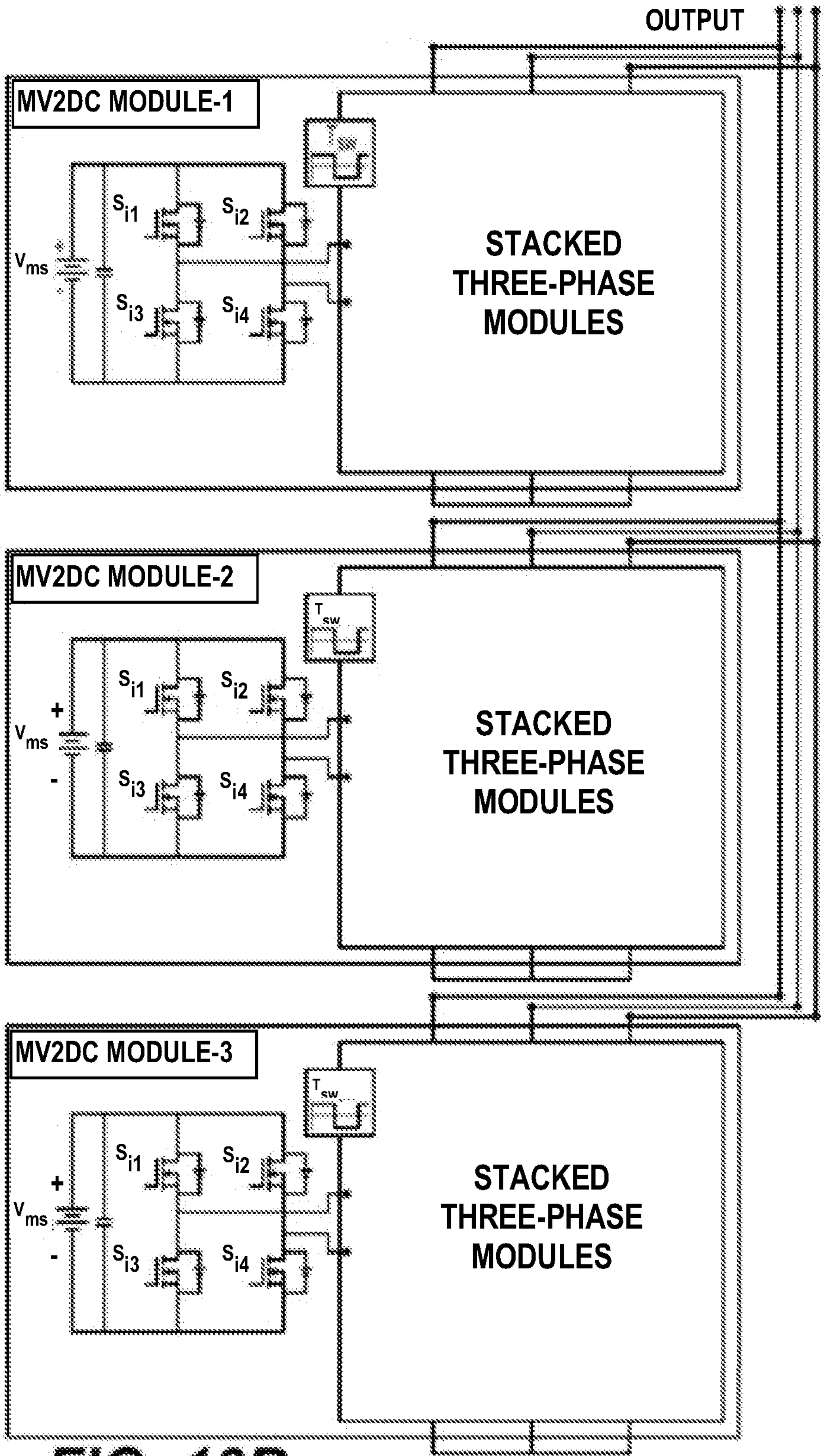
