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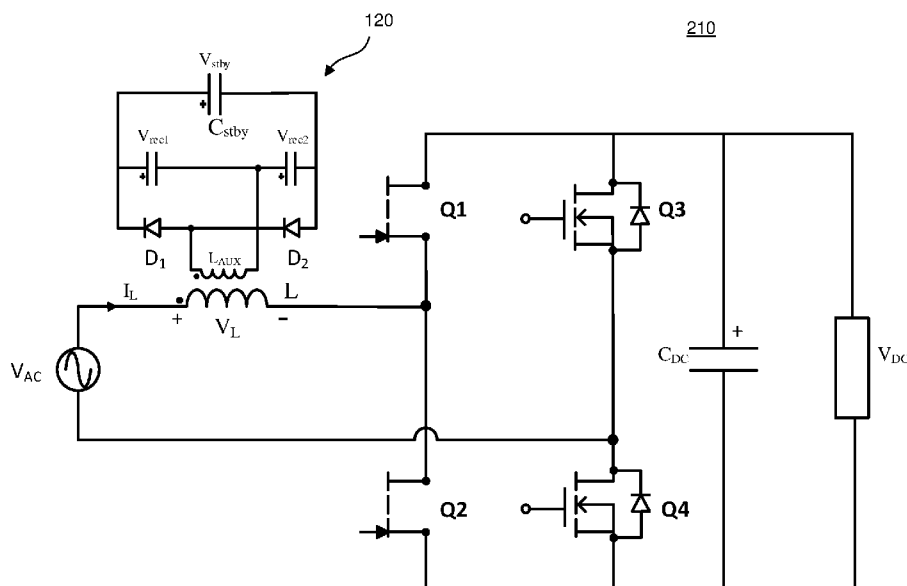


Fig. 3

(57) Abstract: A converter includes a first inductor, a first power switch connected to the first inductor, and an auxiliary power supply coupled to the first inductor to provide an auxiliary voltage from bi-directional current flow in the first inductor. In response to negative current flowing in the first inductor, a duty cycle of the first power switch is increased.

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INTEGRATED AUXILIARY POWER SUPPLY WITH STABLE OUTPUT AT HIGH-LINE AND LIGHT-LOAD CONDITIONS

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates to electrical power converters. More specifically, the present invention relates to AC-DC converters with integrated auxiliary power supplies.

2. Description of the Related Art

[0002] Power density and cost are critical factors in the design of power supplies, particularly in view of increased energy demands. Power-supply design has focused on providing increased power in smaller packages and at reduced cost. Many known power supplies include a main power supply and an auxiliary power supply, in which the auxiliary power supply takes up a significant volume in the known power supplies. Extensive research has been done to eliminate the auxiliary power supply by utilizing magnetics of the main power supply, i.e., by implementing an integrated auxiliary power supply. However, integrated auxiliary power supplies typically provide deteriorated performance at high-line and light-load conditions, which has limited the widespread implementation of integrated solutions.

[0003] In known front-end AC-DC power supplies, a boost inductor can be used in place of a separate auxiliary transformer. Switching voltages on the boost inductor can be reflected to a low-voltage side of the power supply by wrapping several windings around the boost inductor. The reflected voltages can be rectified to generate different voltages to operate the power supply.

[0004] This approach of wrapping several windings around the boost inductor to provide power to the auxiliary power supply can fail in a condition of high-line input and light load on a main output of the power supply. The rectified voltages from the auxiliary power supply collapse, i.e., drop to a very low value (for example, substantially zero), as the boost inductor current becomes discontinuous, i.e., the inductor current becomes zero for a portion of the switching cycle. The duty cycle of the boost converter is very small because very little power is required to maintain a main DC bus at a predetermined voltage. Therefore, the switching voltages appear across the boost inductor for a very small duration of a pulse width modulation

(PWM) period. The remaining duration of the PWM period includes a resonance between junction capacitor(s) and the boost inductor, which delivers substantially zero power. The converter can also enter burst mode when the main output is very close to no-load conditions. Accordingly, when no power flows from the input side to the secondary side of the auxiliary transformer, the output voltage of the auxiliary power supply can collapse (i.e., decrease to a very low level) because there is no continuous power flow to maintain the auxiliary output voltage at the desired voltage level.

