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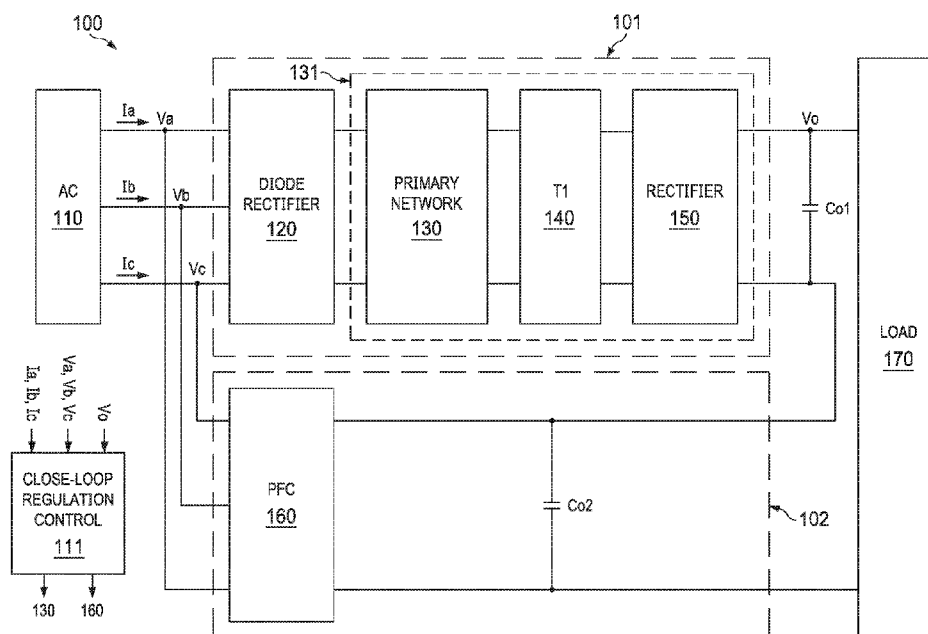


FIG. 2

(57) Abstract: A system includes a first power conversion apparatus and a second power conversion apparatus. The first power conversion apparatus and the second power conversion apparatus are configured to be connected between an ac source and a load. The second power conversion apparatus comprises a power factor correction device. The power factor correction device is configured to generate an output voltage varying in a wide range, and an output voltage of the system is regulated mainly through adjusting the output voltage of the power factor correction device. The power flowing from the ac source to the load through the second power conversion apparatus is a fraction of the power flowing from the ac source to the load through the first power conversion apparatus.

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Hybrid Power Conversion System and Method

TECHNICAL FIELD

[0001] The present disclosure relates to a hybrid power conversion system, and, in particular embodiments, to a hybrid power conversion system including an unregulated power delivery path and a regulated power delivery path.

BACKGROUND

[0002] A power conversion system such as a telecommunication power system usually includes an ac-dc stage converting the power from the ac utility line to a 48V dc distribution bus. A conventional ac-dc stage may comprise a variety of EMI filters, a bridge rectifier formed by four diodes, a power factor correction circuit and an isolated dc/dc power converter. The bridge rectifier converts an ac voltage into a full-wave rectified dc voltage. Such a full-wave rectified dc voltage provides a dc input voltage for the power factor correction circuit. The power factor correction circuit may be implemented by employing a power converter including a boost converter. By employing an appropriate control circuit, the boost converter is capable of shaping the input line current to be sinusoidal and in phase with the sinusoidal input voltage of the ac input source. As a result, the power factor of the ac-dc stage may be close to unity as required by a variety of international standards.

SUMMARY

[0003] These and other problems are generally solved or circumvented, and technical advantages are generally achieved, by preferred embodiments of the present disclosure which provide a hybrid power conversion system for improving power conversion efficiency.

[0004] In accordance with an embodiment, a system comprises a first power conversion apparatus and a second power conversion apparatus. The first power conversion apparatus and the second power conversion apparatus are configured to be connected between an ac source and a load. The second power conversion apparatus comprises a power factor correction device. The power factor correction device is configured to generate an output voltage varying in a wide range, and an output voltage of the system is regulated mainly through adjusting the output voltage of the power factor correction device. The power flowing from the ac source to the load through the second power conversion apparatus is a fraction of the power flowing from the ac source to the load through the first power conversion apparatus.

[0005] In some embodiments, the first power conversion apparatus comprises a diode rectifier and a first isolated power converter connected in cascade. The second power conversion apparatus comprises the power factor correction device, and wherein an output of the first isolated power converter and an output of the power factor correction device are connected in series. The first

isolated power converter is a three-level LLC converter comprising a first primary switching network, a first resonant tank, a first transformer and a first secondary rectifier.

[0006] In some embodiments, the first power conversion apparatus comprises a diode rectifier and a first isolated power converter connected in cascade. The second power conversion apparatus comprises the power factor correction device and a second isolated power converter connected in cascade, and wherein an output of the first isolated power converter and an output of the second isolated power converter are connected in series. The output voltage of the system is regulated mainly through adjusting the output voltage of the power factor correction device. The output voltage of the system is regulated partially through adjusting an output voltage of the first isolated power converter in a narrow range and adjusting an output voltage of the second isolated power converter in a narrow range

[0007] In some embodiments, the first power conversion apparatus comprises a diode rectifier and a first isolated power converter connected in cascade. The second power conversion apparatus comprises the power factor correction device and a second isolated power converter connected in cascade, and wherein an output of the first isolated power converter and an output of the second isolated power converter are connected in parallel.

[0008] In some embodiments, the first power conversion apparatus comprises a diode rectifier and a first hybrid power converter connected in cascade. The second power conversion apparatus comprises the power factor correction device and a second isolated power converter connected in cascade, and wherein an output of the first hybrid power converter and an output of the second isolated power converter are connected in parallel. The first hybrid power converter comprises a first primary switching network, a first transformer, a second primary switching network, a second transformer and an interleaved multi-bridge circuit. The first primary switching network is connected to a primary winding of the first transformer. The second primary switching network is connected to a primary winding of the second transformer. The interleaved multi-bridge circuit is connected to a secondary winding of the first transformer and a secondary winding of the second transformer. The interleaved multi-bridge circuit comprises a first leg comprising a first switch and a second switch connected in series, a second leg comprising a third switch and a fourth switch connected in series, and a third leg comprising a fifth switch and a sixth switch connected in series. The secondary winding of the first transformer is connected between a common node of the first switch and the second switch, and a common node of the third switch and the fourth switch. The secondary winding of the second transformer is connected between a common node of the fifth switch and the sixth switch, and the common node of the third switch and the fourth switch.

[0009] In accordance with another embodiment, a method comprises transferring energy from an ac power source to a load through a first power conversion apparatus, wherein the first power conversion apparatus is an unregulated power conversion apparatus and transferring energy from the ac power source to the load through a second power conversion apparatus, wherein the second power conversion apparatus is a regulated power conversion apparatus.

[0010] The method further comprises configuring the first power conversion apparatus and the second power conversion apparatus such that the energy flowing from the ac power source to the load through the second power conversion apparatus is a fraction of the energy flowing from the ac power source to the load through the first power conversion apparatus.

[0011] The method further comprises under various input line and output load conditions, configuring the first power conversion apparatus such that an inductor-inductor-capacitor (LLC) power converter of the first power conversion apparatus operates at a switching frequency substantially equal to a resonant frequency of the LLC power converter.

[0012] The method further comprises monitoring output voltages of the ac power source, currents flowing from the ac power source and an output voltage applied to the load, adjusting a power factor to unity through adjusting input currents flowing into a power factor correction device of the second power conversion apparatus, and regulating the output voltage applied to the load through having an output voltage of the power factor correction device varying in a wide range and having a switching frequency of an LLC power converter of the second power conversion apparatus varying in a narrow range.

[0013] In accordance with yet another embodiment, a system comprises an unregulated power conversion apparatus configured to be connected between an ac source and a load, and a regulated power conversion apparatus configured to be connected between the ac source and the load. The power flowing from the ac source to the load through the regulated power conversion apparatus is a fraction of the power flowing from the ac source to the load through the unregulated power conversion apparatus.

[0014] The unregulated power conversion apparatus comprises a diode rectifier and a first isolated power converter connected in cascade. The regulated power conversion apparatus comprises a power factor correction device and a second isolated power converter connected in cascade. Inputs of the power factor correction device and inputs of the diode rectifier are connected in parallel. An output of the first isolated power converter and an output of the second isolated power converter are connected in series. Alternatively, the output of the first isolated power converter and the output of the second isolated power converter are connected in parallel.

[0015] The first isolated power converter is an inductor-inductor-capacitor (LLC) power converter. The power factor correction device is a three-phase boost power factor correction converter.

[0016] An advantage of an embodiment of the present disclosure is a hybrid power conversion system is capable of regulating an output voltage through a partial power processing circuit, thereby improving the efficiency, reliability and cost of the power conversion system.

[0017] The foregoing has outlined rather broadly the features and technical advantages of the present disclosure in order that the detailed description of the disclosure that follows may be better understood. Additional features and advantages of the disclosure will be described hereinafter which form the subject of the claims of the disclosure. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures or processes for carrying out the same purposes of the present disclosure. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the disclosure as set forth in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] For a more complete understanding of the present disclosure, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0019] Figure 1 illustrates a hybrid power conversion system in accordance with various embodiments of the present disclosure;

[0020] Figure 2 illustrates a block diagram of a first implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure;

[0021] Figure 3 illustrates a block diagram of a second implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure;

[0022] Figure 4 illustrates a block diagram of a third implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure;

[0023] Figure 5 illustrates a block diagram of a controller for controlling the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure;

[0024] Figure 6 illustrates a schematic diagram of a first implementation of the power factor correction device in accordance with various embodiments of the present disclosure;

[0025] Figure 7 illustrates a schematic diagram of a second implementation of the power factor correction device in accordance with various embodiments of the present disclosure;

[0026] Figure 8 illustrates a schematic diagram of a first implementation of the diode rectifier in accordance with various embodiments of the present disclosure;

[0027] Figure 9 illustrates a schematic diagram of a second implementation of the diode rectifier in accordance with various embodiments of the present disclosure;

[0028] Figure 10 illustrates a schematic diagram of a first implementation of the three-level LLC power converter in accordance with various embodiments of the present disclosure;

[0029] Figure 11 illustrates a schematic diagram of a second implementation of the three-level LLC power converter in accordance with various embodiments of the present disclosure;

[0030] Figure 12 illustrates a schematic diagram of the three-level LLC power converter of the second power conversion apparatus in accordance with various embodiments of the present disclosure;

[0031] Figure 13 illustrates a block diagram of a fourth implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure;

[0032] Figure 14 illustrates a block diagram of a fifth implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure;

[0033] Figure 15 illustrates a schematic diagram of a first implementation of the hybrid LLC power converter shown in Figures 13-14 in accordance with various embodiments of the present disclosure;

[0034] Figure 16 illustrates a timing diagram of various signals of the hybrid LLC power converter shown in Figure 15 when the secondary windings are configured to be connected in series in accordance with various embodiments of the present disclosure;

[0035] Figure 17 illustrates a timing diagram of various signals of the hybrid LLC power converter shown in Figure 15 when the secondary windings are configured to be connected in parallel in accordance with various embodiments of the present disclosure;

[0036] Figure 18 illustrates a schematic diagram of a second implementation of the hybrid LLC power converter shown in Figures 13-14 in accordance with various embodiments of the present disclosure;

[0037] Figure 19 illustrates a timing diagram of various signals of the hybrid LLC power converter shown in Figure 18 when the secondary windings are configured to be connected in series in accordance with various embodiments of the present disclosure;

[0038] Figure 20 illustrates a timing diagram of various signals of the hybrid LLC power converter shown in Figure 18 when the secondary windings are configured to be connected in parallel in accordance with various embodiments of the present disclosure; and

[0039] Figure 21 illustrates a flow chart of a method for controlling the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure.

[0040] Corresponding numerals and symbols in the different figures generally refer to corresponding parts unless otherwise indicated. The figures are drawn to clearly illustrate the relevant aspects of the various embodiments and are not necessarily drawn to scale.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0041] The making and using of the presently preferred embodiments are discussed in detail below. It should be appreciated, however, that the present disclosure provides many applicable inventive concepts that can be embodied in a wide variety of specific contexts. The specific embodiments discussed are merely illustrative of specific ways to make and use the disclosure, and do not limit the scope of the disclosure.

[0042] The present disclosure will be described with respect to preferred embodiments in a specific context, namely a hybrid power conversion system. The present disclosure may also be applied, however, to a variety of power conversion systems. Hereinafter, various embodiments will be explained in detail with reference to the accompanying drawings.

[0043] Figure 1 illustrates a hybrid power conversion system in accordance with various embodiments of the present disclosure. The hybrid power conversion system is connected between an ac power source 110 and a load 170. The ac power source 110 may be a three-phase power system such as a utility grid. The load 170 may be a semiconductor chip, a battery, a downstream power converter and the like.

[0044] The hybrid power conversion system comprises a first power conversion apparatus 101 and a second power conversion apparatus 102. In some embodiments, the first power conversion apparatus 101 is an unregulated power conversion apparatus. The second power conversion apparatus 102 is a regulated power conversion apparatus. Moreover, the second power conversion apparatus 102 comprises a power factor correction device. The power factor correction device of the second power conversion apparatus 102 is configured such that the power factor of the hybrid power conversion system is adjusted to a level approximately equal to unity through adjusting input currents flowing into a power factor correction device of the second power conversion apparatus 102.

[0045] In some embodiments, the first power conversion apparatus 101 comprises a diode rectifier and an inductor-inductor-capacitor (LLC) power converter connected in cascade. Since the first power conversion apparatus 101 is an unregulated power conversion apparatus, the LLC

power converter is able to operate at a switching frequency substantially equal to the resonant frequency of the LLC power converter. As a result of having a diode rectifier and an LLC power converter operating at a switching frequency substantially equal to the resonant frequency, the first power conversion apparatus 101 is a high efficiency power conversion apparatus.

[0046] In order to achieve a unity power factor, the inputs of the second power conversion apparatus 102 are connected in parallel with the inputs of the first power conversion apparatus 101 (not shown but illustrated in Figure 2). In particular, through adjusting the input currents of the second power conversion apparatus 102, the power factor of the hybrid power system can be adjusted accordingly.

[0047] In order to achieve a regulated output voltage, the output of the second power conversion apparatus 102 is connected in series or parallel with the output of the first power conversion apparatus 101. In particular, through adjusting the output voltage of the second power conversion apparatus 102, the output voltage of the hybrid power system can be regulated accordingly.

[0048] In operation, in order to achieve high efficiency and a unity power factor, the power from the ac power source 110 to the load 170 is delivered through two routes as indicated by the arrows shown in Figure 1. In some embodiments, the power flowing from the ac power source 110 to the load 170 through the second power conversion apparatus 102 is a fraction of the power from the ac power source 110 to the load 170 through the first power conversion apparatus 101. For example, only about 10% of the power passes through the second power conversion apparatus 102. The majority of the power (90%) passes through the first power conversion apparatus 101.

[0049] Figure 2 illustrates a block diagram of a first implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure. The hybrid power conversion system 100 comprises the first power conversion apparatus 101 and the second power conversion apparatus 102 connected between the ac power source 110 and the load 170.

[0050] As shown in Figure 2, the inputs of the first power conversion apparatus 101 and the inputs of the second power conversion apparatus 102 are connected in parallel and further connected to the outputs of the ac power source 110. The outputs of the ac power source 110 has three phases, namely phases a, b and c. The first input of the first power conversion apparatus 101 and the first input of the second power conversion apparatus 102 are connected to phase a. The output current I_a of the ac power source 110 is split into two currents flowing into the first power conversion apparatus 101 and the second power conversion apparatus 102 respectively. Likewise, the output currents I_b and I_c of the ac power source 110 are split into two currents flowing into the first power conversion apparatus 101 and the second power conversion apparatus 102

respectively. The output of the first power conversion apparatus 101 and the output the second power conversion apparatus 102 are connected in series and further connected to the load 170.

[0051] As shown in Figure 2, a first capacitor Co1 is placed at an output of the first power conversion apparatus 101. The first capacitor Co1 is employed to smooth the output voltage of the first power conversion apparatus 101. It should be noted that, depending on different applications and design needs, the first capacitor Co1 may be not included in the hybrid power conversion system 100, or the first capacitor Co1 has a small capacitance value. A second capacitor Co2 is placed at an output of the second power conversion apparatus 102. The second capacitor Co2 is employed to produce a steady and smooth output voltage at the output of the second power conversion apparatus 102.