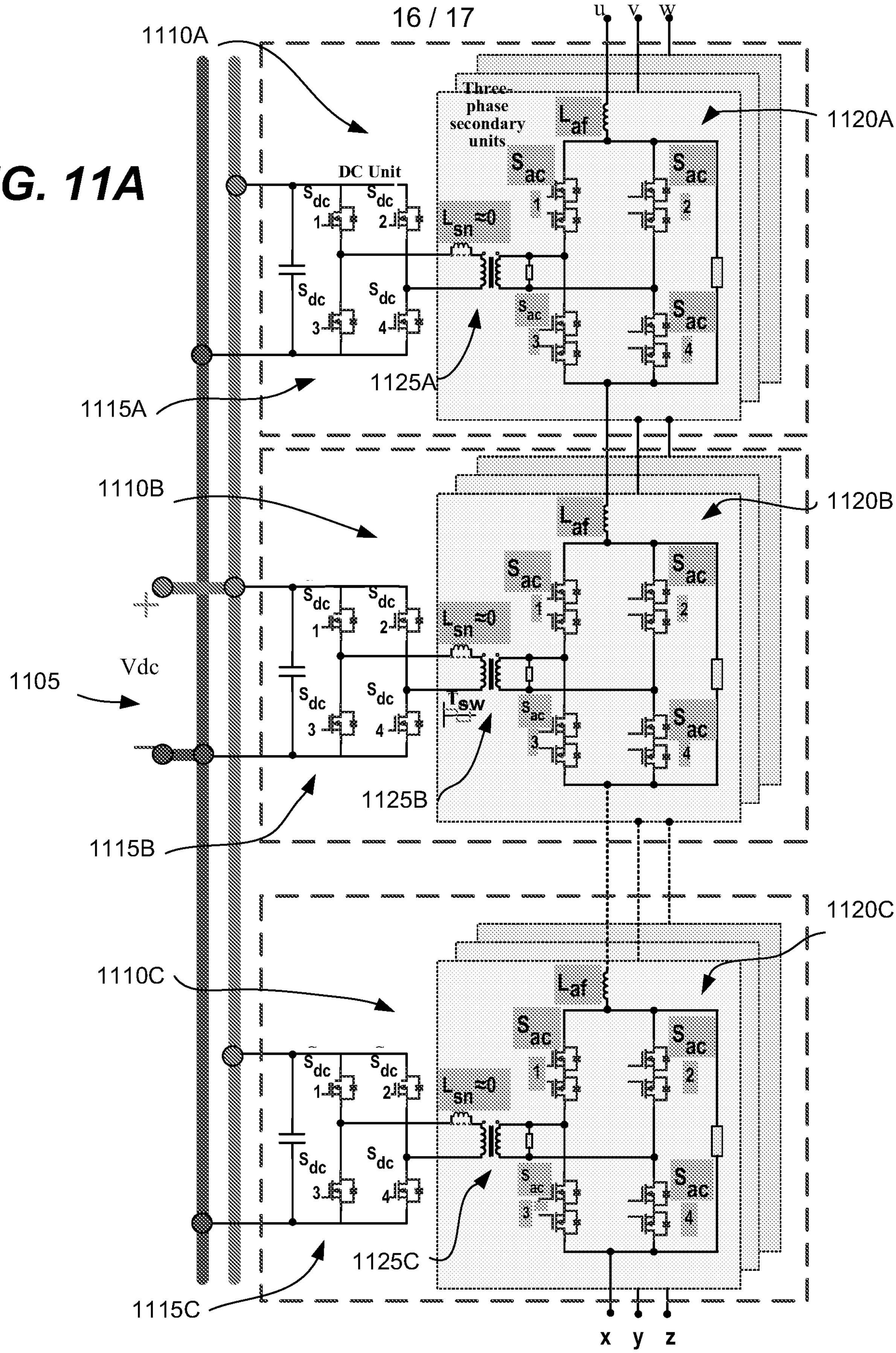