[0005] Fig. 1 shows a circuit diagram 100 of a known unidirectional power factor correction (PFC) boost converter 110 with an integrated auxiliary power supply 120. The unidirectional PFC boost converter 110 includes a boost stage with a boost inductor L and a switch S_1 . The control terminal of the switch S_1 receives a control signal from an external controller or the like. The unidirectional PFC boost converter 110 further includes a diode D_3 to provide unidirectional current flow between the AC voltage V_{AC_RECT} to the DC voltage V_{DC} . That is, by including a diode D_3 in the unidirectional PFC boost converter 110, current can only flow from the AC side to the DC side, i.e., from the AC voltage V_{AC_RECT} to the DC voltage V_{DC} . The unidirectional PFC boost converter 110 also includes a capacitor C_{DC} across the DC voltage V_{DC} . The capacitor C_{DC} operates as a buffer for power flow by filtering a second order harmonic generated by instantaneous power transmission to the DC voltage V_{DC} . In addition, the capacitor C_{DC} filters ripple currents in the unidirectional PFC boost converter 110 and can provide energy to the unidirectional PFC boost converter 110 during a hold-up time.

[0006] The integrated auxiliary power supply 120 includes inductor L_{AUX} . The inductor L_{AUX} is coupled to the boost inductor L to define a transformer. The integrated auxiliary power supply further includes diodes D_1 and D_2 , rectifying capacitors C_{rec1} and C_{rec2} , and a standby capacitor C_{stby} . The diodes D_1 and D_2 rectify the voltage provided by the secondary winding L_{AUX} , and the standby capacitor C_{stby} is a bulk capacitor that provides filtering and helps maintain a stable output voltage at the DC voltage V_{DC} . A voltage V_{stby} across the standby capacitor C_{stby} is dependent upon a load connected to the unidirectional PFC boost converter 110. The output load of the auxiliary power supply 120 can be connected across the rectified voltage provided from the secondary winding L_{AUX} .

[0007] Fig. 2 shows voltage waveform V_L and current waveform I_L of the boost inductor L and voltage waveforms V_{rec1} and V_{rec2} of the rectifying capacitors C_{rec1} and C_{rec2} shown in Fig. 1 at high-line input and light load for two switching cycles. An example of a high-line input is greater than about 220 V, and an example of light load is less than about 10% of a rated load. When current I_L through the boost inductor L is positive, a reflected voltage is induced on the inductor L_{aux} , and power flows to the output of the auxiliary power supply 120 from the input line (AC voltage V_{AC_RECT}). When the current I_L through the boost inductor L reaches zero at time T_2 , junction capacitances (for example, the junction capacitance between the drain and source of the switch S_1) begin resonating with the boost inductor L , and diodes D_1 and D_2 are reverse biased. The power flow to the output of the auxiliary power supply 120 from the input line (AC voltage V_{AC_RECT}) is stopped for the duration from time T_2 to time T_3 , and the load is supplied entirely by the rectifying capacitors C_{rec1} and C_{rec2} and the standby capacitor C_{stby} . Accordingly, the standby voltage V_{stby} falls substantially, especially when a relatively high load is connected to the auxiliary supply.

SUMMARY OF THE INVENTION

[0008] Preferred embodiments of the present invention provide power converters with integrated auxiliary power supplies that can maintain a stable auxiliary output voltage at high-line, i.e., high input voltage, and light-load, i.e., low output power, conditions by allowing bi-directional current flow and that can achieve a reduction of size compared to power converters that include a separate auxiliary power supply.

[0009] A converter according to a preferred embodiment of the present invention includes a first inductor, a first power switch connected to the first inductor, and an auxiliary power supply coupled to the first inductor to provide an auxiliary voltage from bi-directional current flow in the first inductor. In response to negative current flowing in the first inductor, a duty cycle of the first power switch is increased.

[0010] The converter can further include an output capacitor, and the negative current may be provided by the output capacitor. The converter can further include no discrete diodes between the first inductor and the output capacitor.

[0011] The negative current can flow in the first inductor under high-line and light-load conditions. The auxiliary power supply can include a second inductor coupled to the first inductor to provide the auxiliary voltage, and the auxiliary power supply can include a third inductor coupled to the first inductor to provide a second auxiliary voltage.