[0052] In some embodiments, the hybrid power conversion system 100 may comprise an electromagnetic interference (EMI) filter (not shown) connected between the ac power source 110 and the diode rectifier 120. The EMI filter is employed to reduce high frequency noise that may cause interference with other devices of the hybrid power conversion system 100. As a result of employing the EMI filters, the hybrid power conversion system 100 may meet various EMI regulations.

[0053] The EMI filter may comprise a plurality of passive components including capacitors and inductors. The inductors allow dc or low frequency currents to pass through, while blocking the unwanted high frequency currents. The capacitors provide low impedance paths to divert the unwanted high frequency currents or noise from the EMI filter. The unwanted high frequency currents either go back into the input power source or into ground. In some embodiments, the EMI filter is designed to attenuate both differential mode noise and common mode noise. The EMI filter may comprise two differential-mode inductors, two common-mode inductors and a plurality of filter capacitors. The two differential-mode inductors along with the plurality of filter capacitors are implemented to filter out differential-mode noise within the hybrid power conversion system 100. The two common-mode inductors are utilized to filter out common-mode noise within the hybrid power conversion system 100.

[0054] As shown in Figure 2, the first power conversion apparatus 101 comprises a diode rectifier 120 and a first isolated power converter 131 connected in cascade between the ac power source 110 and the load 170. The detailed schematic diagram of the diode rectifier 120 will be described below with respect to Figures 8-9.

[0055] In some embodiments, the first isolated power converter 131 is implemented as a three-level LLC power converter. Throughout the description, the first isolated power converter 131 is alternatively referred to as a three-level LLC power converter. As shown in Figure 2, the three-

level LLC power converter 131 comprises a primary network 130, a first transformer 140 and a rectifier 150 connected in cascade.

[0056] The primary network 130 comprises a plurality of switches and a resonant tank. In some embodiments, the first isolated power converter 131 is configured as an unregulated power converter. The switching frequency of the plurality of switches is equal to the resonant frequency of the resonant tank. Alternatively, depending on design needs and different application, the switching frequency of the plurality of switches may vary in a narrow range to help the second power conversion apparatus 102 regulate the output voltage of the hybrid power conversion system 100. The detailed schematic diagram of the primary network 130 of the three-level LLC power converter 131 will be described below with respect to Figures 10-11.

[0057] The first transformer 140 provides electrical isolation between the primary side and the secondary side of the first isolated power converter 131. In accordance with an embodiment, the first transformer 140 may be formed of two transformer windings, namely a primary transformer winding and a secondary transformer winding. Alternatively, the first transformer 140 may have a center tapped secondary so as to have three transformer windings including a primary transformer winding, a first secondary transformer winding and a second secondary transformer winding. It should be noted that the transformers illustrated herein and throughout the description are merely examples, which should not unduly limit the scope of the claims. One of ordinary skill in the art would recognize many variations, alternatives, and modifications. For example, the first transformer 140 may further comprise a variety of bias windings and gate drive auxiliary windings.

[0058] The rectifier 150 converts an alternating polarity waveform received from the output of the first transformer 140 to a single polarity waveform. The rectifier 150 may be formed of two pairs of switching elements such as n-type metal oxide semiconductor (NMOS) transistors. Alternatively, the rectifier 150 may be formed of two pairs of diodes. Furthermore, the rectifier 150 may be formed by other types of controllable devices such as metal oxide semiconductor field effect transistor (MOSFET) devices, bipolar junction transistor (BJT) devices, super junction transistor (SJT) devices, insulated gate bipolar transistor (IGBT) devices and the like. The detailed operation and structure of the rectifier 150 are well known in the art, and hence are not discussed herein.

[0059] In some embodiments, the three-level LLC power converter 131 is configured as an unregulated power converter operating at a switching frequency substantially equal to the resonant frequency of the three-level LLC power converter 131. The diode rectifier 120 is a high efficiency rectifier. As such, the first power conversion apparatus 101 is a high efficiency power delivery path between the ac power source 110 and the load 170.

[0060] It should be noted that three-level LLC power converter is merely an example, which should not unduly limit the scope of the claims. One of ordinary skill in the art would recognize many variations, alternatives, and modifications. The first isolated power converter 131 can be implemented as any suitable isolated converters such as flyback converters, forward converters, push-pull converters, half-bridge converters, full-bridge converters, any combinations thereof and the like.

[0061] The second power conversion apparatus 102 comprises a power factor correction device 160. As shown in Figure 2, the output of the three-level LLC power converter 131 and the output of the power factor correction device 160 are connected in series. The power factor correction device 160 may be implemented as any suitable power factor correction converters such as active boost power factor correction rectifiers, Vienna rectifiers and the like. The detailed schematic diagram of the power factor correction device 160 will be described below with respect to Figures 6-7.

[0062] Figure 2 further illustrates a controller 111. In some embodiments, the controller 111 is implemented as a close-loop regulation control unit. The controller 111 may detect the voltage V_o across the outputs of the hybrid power conversion system 100, the input voltages V_a , V_b and V_c fed into the hybrid power conversion system and the input currents I_a , I_b and I_c as shown in Figure 2. Based upon the detected voltages and currents, the controller 111 generates gate drive signals to control the on/off of the switches of the power factor correction device 160 and/or the primary network 130.

[0063] In some embodiments, the controller 111 generates gate drive signals to control the on/off of the switches of the power factor correction device 160 so as to adjust the power factor of the hybrid power conversion system 100 and regulate the output voltage of the hybrid power conversion system 100. In alternative embodiments, the controller 111 generates gate drive signals to control the on/off of the switches of the power factor correction device 160 as well as the switches of the primary network 130. In other words, the regulation of the output voltage of the hybrid power conversion system 100 relies on both the power factor correction device 160 and the three-level LLC power converter 131. In some embodiments, the switching frequency of the switches of the primary network 130 may be adjusted within a narrow range (*e.g.*, $\pm 5\%$ of the resonant frequency of the resonant tank of the three-level LLC power converter 131). The switching frequency adjustment of the switches of the primary network 130 helps to regulate the output voltage of the hybrid power conversion system 100.

[0064] In operation, the power from the ac power source 110 to the load 170 is not evenly distributed between the first power conversion apparatus 101 and the second power conversion apparatus 102. In some embodiments, the power flowing from the ac power source 110 to the load

170 through the second power conversion apparatus 102 is a fraction of power from the ac power source 110 to the load 170 through the first power conversion apparatus 101. In some embodiments, the ratio of the power flowing through the first power conversion apparatus 101 to the power flowing through the second power conversion apparatus 102 is equal to 9:1.

[0065] In operation, the input currents of the power factor correction device 160 are adjusted so that the power factor of the hybrid power conversion system 100 approaches unity (1).

Furthermore, under suitable control schemes such as duty cycle control, the power factor correction device 160 is controlled to have an adjustable output voltage across the output capacitor C_{o2} . As a result of having an adjustable output from the power factor correction device 160, the output voltage of the hybrid power conversion system 100 can be regulated accordingly.

[0066] One advantageous feature of the system configuration described above is the hybrid power conversion system 100 is capable of achieving high efficiency as well as tight regulation. In particular, the three-level LLC power converter 131 may be implemented as an unregulated LLC resonant converter operating at a fixed switching (*e.g.*, the resonant frequency of the LLC resonant converter) or a semi-regulated LLC resonant converter having a switching frequency varying in a narrow range. As a result, the LLC resonant converter may achieve high efficiency through zero voltage switching of the primary switches and zero voltage switching and/or zero current switching of the secondary switches. On the other hand, the hybrid power conversion system 100 is tightly regulated through adjusting the output voltage of the second power conversion apparatus 102.

[0067] Figure 3 illustrates a block diagram of a second implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure. The hybrid power conversion system 200 is similar to the hybrid power conversion system 100 shown in Figure 2 except that the second power conversion apparatus 102 comprises a second isolated power converter 136. As shown in Figure 3, the power factor correction device 160 and the second isolated power converter 136 are connected in cascade between the ac power source 110 and the load 170. The output of the second isolated power converter 136 and the output of the first isolated power converter 131 are connected in parallel. The structure of the second isolated power converter 136 is similar to the first isolated power converter 131, and hence is not discussed again herein to avoid repetition.

[0068] Figure 3 further illustrates a controller 111. In some embodiments, the controller 111 is implemented as a close-loop regulation control unit. The controller 111 may detect the voltage V_o across the outputs of the hybrid power conversion system 100, the input voltages V_a , V_b and V_c fed into the hybrid power conversion system and the input currents I_a , I_b and I_c . Based upon the detected voltages and currents, the controller 111 generates gate drive signals to control the on/off

of the switches of the power factor correction device 160, the primary network 135 and/or the primary network 130.

[0069] In some embodiments, the controller 111 generates gate drive signals to control the on/off of the switches of the power factor correction device 160 as well as the switches of the primary network 135. The power factor correction device 160 is controlled so that a variable dc bus voltage is applied to the second isolated power converter 136. The primary network 135 is controlled so that the output voltage of the hybrid power conversion system is regulated. It should be noted that the voltage adjustment of the primary network 135 is carried out through adjusting the switching frequency of the primary network 135. Since the input voltage of the primary network 135 is a variable voltage, the switching frequency of the switches of the primary network 135 may vary within a narrow range. It should further be noted, in order to better regulate the output voltage of the hybrid power conversion system, the switching frequency of the switches of the primary network 130 may vary within a narrow range to help the second isolated power converter 136 regulate the output voltage of the hybrid power conversion system.

[0070] Figure 4 illustrates a block diagram of a third implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure. The hybrid power conversion system 300 is similar to the hybrid power conversion system 200 shown in Figure 3 except that the output of the second isolated power converter 136 and the output of the first isolated power converter 131 are connected in series.

[0071] In operation, the power factor correction device 160 is employed to achieve a unity power factor and a variable voltage bus applied to the input of the second isolated power converter 136. The second isolated power converter 136 is employed to adjust the voltage across the output capacitor C_{o2} , thereby regulating the output voltage of the hybrid power conversion system 300.

[0072] Figure 4 further illustrates a controller 111. The controller 111 shown in Figure 4 is similar to that shown in Figure 3, and hence is not discussed again.

[0073] Figure 5 illustrates a block diagram of a controller for controlling the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure. The controller 111 may detect the voltage V_o across the outputs of the hybrid power conversion system, the input voltages V_a , V_b and V_c fed into the hybrid power conversion system and the input currents I_a , I_b and I_c . Based upon the detected voltages and currents, the controller 111 generates gate drive signals to control the on/off of the switches of the power factor correction device 160 and/or the primary networks (*e.g.*, primary networks 130 and 135).

[0074] The power factor of the hybrid power conversion system is controlled in a close-loop by sensing the total input currents (*e.g.*, I_a , I_b and I_c) and regulating the power factor correction device 160. The output voltage of the hybrid power conversion system is regulated mainly

through adjusting the output voltage of the power factor correction device 160 in a wide range. In some embodiments, the wide range means the output voltage varies from V_{min} to V_{max} . V_{max} is equal to two times V_{min} . During the process of regulating the output voltage of the hybrid power conversion system, the primary networks 130 and 135 may be adjusted in a narrow range. More particularly, the primary networks 130 and 135 may be part of their respective LLC power converters. The switching frequencies of the primary networks 130 and 135 may be adjusted in a narrow range so as to adjust their output voltages. For example, the switching frequencies of the primary networks 130 and 135 may be adjusted in a range from about 95% of the resonant frequency to about 105% of the resonant frequency. Such a narrow switching frequency range helps to improve the efficiency of the hybrid power conversion system.

[0075] In some embodiments, the controller 111 may be configured so that the hybrid power conversion system operates in seven different voltage regulation modes. In a first voltage regulation mode, the power factor correction device 160 is adjusted to have an output voltage varying in a wide range. Both the primary network 130 and the primary network 135 are adjusted to have their output voltages varying in a narrow range. The first voltage regulation mode is applicable to the hybrid power conversion systems shown in Figures 3-4.

[0076] In a second voltage regulation mode, the power factor correction device 160 is adjusted to have an output voltage in a wide range. The primary network 130 operates at a fixed switching frequency (*e.g.*, operating at the resonant frequency), and the output voltage of the three-level LLC power converter 131 is fixed. The primary network 135 is adjusted to have its output voltage varying in a narrow range. The second voltage regulation mode is applicable to the hybrid power conversion systems shown in Figures 3-4.

[0077] In a third voltage regulation mode, the power factor correction device 160 is adjusted to have an output voltage in a wide range. The primary network 135 operates at a fixed switching frequency (*e.g.*, operating at the resonant frequency). The primary network 130 is adjusted to have its output voltage varying in a narrow range. The third voltage regulation mode is applicable to the hybrid power conversion systems shown in Figures 3-4.

[0078] In a fourth voltage regulation mode, the power factor correction device 160 is adjusted to have an output voltage in a wide range. Both the primary network 130 and the primary network 135 operate at a fixed switching frequency (*e.g.*, operating at the resonant frequency). The fourth voltage regulation mode is applicable to the hybrid power conversion systems shown in Figures 3-4.

[0079] In a fifth voltage regulation mode, the power factor correction device 160 is adjusted to have an output voltage in a wide range. The primary network 130 operates at a fixed switching frequency (*e.g.*, operating at the resonant frequency), and the output voltage of the three-level

LLC power converter 131 is fixed. The primary network 135 is adjusted to have its output voltage varying in a wide range. The fifth voltage regulation mode is applicable to the hybrid power conversion systems shown in Figures 3-4.

[0080] In a sixth voltage regulation mode, the power factor correction device 160 is adjusted to have an output voltage in a wide range. The primary network 130 operates at a fixed switching frequency (*e.g.*, operating at the resonant frequency), and the output voltage of the three-level LLC power converter 131 is fixed. The sixth voltage regulation mode is applicable to the hybrid power conversion systems shown in Figure 2.

[0081] In a seventh voltage regulation mode, the power factor correction device 160 is adjusted to have an output voltage in a wide range. The primary network 130 is adjusted to have its output voltage varying in a narrow range. The seventh voltage regulation mode is applicable to the hybrid power conversion systems shown in Figure 2.

[0082] It should further be noted that while Figure 5 shows the controller 111 is employed to generate the gate signals for the hybrid power conversion system, a person skilled in the art will recognize that there may be a variety of alternatives for implementing the function of the controller 111. For example, the controller 111 may be replaced by discrete components. Furthermore, there may be one dedicated driver or multiple dedicated drivers coupled between the controller 111 and the switches of the hybrid power conversion system.

[0083] Figure 6 illustrates a schematic diagram of a first implementation of the power factor correction device in accordance with various embodiments of the present disclosure. The power factor correction device 160 is implemented as a three-phase boost power factor correction converter. The power factor correction device 160 includes three boost converters connected to three phases of the ac power source respectively. A first boost converter comprises a first inductor L_a , a first switch S11 and a second switch S12. The first switch S11 and the second switch S12 are connected in series across the positive and negative terminal of the output capacitor C_o . The first inductor L_a is connected between the input terminal V_a and a common node of the first switch S11 and the second switch S12.

[0084] A second boost converter comprises a second inductor L_b , a third switch S13 and a fourth switch S14. The third switch S13 and the fourth switch S14 are connected in series across the positive and negative terminal of the output capacitor C_o . The second inductor L_b is connected between the input terminal V_b and a common node of the third switch S13 and the fourth switch S14.

[0085] A third boost converter comprises a third inductor L_c , a fifth switch S15 and a sixth switch S16. The fifth switch S15 and the sixth switch S16 are connected in series across the positive and negative terminal of the output capacitor C_o . The third inductor L_c is connected

between the input terminal V_c and a common node of the fifth switch S15 and the sixth switch S16. The operating principle of the three-phase boost power factor correction converter is well known, and hence is not discussed herein.

[0086] In accordance with an embodiment, the switches (*e.g.*, switches S11-S16) may be an IGBT device. Alternatively, the switching element can be any controllable switches such as MOSFET devices, IGCT devices, GTO devices, SCR devices, JFET devices, MCT devices and the like.

[0087] It should be noted that when switches S11-S16 are implemented by MOSFET devices, the body diodes of switches S11-S16 can be used to provide a freewheeling channel. On the other hand, when switches S11-S16 are implemented by IGBT devices, a separate freewheeling diode is required to be connected in parallel with its corresponding switch.

[0088] As shown in Figure 6, diodes D11, D12, D13, D14, D15 and D16 are required to provide reverse conducting paths. In other words, diodes D11-D16 are anti-parallel diodes. In some embodiments, diodes D11-D16 are co-packaged with their respective IGBT devices. In alternative embodiments, diodes D11-D16 are placed outside their respective IGBT devices.