OUTPUT
MV2DC MODULE-1
S_{i1}
S_{i2}
V_{ms}
S_{i3}
S_{i4}
STACKED THREE-PHASE MODULES
MV2DC MODULE-2
T_{sw}
S_{i1}
S_{i2}
+
V_{ms}
-
S_{i3}
S_{i4}
STACKED THREE-PHASE MODULES
MV2DC MODULE-3
T_{sw}
S_{i1}
S_{i2}
+
V_{ms}
-
S_{i3}
S_{i4}
STACKED THREE-PHASE MODULES

FIG. 10B

FIG. 11A


1110A
1120A
Three-phase secondary units
DC Unit
u
v
w
L_{af}
S_{ac}
S_{dc}
$L_{sn}≈0$
1125A
1115A
1110B
1120B
1105
Vdc
T_{sw}
1125B
1115B
1110C
1120C
1125C
1115C
x
y
z

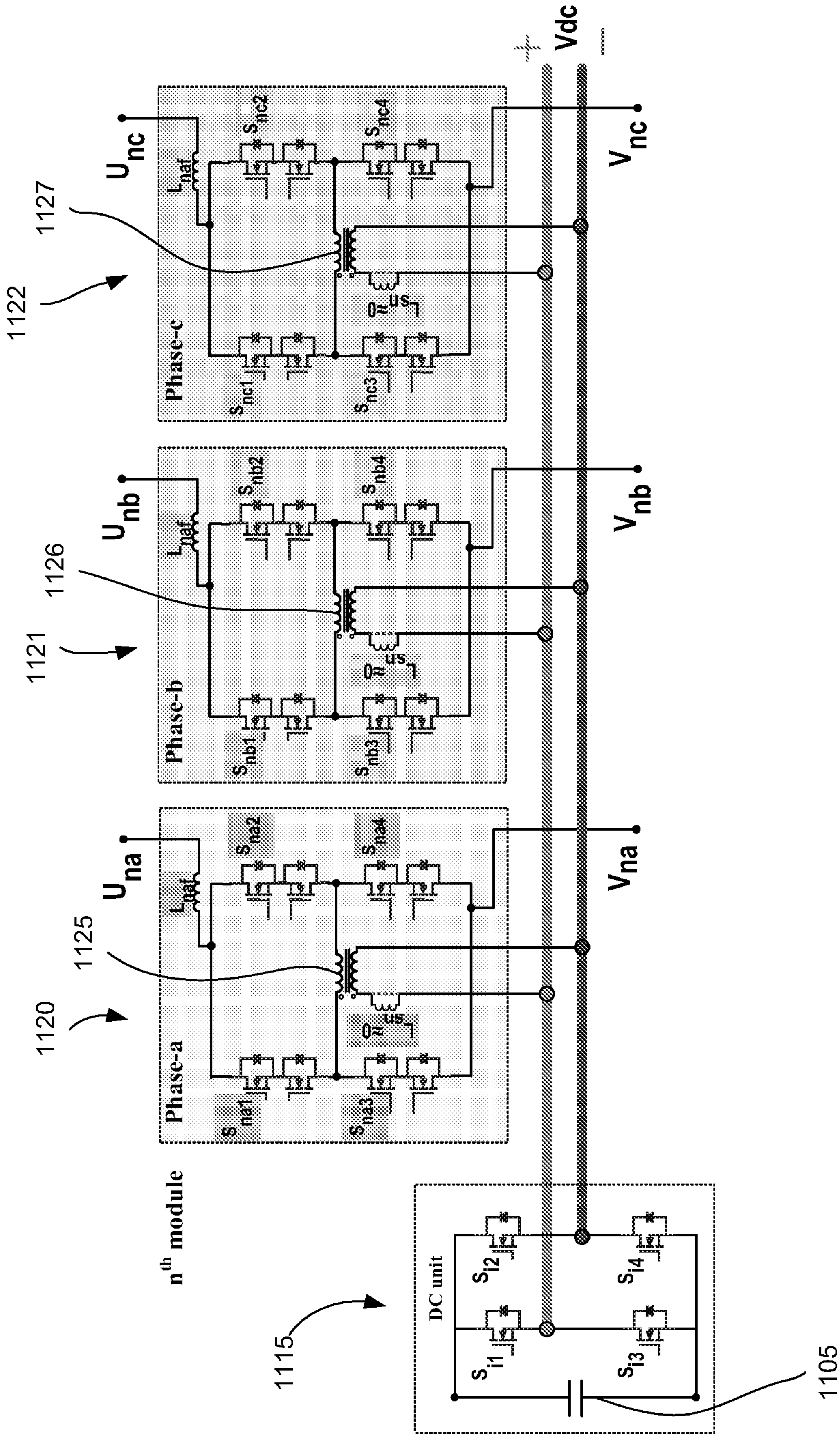

Vdc
+
−
U_{nc}
V_{nc}
U_{nb}
V_{nb}
U_{na}
V_{na}
L_{naf}
S_{nc1}
S_{nc2}
S_{nc3}
S_{nc4}
S_{nb1}
S_{nb2}
S_{nb3}
S_{nb4}
S_{na1}
S_{na2}
S_{na3}
S_{na4}
L_{sn} ≈ 0
Phase-a
Phase-b
Phase-c
n^{th} module
DC unit
S_{i1}
S_{i2}
S_{i3}
S_{i4}
1105
1115
1120
1121
1122
1125
1126
1127

FIG. 11B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2024/037965

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***H02M 3/335*** (2024.01); ***H02M 7/5387*** (2024.01); ***H02M 1/10*** (2024.01); *H02J 3/36* (2024.01)