[0012] The converter can further include a second power switch connected in series with the first power switch. A first node between the first and the second power switches can be connected to the first inductor, and the converter can define a totem-pole power-factor-correction (PFC) boost converter. The converter can further include first and second synchronous rectifiers connected in series with each other and connected in parallel with the first and the second power switches. The first and the second synchronous rectifiers can be field-effect transistors. The output capacitor can be connected in parallel with the first and the second synchronous rectifiers. The first and the second power switches can be GaN high-electron-mobility transistors, silicon carbide metal-oxide-semiconductor field-effect transistors, or insulated-gate bipolar transistors with anti-parallel diodes.

[0013] The converter can further include a synchronous rectifier connected between the first inductor and an output terminal of the converter, and the converter can define a synchronous boost converter.

[0014] The converter can further include a synchronous rectifier. The first power switch can be connected between a first input terminal of the converter and the first inductor, the synchronous rectifier can be connected between a second input terminal of the converter and a node between the first power switch and the first inductor, and the converter can define a synchronous buck converter.

[0015] The auxiliary power supply can include a second inductor coupled to the first inductor, a first capacitor and a second capacitor that can be connected in series with each other such that a node between the first and the second capacitors can be connected to a first terminal of the second inductor, and a first diode and a second diode that can be connected in series with each other such that a node between the first and second diodes can be connected to a second terminal of the second inductor. The first and second capacitors can be collectively connected in parallel with the first and second diodes.

[0016] A totem-pole power-factor-correction (PFC) boost converter according to a preferred embodiment of the present invention includes a first phase including a first boost inductor, a second phase including a second boost inductor, and an auxiliary power supply coupled to the first boost inductor. The first phase is operated as a boost converter to provide a DC output voltage, and the second phase is operated as a buck converter to provide a circulating current to the first boost inductor.

[0017] The second phase can be operated as the buck converter to provide the circulating current to the first boost inductor only under light-load conditions.

[0018] The first phase can include first and second boost switches connected in series, a first node between the first and the second boost switches can be connected to the first boost inductor, the second phase can include third and fourth boost switches connected in series, and a second node between the third and the fourth boost switches can be connected to the second boost inductor. The totem-pole PFC boost converter can further include first and second synchronous rectifiers that can be connected in series with each other, can be connected in parallel with the first and the second boost switches, and can be connected in parallel with the third and the fourth boost switches. The first and the second synchronous rectifiers can be field-effect transistors. An output capacitor can be connected in parallel with the first and the second synchronous rectifiers.

[0019] The first, the second, the third, and the fourth boost switches can be GaN high-electron-mobility transistors, silicon carbide metal-oxide-semiconductor field-effect transistors, and insulated-gate bipolar transistors with anti-parallel diodes.

[0020] The auxiliary power supply can include a third inductor coupled to the first boost inductor, a first capacitor and a second capacitor that can be connected in series with each other such that a node between the first and the second rectifying capacitors can be connected to a first terminal of the third inductor, a first diode and a second diode that can be connected in series with each other such that a node between the first and the second diodes can be connected to a second terminal of the third inductor, and a standby capacitor that can be connected in parallel with the first and the second capacitors. The first and second capacitors can be collectively connected in parallel with the first and second diodes.

[0021] The above and other features, elements, steps, configurations, characteristics, and advantages of the present invention will become more apparent from the following detailed description of preferred embodiments of the present invention with reference to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] Fig. 1 shows a known unidirectional power factor correction (PFC) boost converter with an integrated auxiliary power supply.

[0023] Fig. 2 shows voltage and current waveforms for two switching cycles of the known unidirectional PFC boost converter shown in Fig. 1.

[0024] Fig. 3 shows a totem-pole PFC boost converter that can be operated in fixed-frequency mode.

[0025] Fig. 4 shows voltage and current waveforms for two switching cycles of the totem-pole PFC boost converter shown in Fig. 3.

[0026] Fig. 5 shows a two-phase interleaved totem-pole PFC boost converter.

[0027] Fig. 6 shows inductor switching timing and voltage and current waveforms of two switching cycles of the two-phase interleaved totem-pole PFC boost converter shown in Fig. 5.

[0028] Fig. 7 shows a synchronous boost converter in which a diode is replaced by an active switch.

[0029] Fig. 8 shows a synchronous buck converter.