[0089] It should further be noted that while Figure 6 shows each bidirectional switch is formed by diodes and IGBT devices connected in an anti-parallel arrangement, one of ordinary skill in the art would recognize many variations, alternatives and modifications. For example, the bidirectional switch may be implemented by some new semiconductor switches such as anti-parallel reverse blocking IGBTs arrangement. The discussion of the IGBT devices herein is applicable to other IGBT devices of this disclosure.

[0090] Figure 7 illustrates a schematic diagram of a second implementation of the power factor correction device in accordance with various embodiments of the present disclosure. The power factor correction device 160 is implemented as a three-phase neutral-point clamped (NPC) boost power factor correction converter. The power factor correction device 160 includes three NPC boost converters connected to three phases of the ac power source 110 respectively. Two output capacitors Co1 and Co2 are connected in series across the output terminals of the power factor correction device 160.

[0091] A first NPC boost converter comprises a first inductor L_a , four switches S11-S14 and two diodes D15-D16. The switches S11-S14 are connected in series across the positive terminal of Co1 and the negative terminal of Co2. The first inductor L_a is connected between the input terminal V_a and a common node of switches S12 and S13. The diodes D15 and D16 are connected in series between a common node of switches S11 and S12, and a common node of switches S13 and S14.

[0092] A second NPC boost converter comprises a second inductor L_b , four switches S21-S24 and two diodes D25-D26. The switches S21-S24 are connected in series across the positive terminal of Co1 and the negative terminal of Co2. The second inductor L_b is connected between the input terminal Vb and a common node of switches S22 and S23. The diodes D25 and D26 are connected in series between a common node of switches S21 and S22, and a common node of switches S23 and S24.

[0093] A third NPC boost converter comprises a third inductor L_c , four switches S31-S34 and two diodes D35-D36. The switches S31-S34 are connected in series across the positive terminal of Co1 and the negative terminal of Co2. The third inductor L_c is connected between the input terminal Vc and a common node of switches S32 and S33. The diodes D35 and D36 are connected in series between a common node of switches S31 and S32, and a common node of switches S33 and S34.

[0094] The common node of diodes D15-D16, the common node of diodes D25-D26 and the common node of diodes D35-D36 are connected together and further connected to a common node of output capacitors Co1 and Co2. The operating principle of the three-phase NPC boost power factor correction converter is well known, and hence is not discussed herein.

[0095] In accordance with an embodiment, the switches (*e.g.*, switches S11-S14, S21-S24 and S31-S34) may be an IGBT device. Alternatively, the switching element can be any controllable switches such as MOSFET devices, IGCT devices, GTO devices, SCR devices, JFET devices, MCT devices and the like.

[0096] Figure 8 illustrates a schematic diagram of a first implementation of the diode rectifier in accordance with various embodiments of the present disclosure. The diode rectifier 120 converts the ac input waveforms to a pulsating dc waveform. The capacitor C120 is employed to reduce the ripple content of the pulsating dc waveform.

[0097] The diode rectifier 120 comprises six diodes. The six diodes form three legs. A first leg comprises diodes D121 and D124 connected in series across a positive terminal and a negative terminal of an output capacitor C120. The common node of diodes D121 and D124 is connected to the input terminal Va. A second leg comprises diodes D122 and D125 connected in series across the positive terminal and the negative terminal of the output capacitor C120. The common node of diodes D122 and D125 is connected to the input terminal Vb. A third leg comprises diodes D123 and D126 connected in series across the positive terminal and the negative terminal of the output capacitor C120. The common node of diodes D123 and D126 is connected to the input terminal Vc. The operating principle of the three-phase diode rectifier is well known, and hence is not discussed herein.

[0098] Figure 9 illustrates a schematic diagram of a second implementation of the diode rectifier in accordance with various embodiments of the present disclosure. The rectifier shown in Figure 9 is similar to that shown in Figure 8 except that the diodes have been replaced by respective switches S121-S126. In operation, the gates of the switches S121-S126 are controlled so that the switches S121-S126 emulate the operation of the respective diodes shown in Figure 8. One advantageous feature of having the rectifier shown in Figure 9 is that the switches S121-S126 can help to save the conduction losses caused by the forward voltage drop of the diodes D121-D126.

[0099] Figure 10 illustrates a schematic diagram of a first implementation of the three-level LLC power converter in accordance with various embodiments of the present disclosure. The three-level LLC power converter 131 comprises a primary network 130 comprising a switch network and a resonant tank, a transformer 140 and a rectifier 150. As shown in Figure 10, the switch network, the resonant tank, the transformer 140 and the rectifier 150 are coupled to each other and connected in cascade.

[0100] The switch network comprises switches S131, S132, S133 and S134 connected in series between the positive terminal of the input capacitor C131 and the negative terminal of the input capacitor C132. The common node of switches S132 and S133 is connected to the common node of the capacitors C131 and C132. The common node of switches S131 and S132 is connected to a first terminal of the transformer 140 through the resonant tank. The common node of switches S133 and S134 is connected to a second terminal of the transformer 140.

[0101] The resonant tank may be implemented in a variety of ways. For example, the resonant tank comprises a series resonant inductor L_{r1} , a parallel resonant inductor L_m and a series resonant capacitor C_{r1} .

[0102] The series resonant inductor and the parallel resonant inductor may be implemented as external inductors. A person skilled in the art will recognize that there may be many variation, alternatives and modifications. For example, the series resonant inductor may be implemented as a leakage inductance of the transformer 140.

[0103] In sum, the resonant tank includes three key resonant elements, namely the series resonant inductor, the series resonant capacitor and the parallel resonant inductor. Such a configuration is commonly referred to as an LLC resonant converter. According to the operating principle of LLC resonant converters, at a switching frequency approximately equal to the resonant frequency of the resonant tank, the resonant tank helps to achieve zero voltage switching for the primary side switching elements and zero current switching for the secondary side switching elements.

[0104] The transformer 140 may be formed of two transformer windings, namely a primary transformer winding NP1 and a secondary transformer winding NS1 as shown in Figure 10. Alternatively, the transformer 140 may have a center tapped secondary so as to have three transformer windings including a primary transformer winding, a first secondary transformer winding and a second secondary transformer winding. The rectifier 150 converts an alternating polarity waveform received from the output of the transformer 140 to a single polarity waveform. The rectifier 150 comprises four diodes D231-D234.

[0105] Figure 11 illustrates a schematic diagram of a second implementation of the three-level LLC power converter in accordance with various embodiments of the present disclosure. The three-level LLC power converter shown in Figure 11 is similar to that shown in Figure 10 except that the diodes of the rectifier 150 have been replaced by respective switches S231-S234. In operation, the gates of the switches S231-S234 are controlled so that the switches S231-S234 emulate the operation of the respective diodes shown in Figure 10. One advantageous feature of having the three-level LLC power converter shown in Figure 11 is the switches S231-S234 can help to save the conduction losses caused by the forward voltage drop of the diodes.

[0106] Figure 12 illustrates a schematic diagram of the three-level LLC power converter of the second power conversion apparatus in accordance with various embodiments of the present disclosure. The three-level LLC power converter 136 is the isolated power converter used in the second power conversion apparatus 102. As shown in Figure 12, the three-level LLC power converter 136 is similar to that shown in Figure 10, and hence is not discussed herein to avoid repetition.

[0107] Figure 13 illustrates a block diagram of a fourth implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure. The hybrid power conversion system 1300 is similar to the hybrid power conversion system 200 shown in Figure 3 except that the first isolated power converter is implemented as a hybrid LLC power converter 132. As shown in Figure 13, the hybrid LLC power converter 132 comprises a first primary network 130, a first transformer 140, a second primary network 180, a third transformer 141 and an interleaved multi-bridge circuit 190.

[0108] The first primary network 130 is connected to a primary winding of the first transformer 140. The second primary network 180 is connected to a primary winding of the third transformer 141. The interleaved multi-bridge circuit 190 is connected to a secondary winding of the first transformer 140 and a secondary winding of the third transformer 141. The detailed schematic diagram of the hybrid LLC power converter 132 will be described below with respect to Figures 15 and 18.

[0109] It should be noted that the primary network 135 shown in Figure 13 can be implemented as any suitable power converters. The primary network 135 may be implemented as a three-level LLC power converter. Alternatively, depending on different applications and design needs, the primary network 135, the transformer 145 and the rectifier 155 may form a phase-shift full bridge power converter. The power factor correction device 160 is configured to provide a variable voltage bus fed into the phase-shift full bridge power converter. The phase-shift full bridge power converter is configured to regulate the output voltage applied to the load 170.

[0110] Figure 13 further illustrates a controller 111. In some embodiments, the controller 111 is implemented as a close-loop regulation control unit. The controller 111 may detect the voltage V_o across the outputs of the hybrid power conversion system 1300, the input voltages V_a , V_b and V_c fed into the hybrid power conversion system and the input currents I_a , I_b and I_c . Based upon the detected voltages and currents, the controller 111 generates gate drive signals to control the on/off of the switches of the power factor correction device 160 and/or the primary networks 130, 180 and 135.

[0111] In some embodiments, the controller 111 generates gate drive signals to control the on/off of the switches of the power factor correction device 160 so as to adjust the power factor of the hybrid power conversion system 1300 and regulate the output voltage of the hybrid power conversion system 1300. In alternative embodiments, the controller 111 generates gate drive signals to control the on/off of the switches of the power factor correction device 160 as well as the switches of the primary networks 130, 180 and 135. The switching frequency of the switches of the primary networks may be adjusted within a narrow range (*e.g.*, $\pm 5\%$ of the resonant frequency of the resonant tank). The switching frequency adjustment of the switches of the primary networks helps to regulate the output voltage of the hybrid power conversion system 1300. It should be noted that the control schemes discussed above with respect to Figure 5 are applicable to the hybrid power conversion system 1300.

[0112] Figure 14 illustrates a block diagram of a fifth implementation of the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure. The hybrid power conversion system 1400 is similar to the hybrid power conversion system 1300 shown in Figure 13 except that the output of the second isolated power converter 136 and the output of the first isolated power converter 131 are connected in series.

[0113] Similar to that shown in Figure 13, the power factor correction device 160 of Figure 14 is configured to provide a variable voltage bus fed into the phase-shift full bridge power converter. The phase-shift full bridge power converter is configured to regulate the output voltage applied to the load 170.

[0114] Figure 14 further illustrates a controller 111. The controller 111 shown in Figure 14 is similar to that shown in Figure 13, and hence is not discussed again. It should be noted that the control schemes discussed above with respect to Figure 5 are applicable to the hybrid power conversion system 1400.

[0115] Figure 15 illustrates a schematic diagram of a first implementation of the hybrid LLC power converter shown in Figures 13-14 in accordance with various embodiments of the present disclosure. The hybrid LLC power converter includes two transformers T1 and T3 as shown in Figure 15. The primary side of the transformer T1 is connected to the primary side of a first three-level LLC power converter. Likewise, the primary side of the transformer T3 is connected to the primary side of a second three-level LLC power converter. The primary side of the three-level LLC power converter has been described above with respect to Figure 10, and hence is not discussed herein.

[0116] The secondary side of transformer T1 and the secondary side of transformer T3 are connected to the interleaved multi-bridge circuit 151. As shown in Figure 15, the inputs of the interleaved multi-bridge circuit 151 are connected to the secondary windings NS1 and NS3 respectively. The outputs of the interleaved multi-bridge circuit 151 are connected to an output capacitor C150.

[0117] As shown in Figure 15, the interleaved multi-bridge circuit 151 comprises three legs. A first leg comprises a first diode D151 and a second diode D152 connected in series. A second leg comprises a third diode D153 and a fourth diode D154 connected in series. A third leg comprises a fifth diode D155 and a sixth diode D156 connected in series. The secondary winding NS1 of the first transformer T1 is connected between a common node of the first diode D151 and the second diode D152, and a common node of the third diode D153 and the fourth diode D154. The secondary winding NS3 of the second transformer T2 is connected between a common node of the fifth diode D155 and the sixth diode D156, and the common node of the third diode D153 and the fourth diode D154.

[0118] In operation, depending on the phase shift between the two three-level LLC power converters, the secondary winding NS1 and the second winding NS3 are connected either in parallel or in series. When the phase shift between the switches of the primary network 130 and the switches of the primary network 180 is equal to zero degrees, the secondary winding NS1 and the secondary winding NS3 are connected in series. In a first half of a cycle, the diodes D151 and D156 conduct. In a second half of the cycle, the diodes D152 and D155 conduct. On the other hand, when the phase shift between the switches of the primary network 130 and the switches of the primary network 180 is equal to 180 degrees, the secondary winding NS1 and the secondary winding NS3 are connected in parallel. In a first half of a cycle, the diodes D151 and D154

conduct to deliver the power from the secondary winding NS1 to the load. The diodes D155 and D154 conduct to deliver the power from the secondary winding NS3 to the load. In a second half of the cycle, the diodes D152 and D153 conduct to deliver the power from the secondary winding NS1 to the load. The diodes D153 and D156 conduct to deliver the power from the secondary winding NS3 to the load.

[0119] Figure 16 illustrates a timing diagram of various signals of the hybrid LLC power converter shown in Figure 15 when the secondary windings are configured to be connected in series in accordance with various embodiments of the present disclosure. There may be six vertical axes. The first vertical axis Y1 represents the gate drive signals of switches S131 and S134. The second vertical axis Y2 represents the gate drive signals of switches S132 and S133. The third vertical axis Y3 represents the gate drive signals of switches S181 and S184. The fourth vertical axis Y4 represents the gate drive signals of switches S182 and S183. The fifth vertical axis Y5 represents the voltage across the nodes A and B shown in Figure 15. The sixth vertical axis Y6 represents the voltage across the nodes B and C shown in Figure 15.

[0120] A switching cycle of the hybrid LLC power converter is from the time instant t_0 to the time instant t_2 . A first half cycle is from the time instant t_0 to the time instant t_1 . A second half cycle is from the time instant t_1 to the time instant t_2 . In the first half cycle, the turn-on of the switches S131 and S134 are in sync with the turn-on of the switches S181 and S184. In other words, the phase shift between the two three-level LLC power converters is equal to zero degrees. The voltage VAB and the voltage VBC are in phase. In other words, the voltage VAB and the voltage VBC are added together and then fed to the output capacitor C150 shown in Figure 15.

[0121] In the second half cycle, the turn-on of the switches S132 and S133 are in sync with the turn-on of the switches S182 and S183. The phase shift between the two three-level LLC power converters is equal to zero degrees. The voltage VAB and the voltage VBC are in phase. The voltage VAB and the voltage VBC are added together and then fed to the output capacitor C150.

[0122] Figure 17 illustrates a timing diagram of various signals of the hybrid LLC power converter shown in Figure 15 when the secondary windings are configured to be connected in parallel in accordance with various embodiments of the present disclosure. There may be six vertical axes. The first vertical axis Y1 represents the gate drive signals of switches S131 and S134. The second vertical axis Y2 represents the gate drive signals of switches S132 and S133. The third vertical axis Y3 represents the gate drive signals of switches S181 and S184. The fourth vertical axis Y4 represents the gate drive signals of switches S182 and S183. The fifth vertical axis Y5 represents the voltage across the nodes A and B shown in Figure 15. The sixth vertical axis Y6 represents the voltage across the nodes B and C shown in Figure 15.

[0123] A switching cycle of the hybrid LLC power converter is from the time instant t_0 to the time instant t_2 . A first half cycle is from the time instant t_0 to the time instant t_1 . A second half cycle is from the time instant t_1 to the time instant t_2 . In the first half cycle, the turn-on of the switches S131 and S134 are in sync with the turn-on of the switches S182 and S183. In other words, the phase shift between the two three-level LLC power converters is equal to 180 degrees. The voltage VAB and the voltage VBC are out of phase. Referring back to Figure 15, when the voltage VAB and the voltage VBC are out of phase, the secondary windings NS1 and NS3 are in parallel. VAB is applied to the output capacitor C150 through diodes D151 and D154. VBC is applied to the output capacitor C150 through diodes D155 and D154.

[0124] In the second half cycle, the turn-on of the switches S132 and S133 are in sync with the turn-on of the switches S181 and S184. The phase shift between the two three-level LLC power converters is equal to 180 degrees. The voltage VAB and the voltage VBC are out of phase. Referring back to Figure 15, the secondary windings NS1 and NS3 are in parallel. VAB is applied to the output capacitor C150 through diodes D153 and D152. VBC is applied to the output capacitor C150 through diodes D153 and D156.

[0125] Figure 18 illustrates a schematic diagram of a second implementation of the hybrid LLC power converter shown in Figures 13-14 in accordance with various embodiments of the present disclosure. The hybrid LLC power converter shown in Figure 18 is similar to that shown in Figure 15 except that the diodes of the interleaved multi-bridge circuit 151 have been replaced by respective switches.