CPC: ***H02M 3/335; H02M 1/10; H02M 7/5387;*** *H02J 3/36*

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History Document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History Document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History Document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2021/0242788 A1 (ENPHASE ENERGY INC.) 05 August 2021 (05.08.2021) entire document	1-20
A	US 2010/0014336 A1 (FUKUMOTO) 21 January 2010 (21.01.2010) entire document	1-20
A	US 5,793,624 A (COUTURE et al.) 11 August 1998 (11.08.1998) entire document	1-20
A	US 2021/0344283 A1 (GENERAL ELECTRIC COMPANY) 04 November 2021 (04.11.2021) entire document	1-20
A	US 5,737,206 A (YAMAMOTO) 07 April 1998 (07.04.1998) entire document	1-20
A	US 2017/0009743 A1 (SIEMENS AKTIENGESELLSCHAFT) 12 January 2017 (12.01.2017) entire document	1-20

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

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

Date of the actual completion of the international search	Date of mailing of the international search report
13 September 2024 (13.09.2024)	**18 October 2024 (18.10.2024)**

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US **Commissioner for Patents** **P.O. Box 1450, Alexandria, VA 22313-1450**	**MATOS** **TAINA**
Facsimile No. **571-273-8300**	Telephone No. **571-272-4300**

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-20, is drawn to a power converter, comprising: a controller configured to control the DC bridge and the plurality of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to DC or AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the plurality of AC bridges.

Group II, claims 21-40, is drawn to a power converter, comprising: a second plurality of AC bridges electrically coupled in series and configured to output an AC power signal at a second phase.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: a controller configured to control the DC bridge and the plurality of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to DC or AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the plurality of AC bridges as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: a second plurality of AC bridges electrically coupled in series and configured to output an AC power signal at a second phase, each of the second plurality of AC bridges electrically interfacing with a respective second secondary winding of the plurality of transformers; a third plurality of AC bridges electrically coupled in series and configured to output an AC power signal at a third phase, each of the third plurality of AC bridges electrically interfacing with a respective third secondary winding of the plurality of transformers; and a controller configured to control the DC bridge and the first, second, and third pluralities of AC bridges to convert DC power from the DC power source having a voltage level at a first magnitude to three-phase AC power having a voltage level at a second magnitude greater than the first magnitude at an output of the first, second, and third pluralities of AC bridges as claimed therein is not present in the invention of Group I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of a power converter, comprising: a DC bridge electrically coupled to a DC power source; a first transformer comprising: a primary winding electrically interfacing with the DC bridge; and a plurality of secondary windings; a plurality of AC bridges electrically coupled in series, each of the plurality of AC bridges electrically interfacing with a respective secondary winding of the plurality of secondary windings, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2017/0009743 to SIEMENS AKTIENGESELLSCHAFT teaches a power converter, comprising: a DC bridge electrically coupled to a DC power source; a first transformer comprising: a primary winding electrically interfacing with the DC bridge; and a plurality of secondary windings; a plurality of AC bridges electrically coupled in series, each of the plurality of AC bridges electrically interfacing with a respective secondary winding of the plurality of secondary windings (The electric generator 230 comprises a stator 234 having a winding system with which the electric power, typically a three phase power, is generated. Downstream with respect to the stator 234 there is connected a power converter 240. The power converter 240 comprises a generator (AC-DC) bridge 242, which in normal operation operates as an active rectifier to supply power to a direct current (DC) link 244. The power converter 240 further comprises a network bridge 246 which converts the DC power of the DC link 244 to an AC power output. According to the embodiment described here this AC power output comprises a three phase current and is fed via a line reactor 247 to a step-up transformer 248. The (power) output of the step-up transformer 248 is fed to the respective bus bar 112 shown in FIG. 1, para. 0095. FIG. 4 shows the rectifier 180 in more detail. By contrast to a power AC-DC converter having typically six controllable high power semiconductor switches, the rectifier 180 has only passive power electric components which are power diodes 482. As can be seen from FIG. 3, the rectifier 180 comprises three half bridges each of which connect between two DC output terminals. Between these two output terminals the output Voltage Udc is provided. Each half bridge comprises a series connection of two power diodes 482. At an intermediate node between the two power diodes 482 of each half bridge, which

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

intermediate node is not provided with a reference numeral, there is applied one phase of a three phase AC power signal being fed into the rectifier 180, para. 0113).

Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☑ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.: **1-20**

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.