[0126] As shown in Figure 18, the interleaved multi-bridge circuit comprises three legs. A first leg comprises a first switch S151 and a second switch S152 connected in series. A second leg comprises a third switch S153 and a fourth switch S154 connected in series. A third leg comprises a fifth switch S155 and a sixth switch S156 connected in series. The secondary winding NS1 of the first transformer T1 is connected between a common node of the first switch S151 and the second switch S152, and a common node of the third switch S153 and the fourth switch S154. The secondary winding NS3 of the second transformer T2 is connected between a common node of the fifth switch S155 and the sixth switch S156, and the common node of the third switch S153 and the fourth switch S154. The operation principle of the interleaved multi-bridge circuit will be described with respect to Figures 19-20.

[0127] Figure 19 illustrates a timing diagram of various signals of the hybrid LLC power converter shown in Figure 18 when the secondary windings are configured to be connected in series in accordance with various embodiments of the present disclosure. There may be eight vertical axes. The first vertical axis Y1 represents the gate drive signals of switches S131 and S134. The second vertical axis Y2 represents the gate drive signals of switches S132 and S133.

The third vertical axis Y3 represents the gate drive signals of switches S181 and S184. The fourth vertical axis Y4 represents the gate drive signals of switches S182 and S183. The fifth vertical axis Y5 represents the voltage across the nodes A and B shown in Figure 18. The sixth vertical axis Y6 represents the voltage across the nodes B and C shown in Figure 18. The seventh vertical axis Y7 represents the gate drive signals of switches S151 and S156. The eighth vertical axis Y8 represents the gate drive signals of switches S152 and S155.

[0128] A switching cycle of the hybrid LLC power converter is from the time instant t_0 to the time instant t_2 . A first half cycle is from the time instant t_0 to the time instant t_1 . A second half cycle is from the time instant t_1 to the time instant t_2 . In the first half cycle, the turn-on of the switches S131 and S134 are in sync with the turn-on of the switches S181 and S184. In other words, the phase shift between the two three-level LLC power converters is equal to zero degrees. The voltage VAB and the voltage VBC are in phase. The voltage VAB and the voltage VBC are added together and then fed to the output capacitor C150 through the switches S151 and S156. As shown in Figure 19, from the time instant t_0 to the time instant t_1 , the switches S151 and S156 conduct.

[0129] In the second half cycle, the turn-on of the switches S132 and S133 are in sync with the turn-on of the switches S182 and S183. The phase shift between the two three-level LLC power converters is equal to zero degrees. The voltage VAB and the voltage VBC are in phase. The voltage VAB and the voltage VBC are added together and then fed to the output capacitor C150 through the switches S152 and S155. As shown in Figure 19, from the time instant t_1 to the time instant t_2 , the switches S152 and S155 conduct. It should be noted during the system configuration shown in Figure 19, the switches S153 and S154 are always off.

[0130] Figure 20 illustrates a timing diagram of various signals of the hybrid LLC power converter shown in Figure 18 when the secondary windings are configured to be connected in parallel in accordance with various embodiments of the present disclosure. There may be eight vertical axes. The first vertical axis Y1 represents the gate drive signals of switches S131 and S134. The second vertical axis Y2 represents the gate drive signals of switches S132 and S133. The third vertical axis Y3 represents the gate drive signals of switches S181 and S184. The fourth vertical axis Y4 represents the gate drive signals of switches S182 and S183. The fifth vertical axis Y5 represents the voltage across the nodes A and B shown in Figure 18. The sixth vertical axis Y6 represents the voltage across the nodes B and C shown in Figure 18. The seventh vertical axis Y7 represents the gate drive signals of switches S151 and S156. The eighth vertical axis Y8 represents the gate drive signals of switches S152 and S155.

[0131] A switching cycle of the hybrid LLC power converter is from the time instant t_0 to the time instant t_2 . A first half cycle is from the time instant t_0 to the time instant t_1 . A second half

cycle is from the time instant t1 to the time instant t2. In the first half cycle, the turn-on of the switches S131 and S134 are in sync with the turn-on of the switches S182 and S183. In other words, the phase shift between the two three-level LLC power converters is equal to 180 degrees. The voltage VAB and the voltage VBC are out of phase. Referring back to Figure 18, the secondary windings NS1 and NS3 are in parallel. VAB is applied to the output capacitor C150 through switches S151 and S154. VBC is applied to the output capacitor C150 through switches S155 and S154.

[0132] In the second half cycle, the turn-on of the switches S132 and S133 are in sync with the turn-on of the switches S181 and S184. The phase shift between the two three-level LLC power converters is equal to 180 degrees. The voltage VAB and the voltage VBC are out of phase. Referring back to Figure 18, the secondary windings NS1 and NS3 are in parallel. VAB is applied to the output capacitor C150 through switches S153 and S152. VBC is applied to the output capacitor C150 through switches S153 and S156.

[0133] Figure 21 illustrates a flow chart of a method for controlling the hybrid power conversion system shown in Figure 1 in accordance with various embodiments of the present disclosure. This flowchart shown in Figure 21 is merely an example, which should not unduly limit the scope of the claims. One of ordinary skill in the art would recognize many variations, alternatives, and modifications. For example, various steps illustrated in Figure 21 may be added, removed, replaced, rearranged and repeated.

[0134] A hybrid power conversion system comprises a first power conversion apparatus and a second power conversion apparatus connected between an ac source and a load. The inputs of the first power conversion apparatus and the inputs of the second power conversion apparatus are connected in parallel. The output of the first power conversion apparatus and the output of the second power conversion apparatus are connected in series or in parallel.

[0135] At step 2102, the first power conversion apparatus is configured as an unregulated power converter. The first power conversion apparatus comprises an LLC power converter operating at a fixed switching frequency.

[0136] At step 2104, the second power conversion apparatus is configured as a regulated power converter. The second power conversion apparatus comprises a power factor correction converter and a regulated power converter. The power factor correction converter is employed to achieve a unity power factor for the hybrid power conversion system. In addition, the power factor correction converter is able to provide a variable voltage bus for the regulated power converter. The regulated power converter is employed to adjust its output voltage, thereby regulating the output voltage of the hybrid power conversion system.

[0137] At step 2106, the output of the first power conversion apparatus and the output of the second power conversion apparatus are connected in series. Alternatively, the output of the first power conversion apparatus and the output of the second power conversion apparatus are connected in parallel.

[0138] Although embodiments of the present disclosure and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the disclosure as defined by the appended claims.

[0139] Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present disclosure, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed, that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present disclosure. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps. The specification and drawings are, accordingly, to be regarded simply as an illustration of the disclosure as defined by the appended claims, and are contemplated to cover any and all modifications, variations, combinations or equivalents that fall within the scope of the present disclosure.

WHAT IS CLAIMED IS:

1. A system comprising:
 - a first power conversion apparatus configured to be connected between an ac source and a load; and
 - a second power conversion apparatus configured to be connected between the ac source and the load, wherein:
 - the second power conversion apparatus comprises a power factor correction device, and wherein the power factor correction device is configured to generate an output voltage varying in a wide range, and an output voltage of the system is regulated mainly through adjusting the output voltage of the power factor correction device; and
 - power flowing from the ac source to the load through the second power conversion apparatus is a fraction of power flowing from the ac source to the load through the first power conversion apparatus.
2. The system of claim 1, wherein:
 - the first power conversion apparatus comprises a diode rectifier and a first isolated power converter connected in cascade; and
 - the second power conversion apparatus comprises the power factor correction device, and wherein an output of the first isolated power converter and an output of the power factor correction device are connected in series.
3. The system of any one of claims 1-2, wherein:
 - the first isolated power converter is a three-level LLC converter comprising a first primary switching network, a first resonant tank, a first transformer and a first secondary rectifier.
4. The system of claim 1, wherein:
 - the first power conversion apparatus comprises a diode rectifier and a first isolated power converter connected in cascade; and
 - the second power conversion apparatus comprises the power factor correction device and a second isolated power converter connected in cascade, and wherein an output of the first isolated power converter and an output of the second isolated power converter are connected in series, and wherein the output voltage of the system is regulated mainly through adjusting the output voltage of the power factor correction device, partially through adjusting an output voltage of the first isolated power converter in a narrow range, and partially through adjusting an output voltage of the second isolated power converter in a narrow range.
5. The system of claim 1, wherein:
 - the first power conversion apparatus comprises a diode rectifier and a first isolated power converter connected in cascade; and

the second power conversion apparatus comprises the power factor correction device and a second isolated power converter connected in cascade, and wherein an output of the first isolated power converter and an output of the second isolated power converter are connected in parallel.

6. The system of claim 1, wherein:

the first power conversion apparatus comprises a diode rectifier and a first hybrid power converter connected in cascade; and

the second power conversion apparatus comprises the power factor correction device and a second isolated power converter connected in cascade, and wherein an output of the first hybrid power converter and an output of the second isolated power converter are connected in parallel.

7. The system of any one of claims 1 and 6, wherein the first hybrid power converter comprises:

a first primary switching network, a first transformer, a second primary switching network, a second transformer and an interleaved multi-bridge circuit, and wherein:

the first primary switching network is connected to a primary winding of the first transformer;

the second primary switching network is connected to a primary winding of the second transformer; and

the interleaved multi-bridge circuit is connected to a secondary winding of the first transformer and a secondary winding of the second transformer.

8. The system of any one of claims 1 and 6-7, wherein:

the interleaved multi-bridge circuit comprises a first leg comprising a first switch and a second switch connected in series, a second leg comprising a third switch and a fourth switch connected in series, and a third leg comprising a fifth switch and a sixth switch connected in series, and wherein:

the secondary winding of the first transformer is connected between a common node of the first switch and the second switch, and a common node of the third switch and the fourth switch; and

the secondary winding of the second transformer is connected between a common node of the fifth switch and the sixth switch, and the common node of the third switch and the fourth switch.

9. The system of any one of claims 1 and 6-7, wherein:

the interleaved multi-bridge circuit comprises a first leg comprising a first diode and a second diode connected in series, a second leg comprising a third diode and a fourth diode connected in series, and a third leg comprising a fifth diode and a sixth diode connected in series,

and wherein:

the secondary winding of the first transformer is connected between a common node of the first diode and the second diode, and a common node of the third diode and the fourth diode; and

the secondary winding of the second transformer is connected between a common node of the fifth diode and the sixth diode, and the common node of the third diode and the fourth diode.

10. The system of any one of claims 1-9, wherein:

the power factor correction device is a three-phase boost power factor correction converter.

11. The system of any one of claims 1-9, wherein:

the power factor correction device is a three-phase neutral-point clamped (NPC) three-level boost power factor correction converter.

12. A method comprising:
transferring energy from an ac power source to a load through a first power conversion apparatus, wherein the first power conversion apparatus is an unregulated power conversion apparatus; and
transferring energy from the ac power source to the load through a second power conversion apparatus, wherein the second power conversion apparatus is a regulated power conversion apparatus.
13. The method of claim 12, further comprising:
configuring the first power conversion apparatus and the second power conversion apparatus such that the energy flowing from the ac power source to the load through the second power conversion apparatus is a fraction of the energy flowing from the ac power source to the load through the first power conversion apparatus.
14. The method of any one of claims 12-13, further comprising:
under various input line and output load conditions, configuring the first power conversion apparatus such that an inductor-inductor-capacitor (LLC) power converter of the first power conversion apparatus operates at a switching frequency substantially equal to a resonant frequency of the LLC power converter.
15. The method of any one of claims 12-14, further comprising:
monitoring output voltages of the ac power source, currents flowing from the ac power source and an output voltage applied to the load;
adjusting a power factor to unity through adjusting input currents flowing into a power factor correction device of the second power conversion apparatus; and
regulating the output voltage applied to the load through having an output voltage of the power factor correction device varying in a wide range and having a switching frequency of an LLC power converter of the second power conversion apparatus varying in a narrow range.
16. The method of any one of claims 12-15, wherein:
the power factor correction device is an active boost power factor correction rectifier configured to regulate the output voltage.

17. A system comprising:

an unregulated power conversion apparatus configured to be connected between an ac source and a load; and

a regulated power conversion apparatus configured to be connected between the ac source and the load, wherein power flowing from the ac source to the load through the regulated power conversion apparatus is a fraction of power flowing from the ac source to the load through the unregulated power conversion apparatus.

18. The system of claim 17, wherein:

the unregulated power conversion apparatus comprises a diode rectifier and a first isolated power converter connected in cascade; and

the regulated power conversion apparatus comprises a power factor correction device and a second isolated power converter connected in cascade, and wherein:

inputs of the power factor correction device and inputs of the diode rectifier are connected in parallel; and

an output of the first isolated power converter and an output of the second isolated power converter are connected in series.

19. The system of claim 17, wherein:

the unregulated power conversion apparatus comprises a diode rectifier and a first isolated power converter connected in cascade; and

the regulated power conversion apparatus comprises a power factor correction device and a second isolated power converter connected in cascade, and wherein:

inputs of the power factor correction device and inputs of the diode rectifier are connected in parallel; and

an output of the first isolated power converter and an output of the second isolated power converter are connected in parallel.

20. The system of any one of claims 17-19, wherein:

the first isolated power converter is an inductor-inductor-capacitor (LLC) power converter; and

the power factor correction device is a three-phase boost power factor correction converter.

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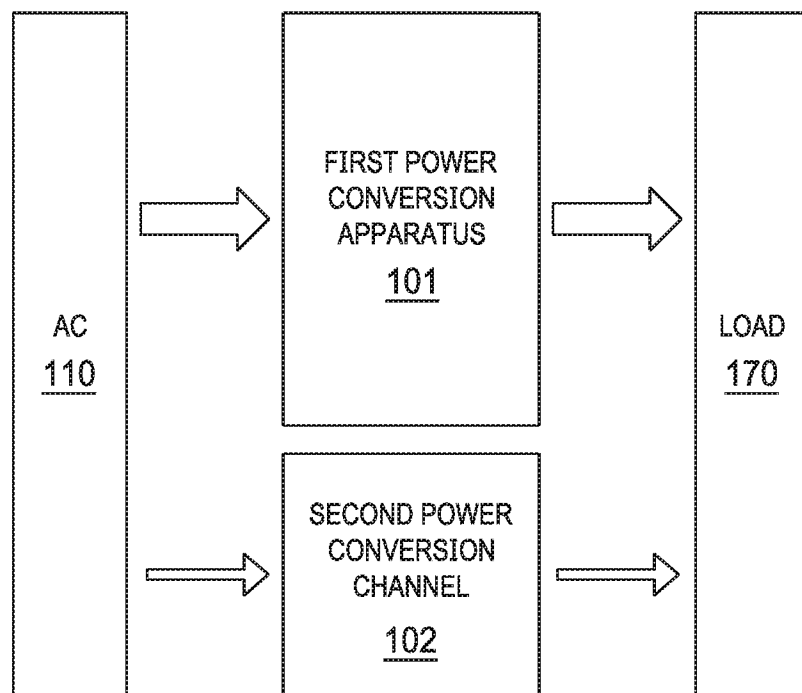


FIG. 1

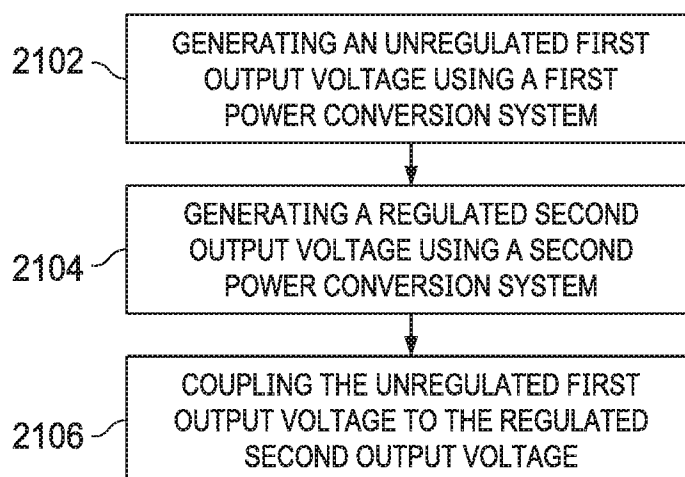


FIG. 21

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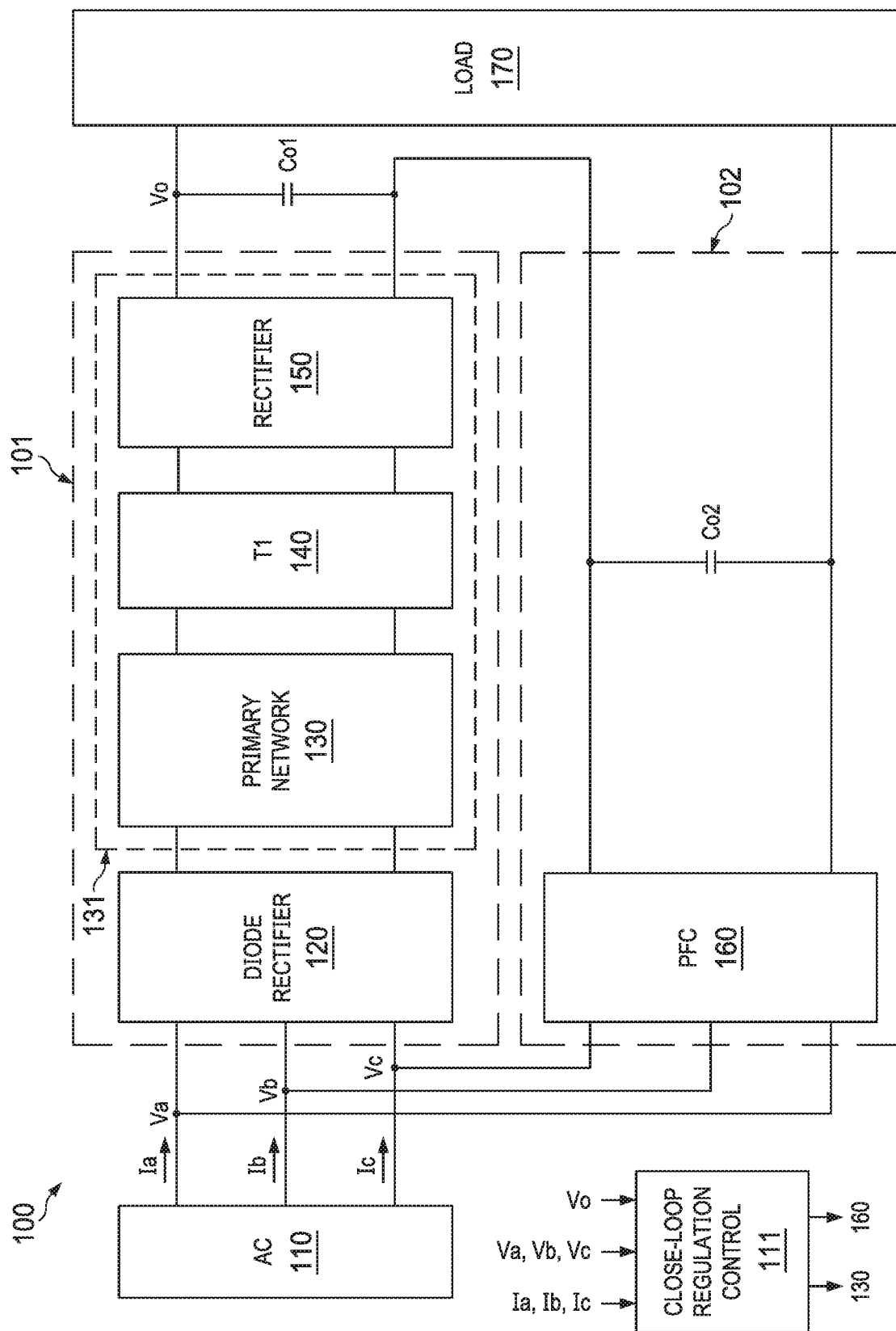


FIG. 2

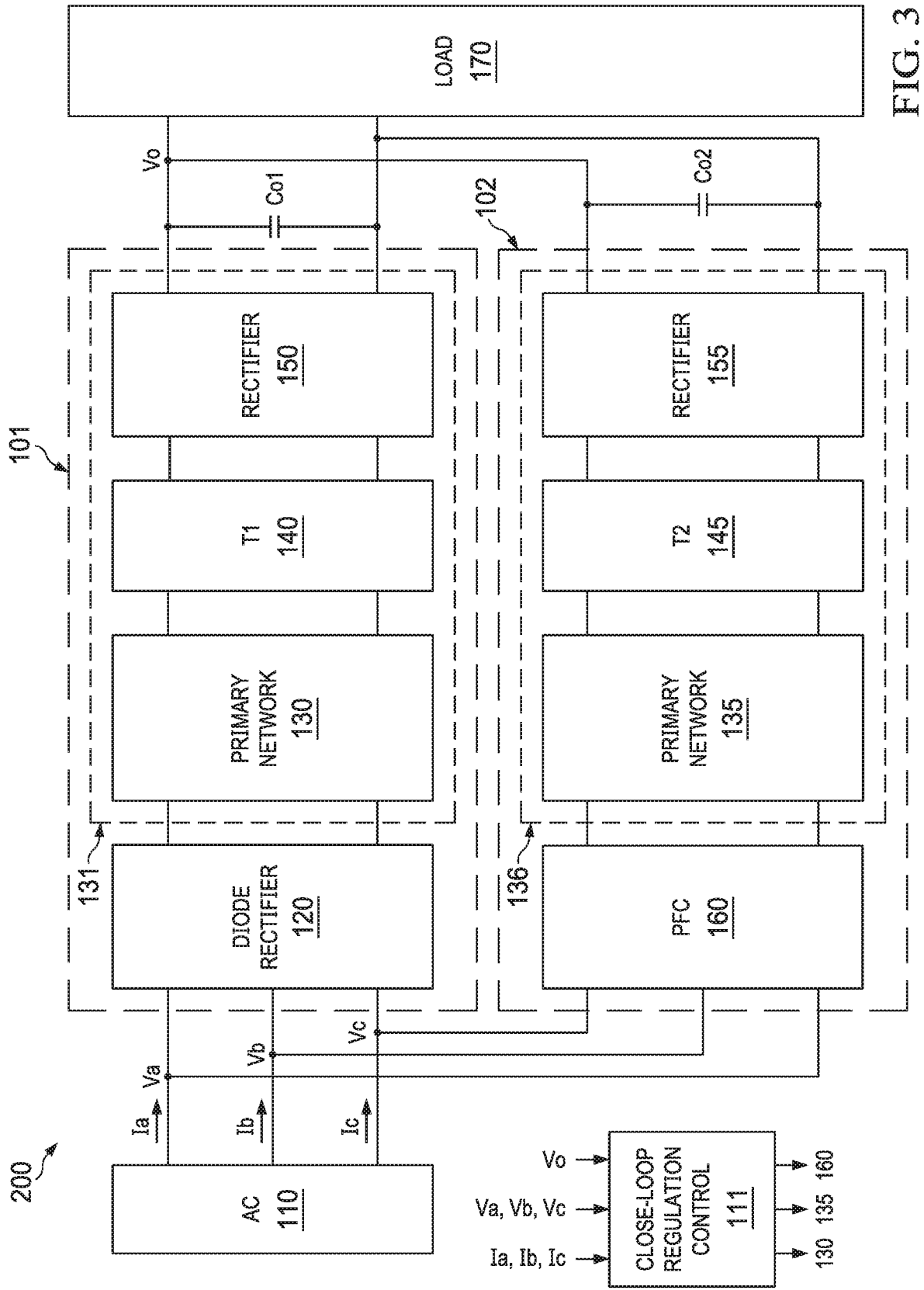


FIG. 3

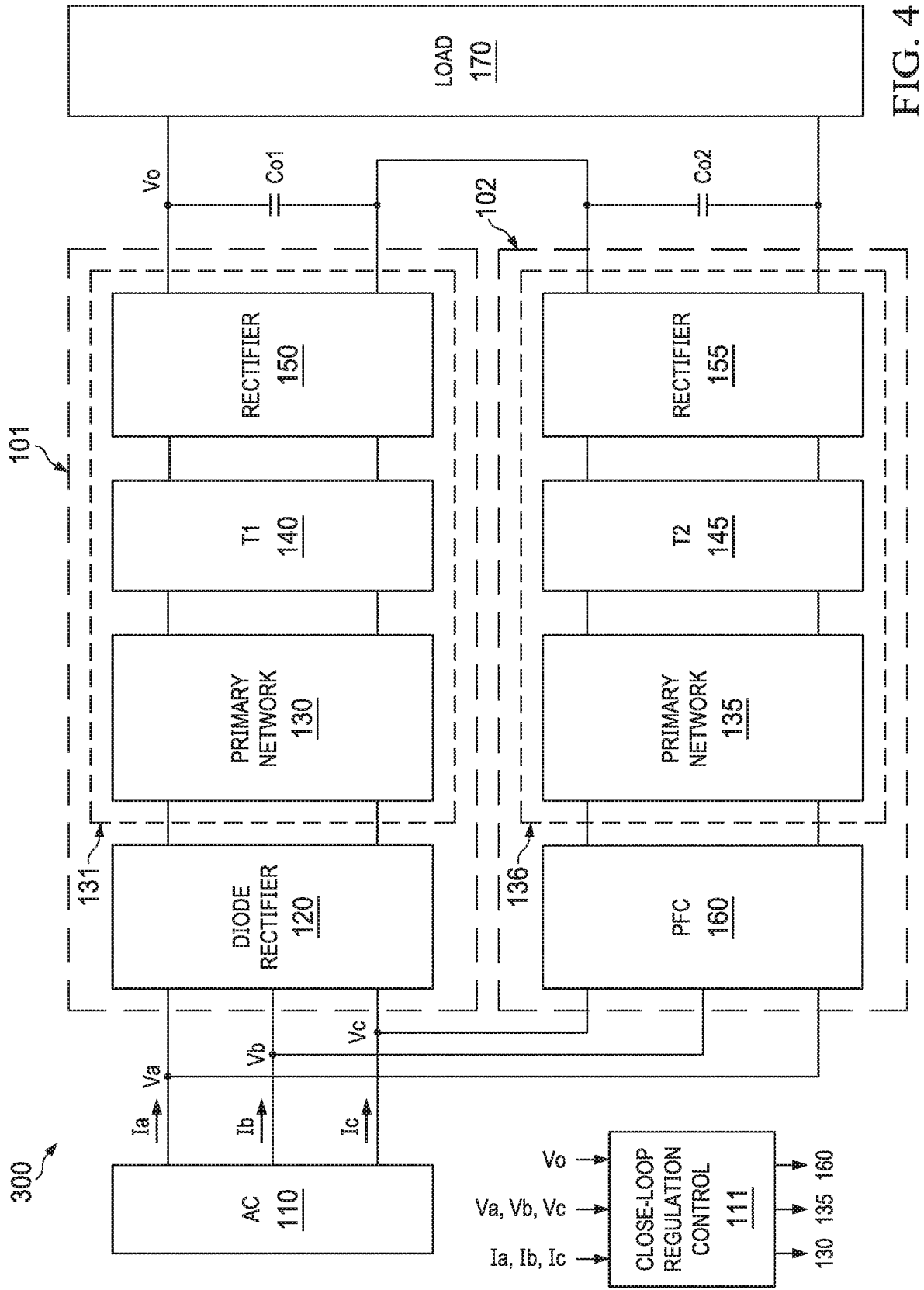


FIG. 4

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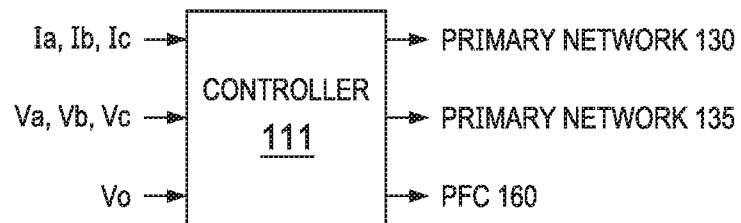


FIG. 5

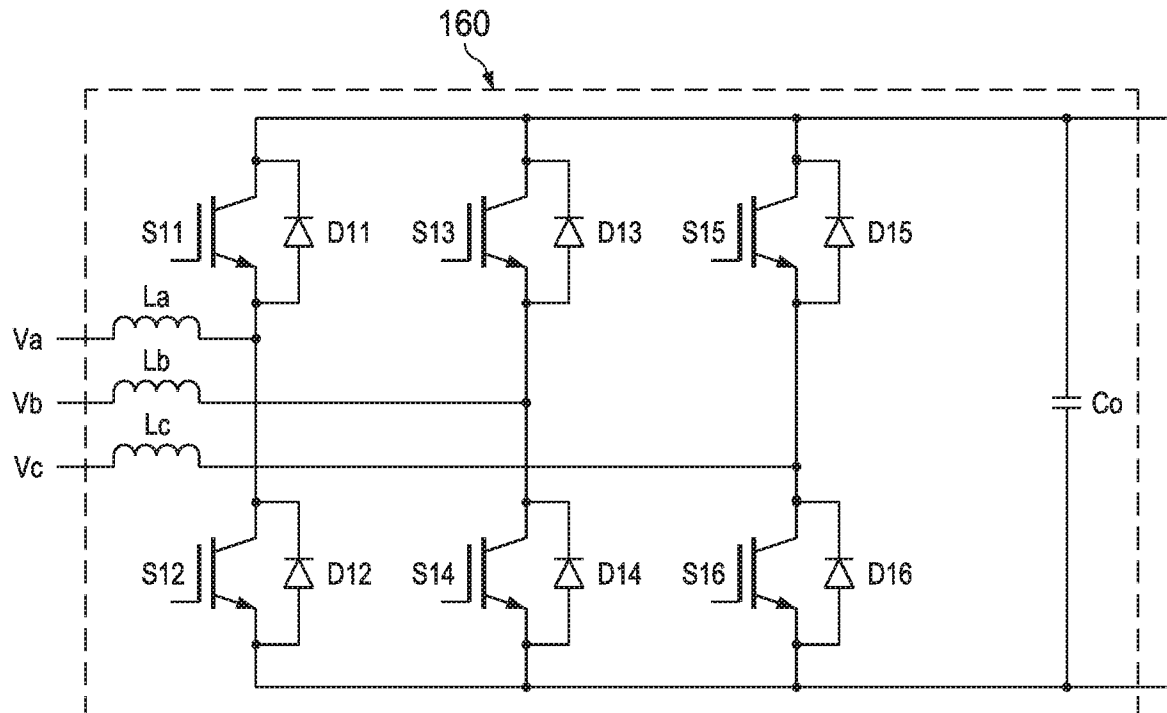


FIG. 6

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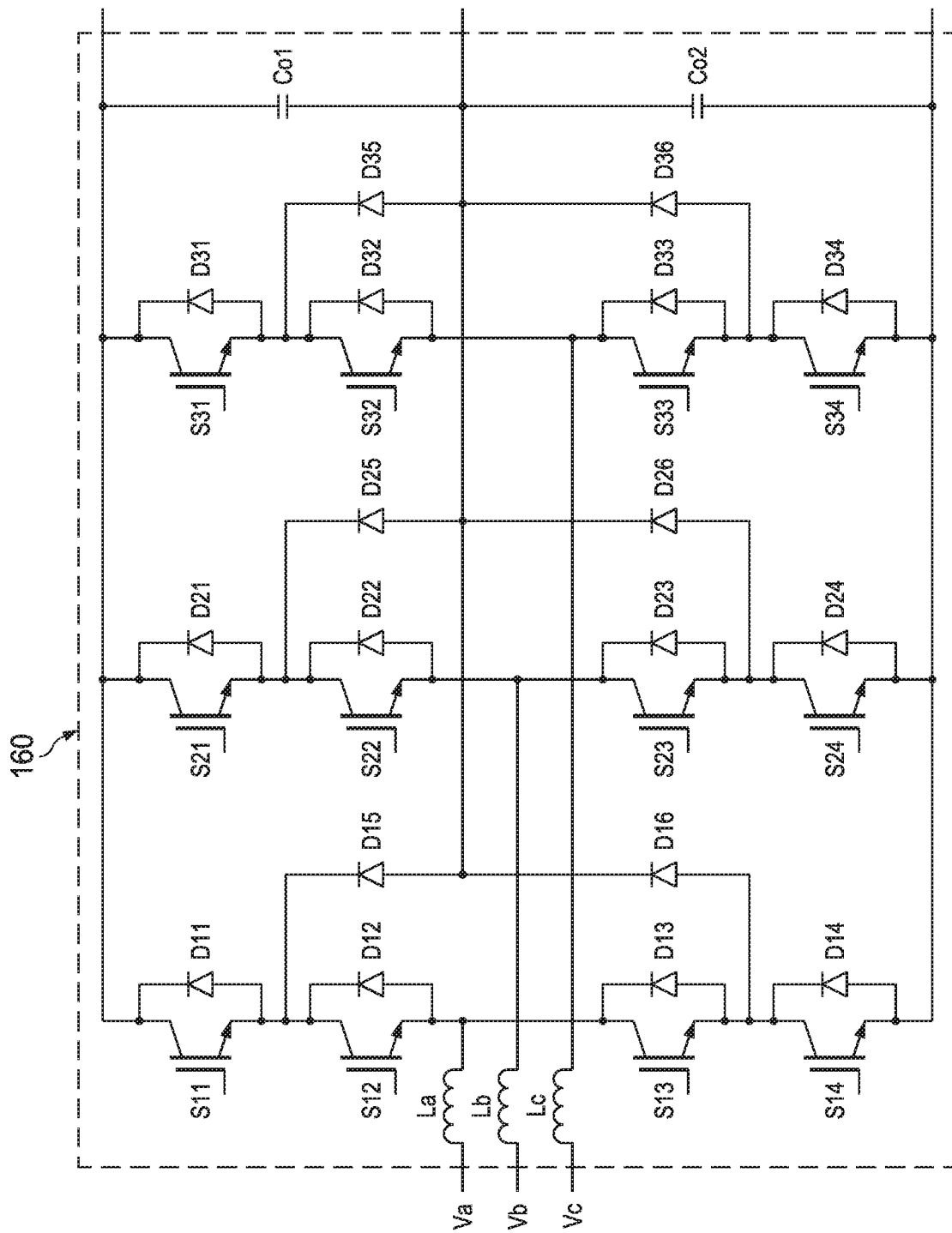


FIG. 7*

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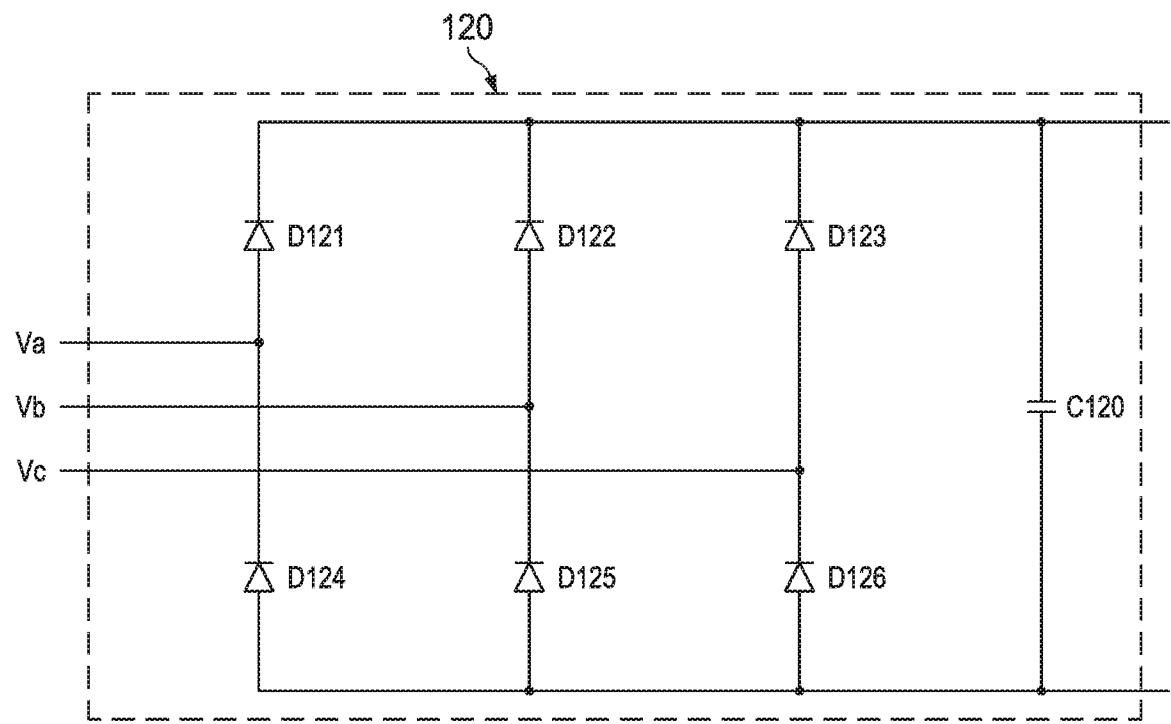


FIG. 8

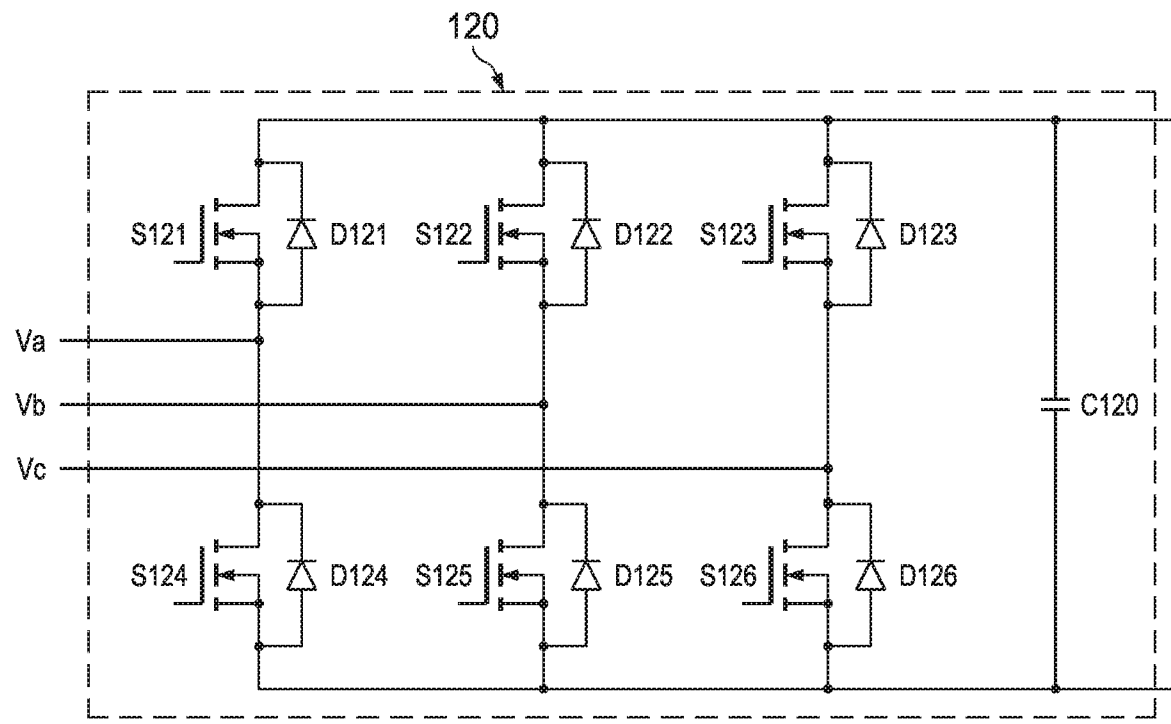


FIG. 9

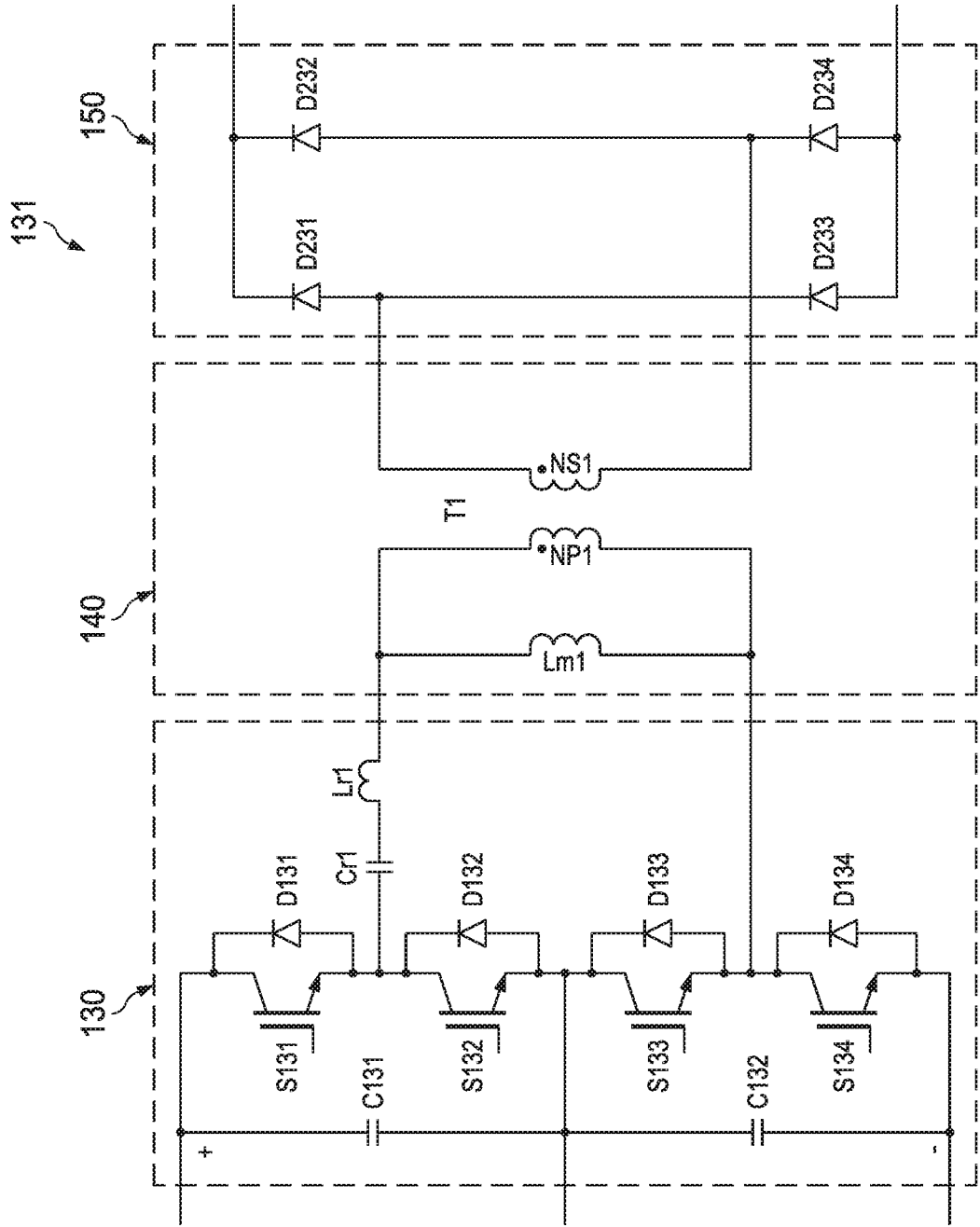


FIG. 10

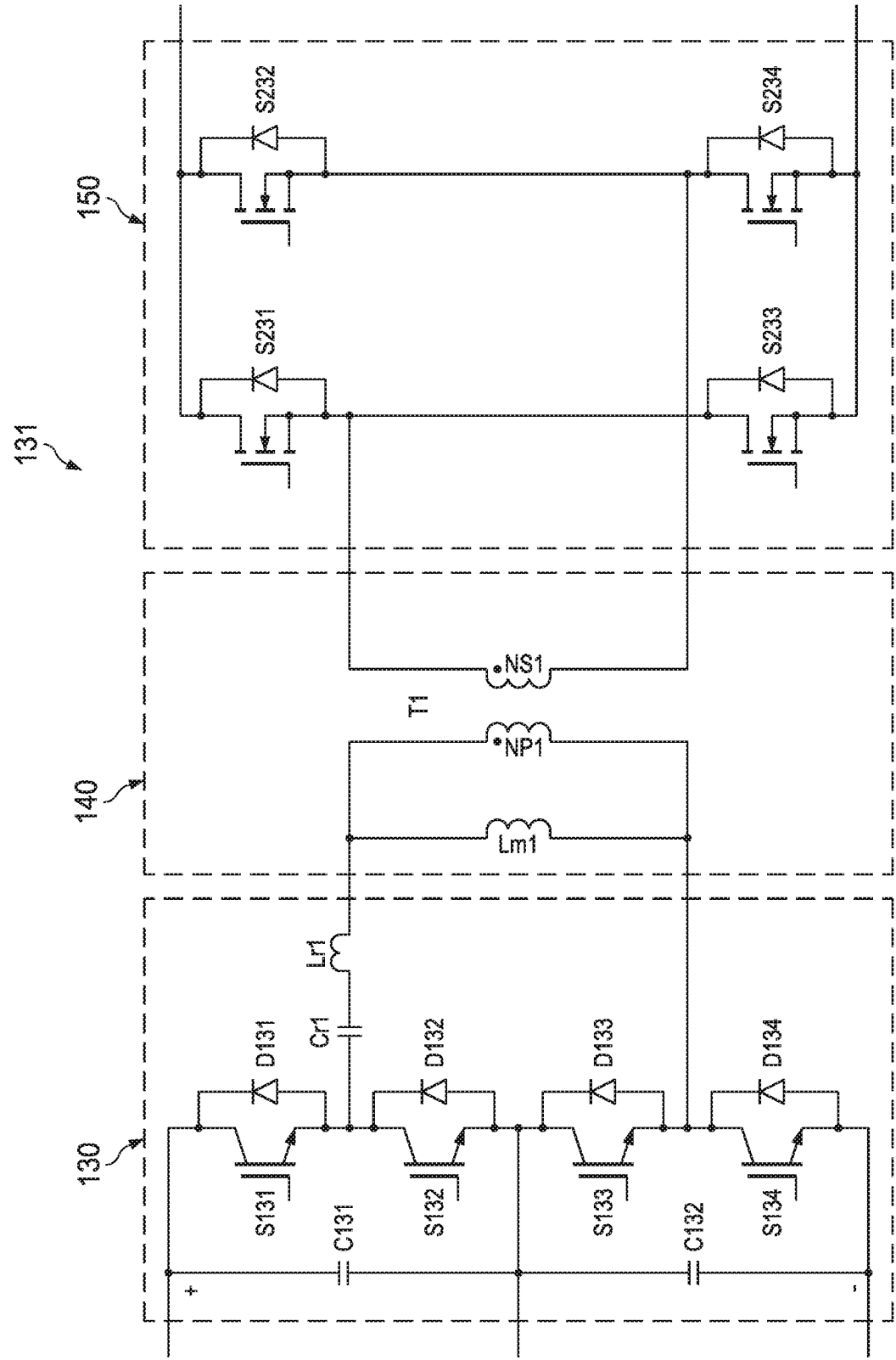


FIG. 11

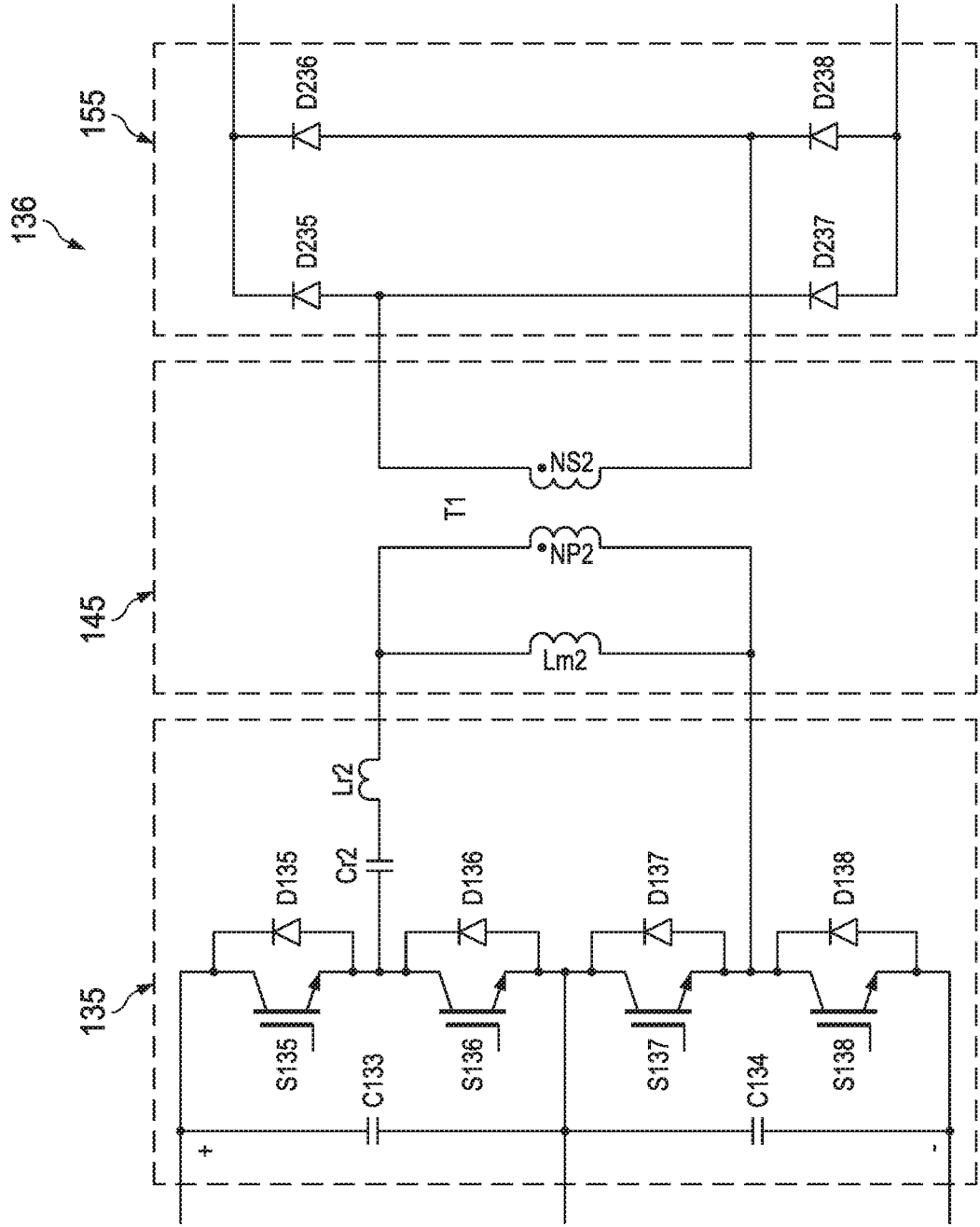


FIG. 12

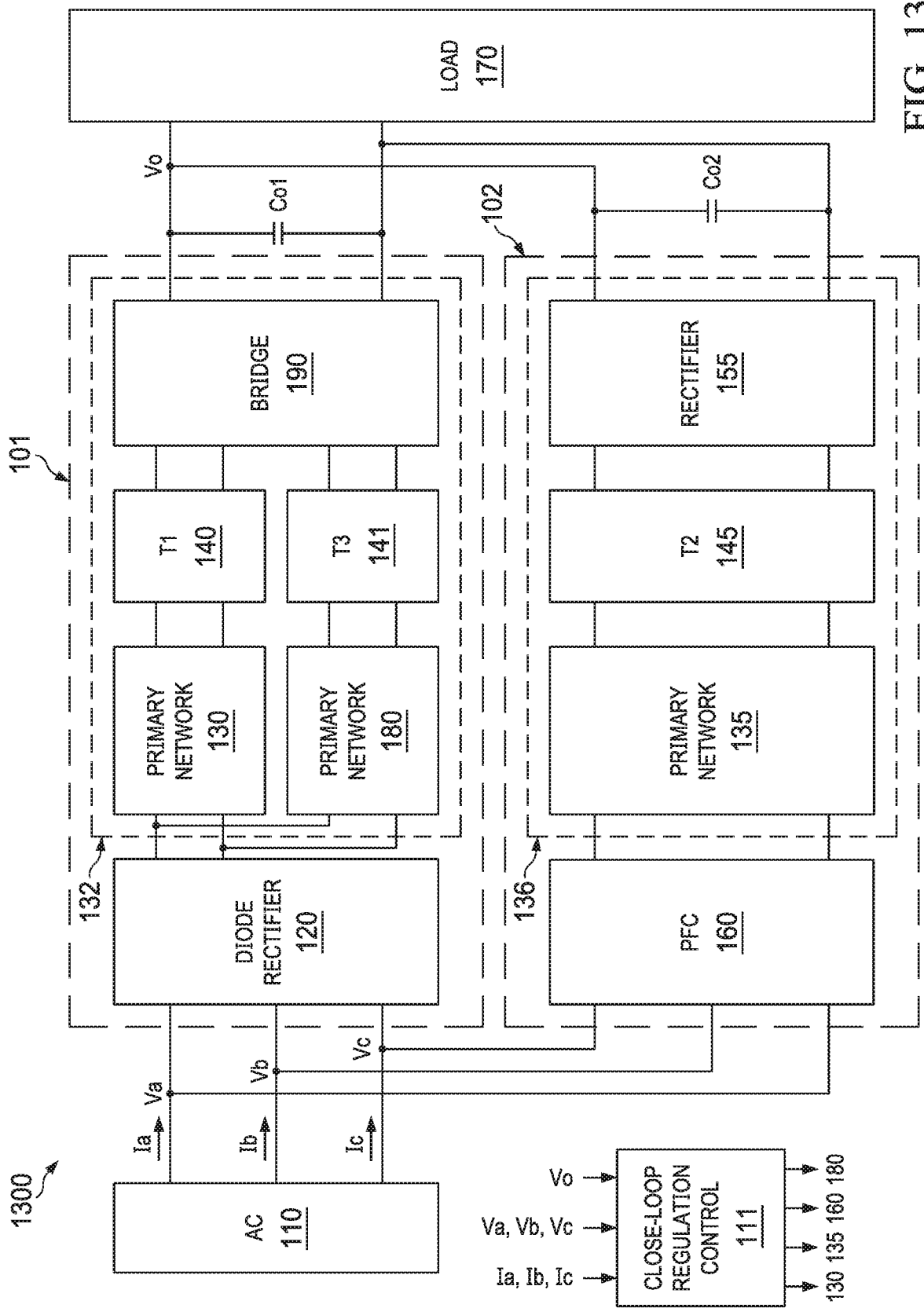


FIG. 13

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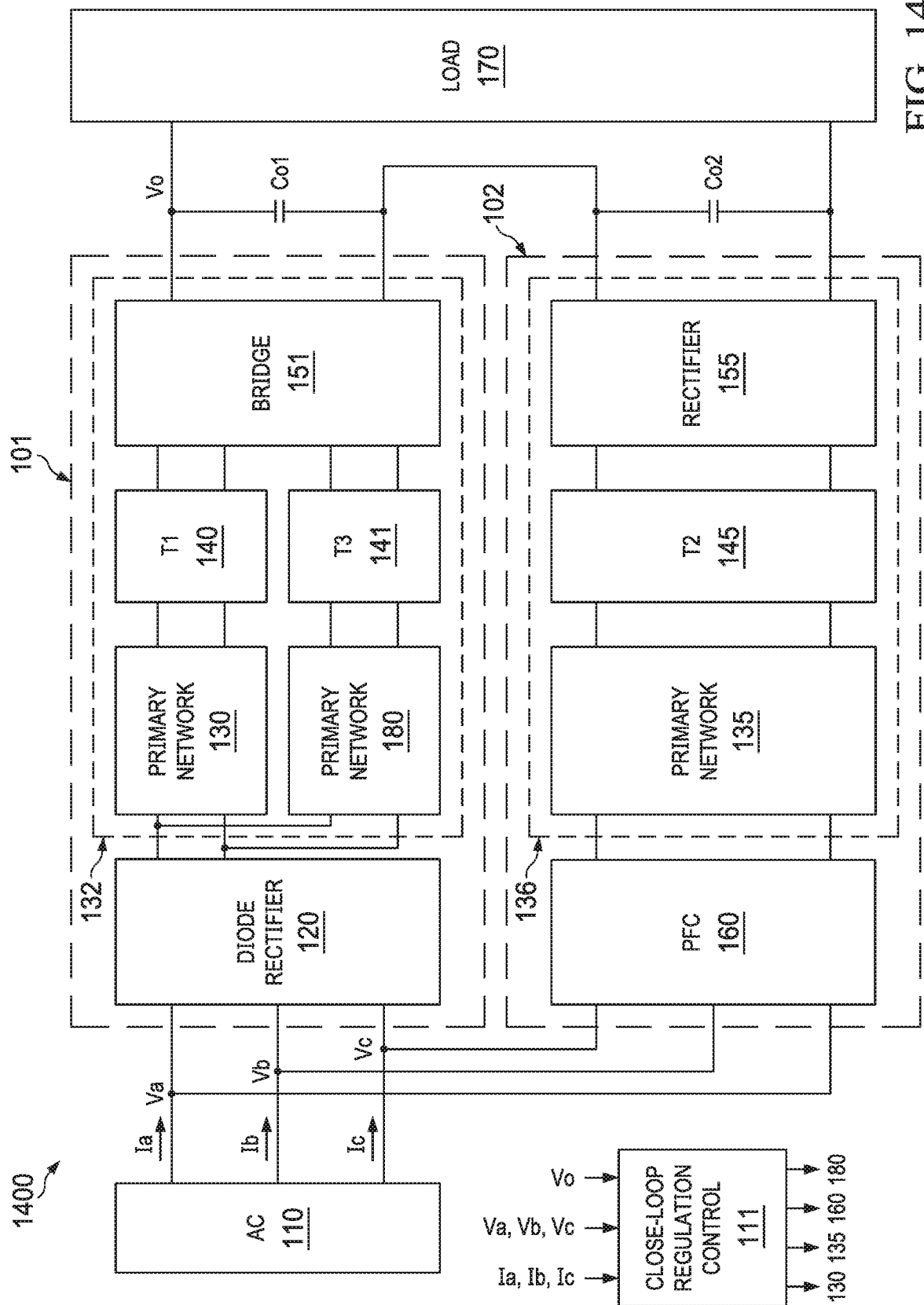


FIG. 14

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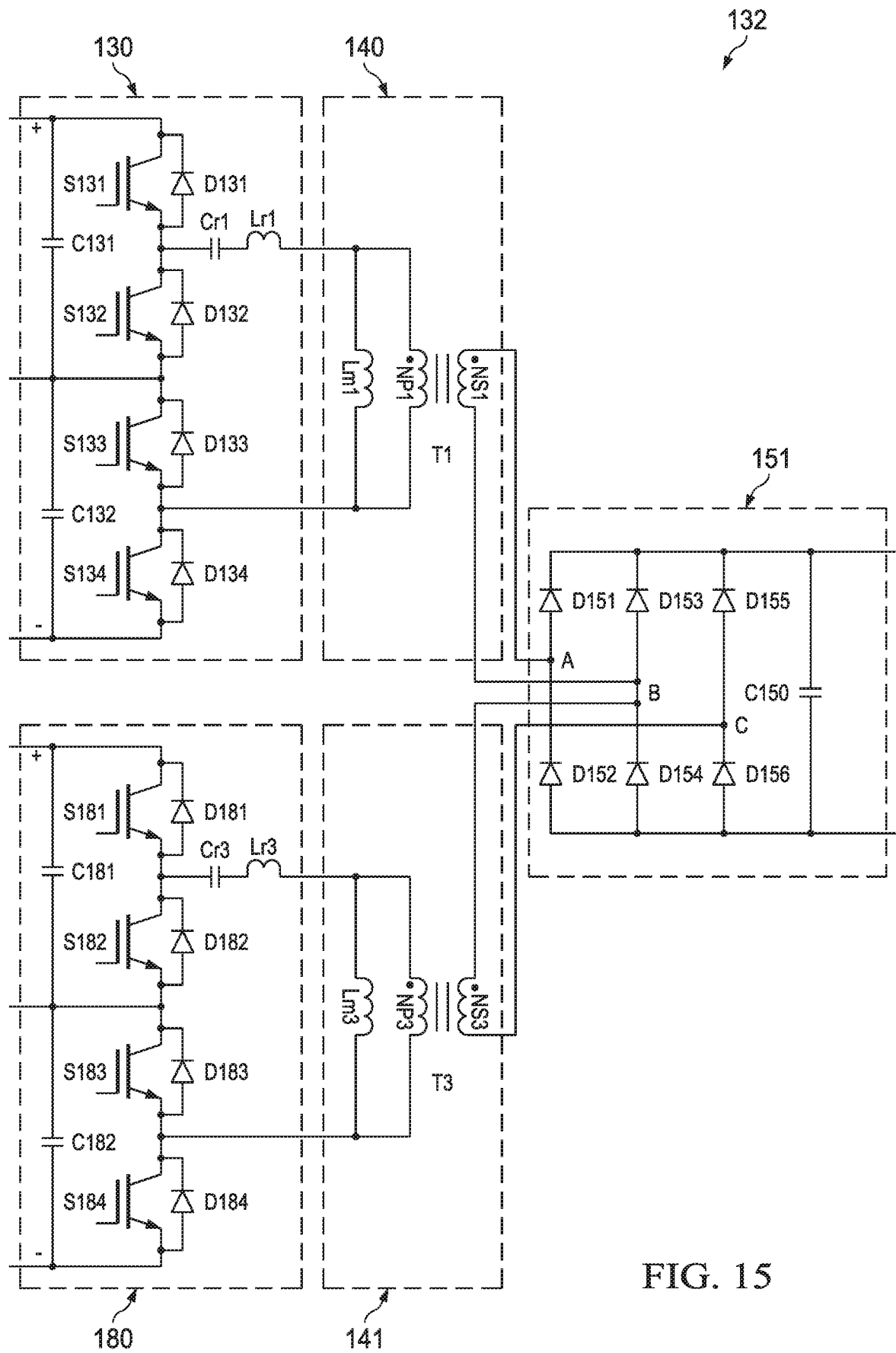


FIG. 15

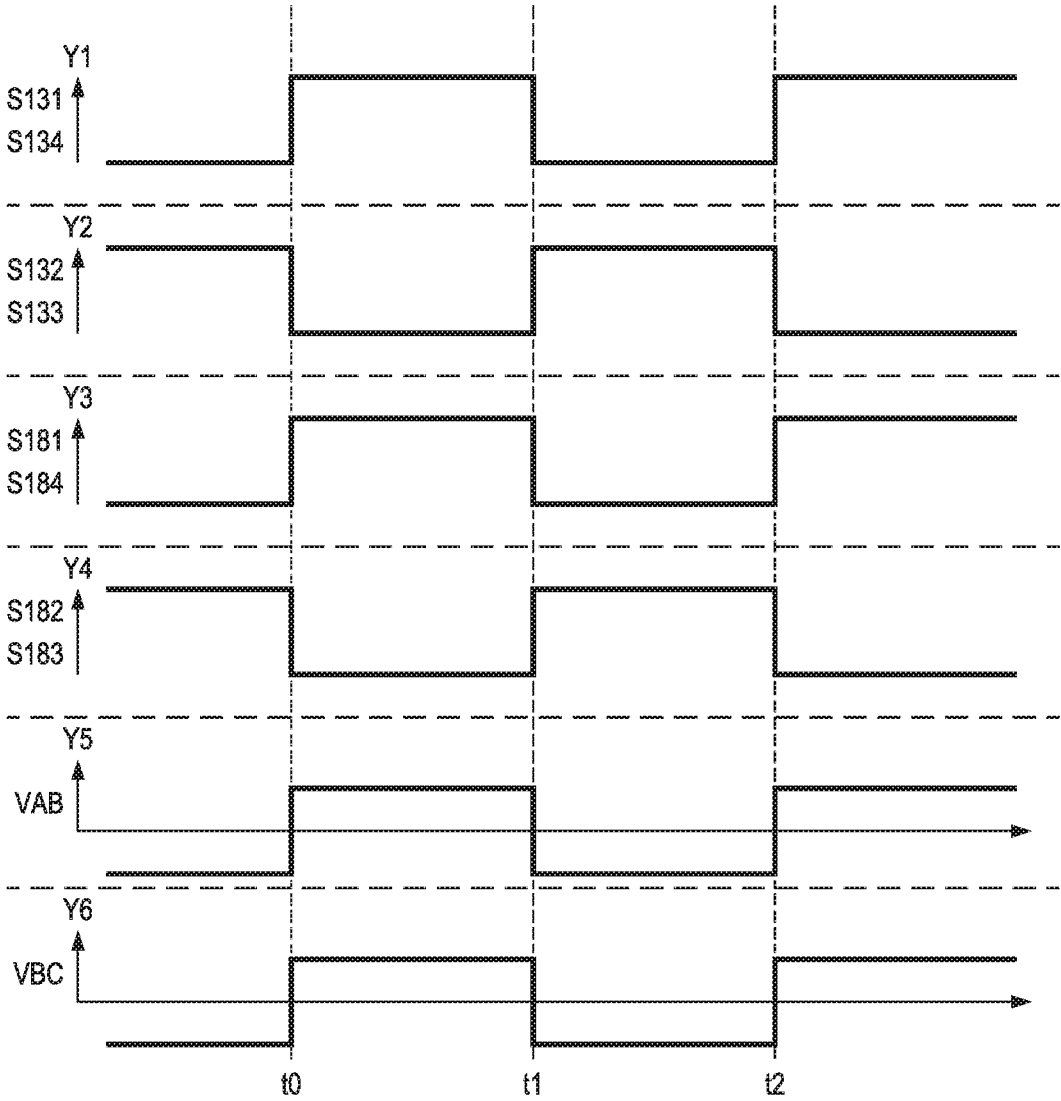


FIG. 16

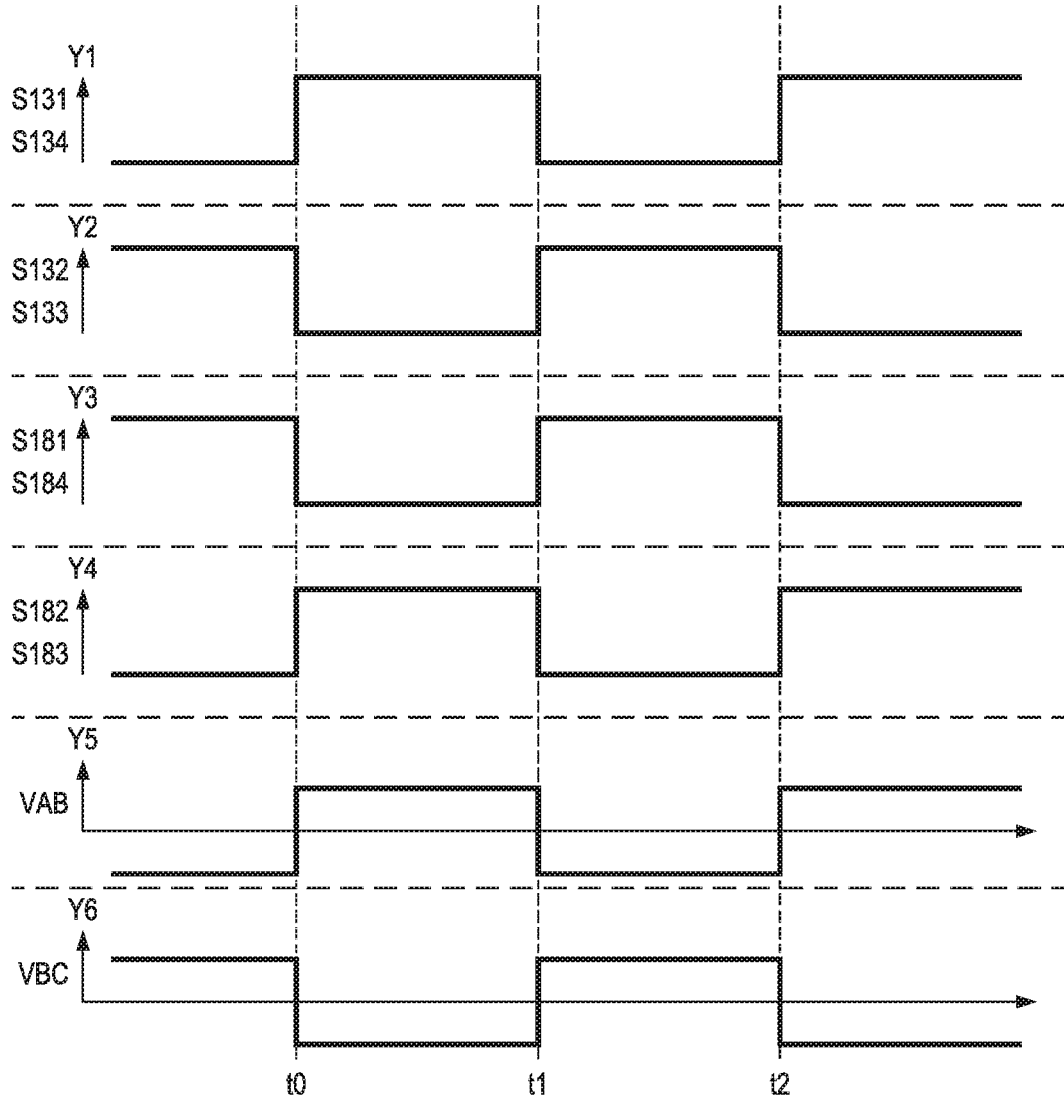


FIG. 17

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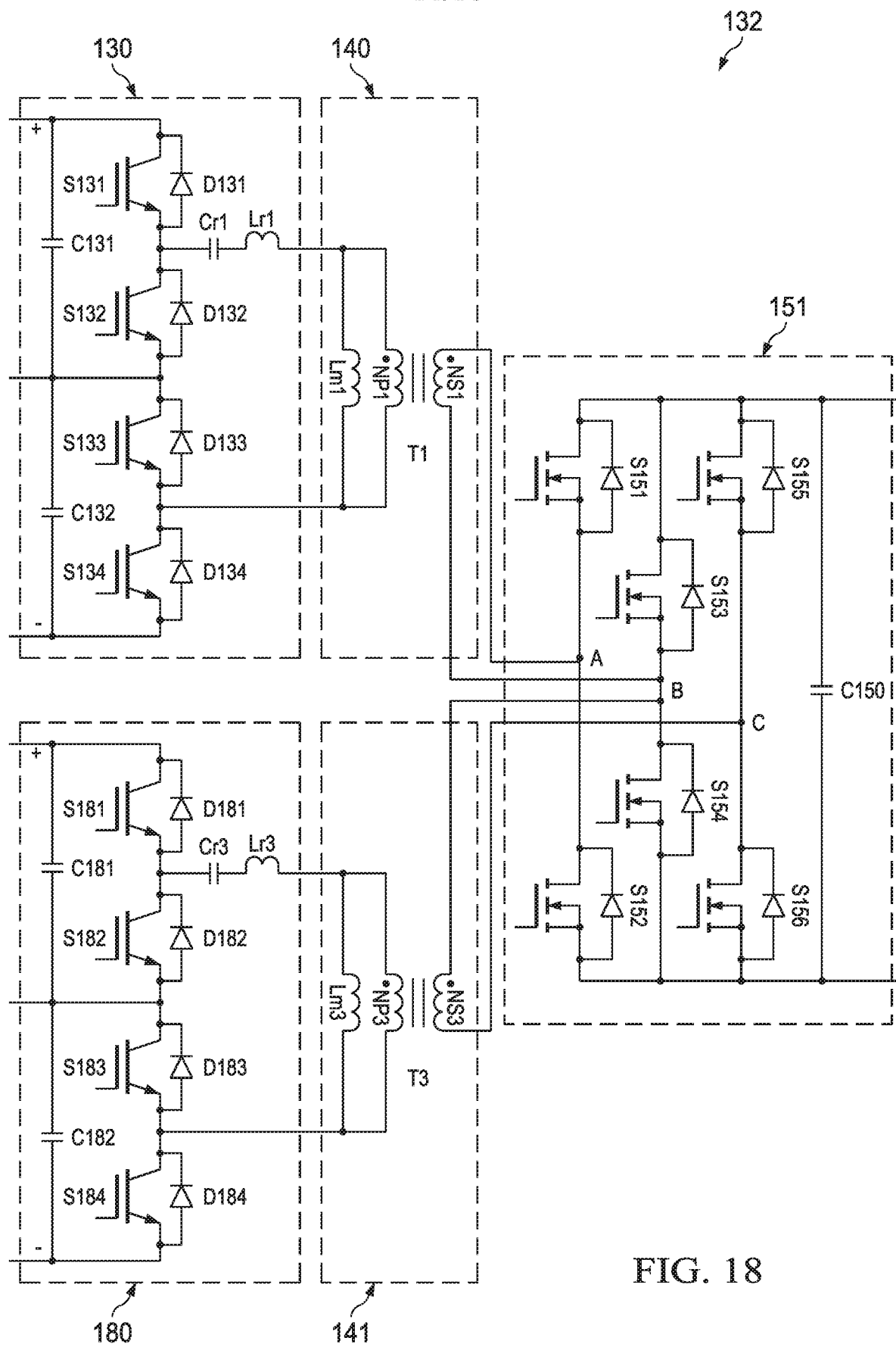


FIG. 18

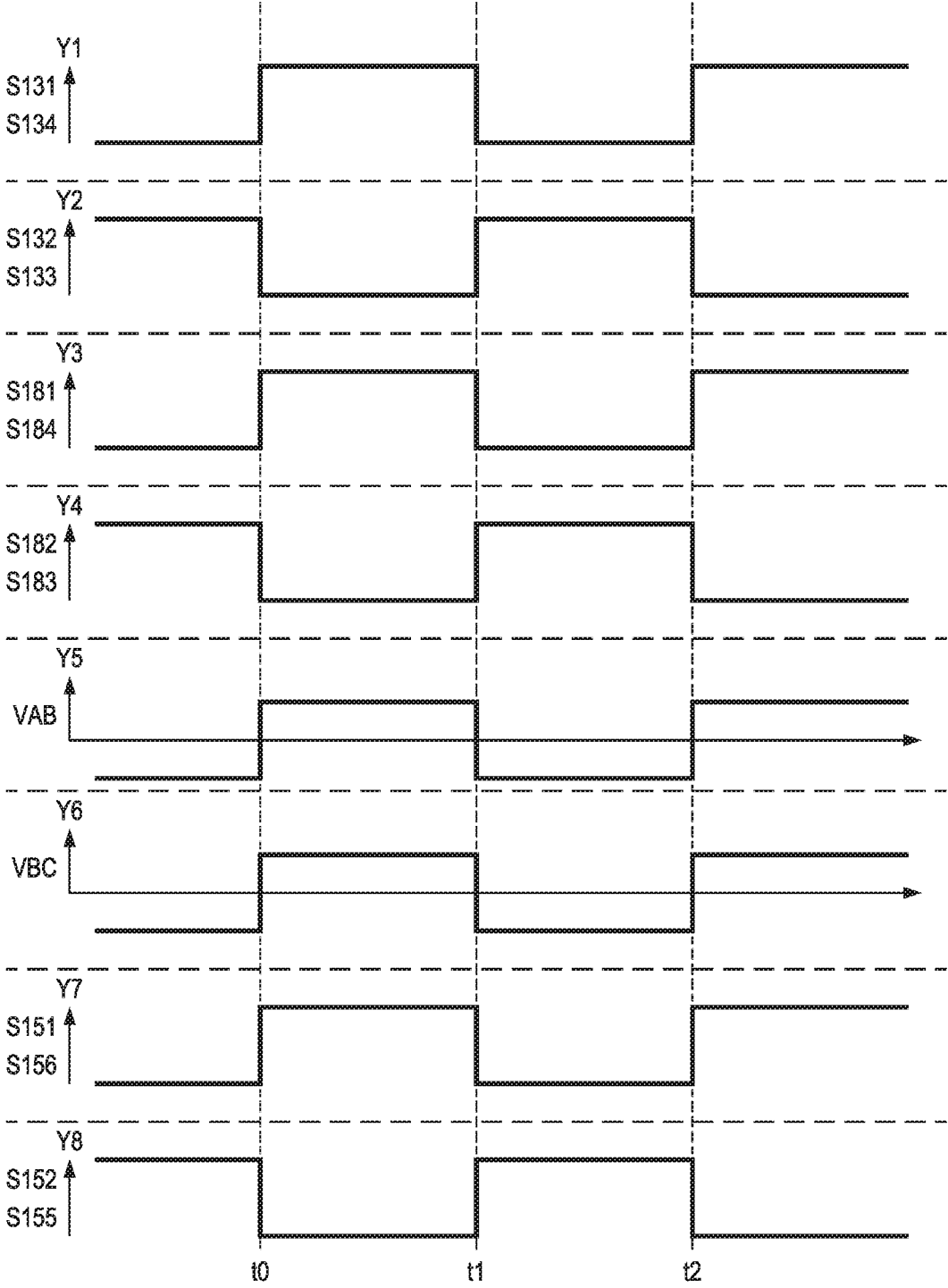


FIG. 19

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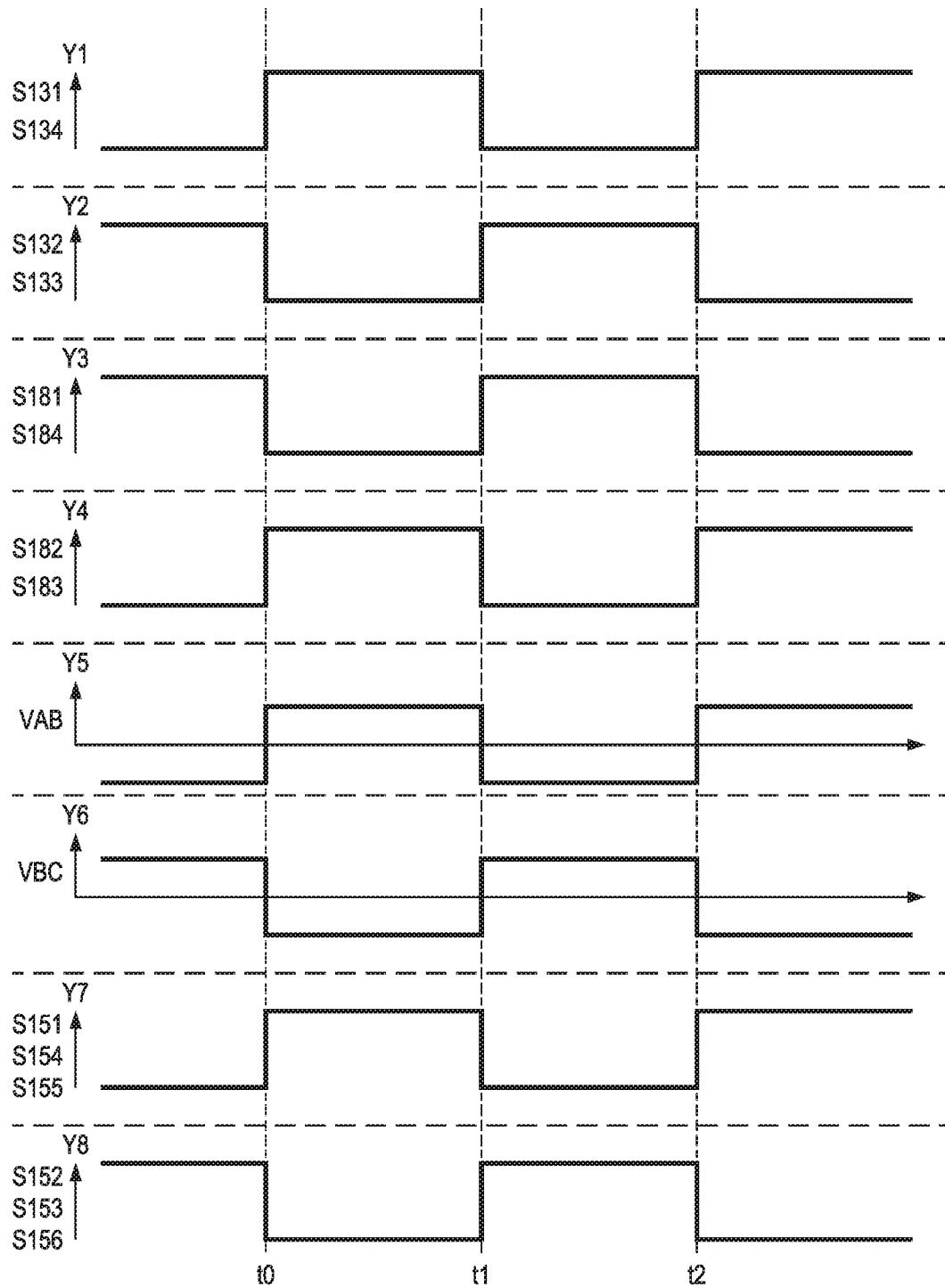


FIG. 20

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2019/033034

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M1/00
ADD.

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)
H02M

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

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

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SANDEEP BALA ET AL: "Hybrid distribution transformer: Concept development and field demonstration", ENERGY CONVERSION CONGRESS AND EXPOSITION (ECCE), 2012 IEEE, IEEE, 15 September 2012 (2012-09-15), pages 4061-4068, XP032467099, DOI: 10.1109/ECCE.2012.6342271 ISBN: 978-1-4673-0802-1 figure 12 table 1	1-20
X	----- US 2015/349655 A1 (PETERSEN JESPER ELLIOT [DK] ET AL) 3 December 2015 (2015-12-03) figure 1 paragraph [0012] paragraph [0032] ----- -/--	1,12



Further documents are listed in the continuation of Box C.



See patent family annex.

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"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

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"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

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Date of the actual completion of the international search

29 January 2020

Date of mailing of the international search report

05/02/2020

Name and mailing address of the ISA/

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Authorized officer

Gotzig, Bernhard

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2019/033034

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2018/294732 A1 (YE LIMING [US] ET AL) 11 October 2018 (2018-10-11) paragraph [0052] - paragraph [0068] figures 1,2,4A	1-20
X	----- US 10 116 204 B1 (ECKHARDT CHAD [US] ET AL) 30 October 2018 (2018-10-30) figures 3,4 -----	1,12

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2019/033034

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2015349655 A1	03-12-2015	CN 105322530 A	10-02-2016
		EP 2953228 A1	09-12-2015
		US 2015349655 A1	03-12-2015

US 2018294732 A1	11-10-2018	NONE	

US 10116204 B1	30-10-2018	US 10116204 B1	30-10-2018
		US 2019028023 A1	24-01-2019