[0030] Fig. 9 shows voltage and current waveforms for two switching cycles of the synchronous buck converter shown in Fig. 8.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0031] Preferred embodiments of the present invention include converters each including an inductor, a power switch connected to the inductor to control current in the inductor, and an auxiliary power supply coupled to the inductor. The converter can be any suitable converter, including, for example, a totem-pole PFC boost converter, an interleaved totem-pole PFC boost converter, a synchronous boost converter, and a synchronous buck converter as discussed below. The auxiliary power supply can be any suitable power supply that can be coupled to the

inductor. Under certain operating conditions, e.g., high-line and light-load conditions, in which the duty cycle of the power switch is small, the converter can be operated to allow negative current to flow through the inductor to ensure a stable auxiliary output voltage. The converter can include an output capacitor that provides the negative current to the inductor. To ensure that the negative current can flow from the capacitor to the inductor, no separate discrete diodes are included between the capacitor and the inductor. Instead of diodes, synchronous rectifiers can be used to allow the negative current to flow into the inductor. To compensate for the negative current provided by the output capacitor, the duty cycle of the power switch can be increased, which increases the power-delivery duration. The duty cycle can be increased in the switching cycle after the switching cycle that includes the negative current. In some applications, the duty cycle can be increased in more than one switching cycle to compensate for the negative current. The magnitude of the negative current depends on the load and the efficiency of the converter. When the AC input voltage of the converter approaches zero, the power switch cannot be kept on for a long time because doing so can cause a negative-current spike. How much the duty cycle is increased can be determined in any suitable manner. For example, a look-up table can be used that provides how much the duty cycle is to be increased based on, for example, the magnitude of the negative current and the AC input voltage, or a predetermined algorithm or model with respect to the magnitude of the negative current can be used to calculate how much the duty cycle should be increased.

[0032] Fig. 3 shows a totem-pole PFC boost converter 210 according to a first preferred embodiment of the present invention. The totem-pole PFC boost converter 210 includes an AC voltage V_{AC} as an input voltage connected to inductor L (also referred to as the boost inductor), an integrated auxiliary power supply 120 coupled to the inductor L, two series-connected boost switches Q_1 and Q_2 , which can also be referred to as power switches, connected to the inductor L, two series-connected synchronous rectifiers Q_3 and Q_4 connected in parallel with the boost switches Q_1 and Q_2 , and an output capacitor C_{DC} connected in parallel with the synchronous rectifiers Q_3 and Q_4 . The output capacitor C_{DC} can be connected to a load, shown as DC voltage V_{DC} as the output voltage. A first node between the boost switches Q_1 and Q_2 is connected to a

first terminal of the AC voltage V_{AC} via the inductor L , and a second node between the synchronous rectifiers Q_3 and Q_4 is connected to a second terminal of the AC voltage V_{AC} .

[0033] The boost switches Q_1 and Q_2 of the totem-pole PFC boost converter 210 can be gallium nitride (GaN) transistors, for example, GaN high-electron-mobility transistors (HEMTs) that do not provide any or provide very little reverse recovery loss, or can be other suitable devices, including, for example, silicon carbide metal-oxide-semiconductor field-effect transistors (MOSFETs) and insulated-gate bipolar transistors (IGBTs) with antiparallel connected diodes. The synchronous rectifiers Q_3 and Q_4 can be MOSFETs, silicon carbide MOSFETs, or other suitable devices. The boost switches Q_1 and Q_2 can be switched at a higher frequency than the synchronous rectifiers Q_3 and Q_4 . During the positive AC cycle of the AC voltage V_{AC} , the synchronous rectifier Q_3 is turned on, the synchronous rectifier Q_4 is turned off, and the boost switches Q_1 and Q_2 are complementarily turned on and off to alternatively boost the inductor L and charge the output capacitor C_{DC} . During the positive AC cycle of the AC voltage V_{AC} , the boost switch Q_1 is turned off and the boost switch Q_2 is turned on to boost the inductor L , and the boost switch Q_1 is turned on and the boost switch Q_2 is turned off to charge the capacitor C_{DC} . During the negative AC cycle of the AC voltage V_{AC} , the synchronous rectifier Q_4 is turned on, the synchronous rectifier Q_3 is turned off, and the boost switches Q_1 and Q_2 are complementarily turned on and off to alternatively boost the inductor L and charge the output capacitor C_{DC} . During the negative AC cycle of the AC voltage V_{AC} , the boost switch Q_1 is turned on and the boost switch Q_2 is turned off to boost the inductor L , and the boost switch Q_1 is turned off and the boost switch Q_2 is turned on to charge the capacitor C_{DC} .

[0034] The integrated auxiliary power supply 120 includes inductor L_{aux} , diodes D_1 and D_2 , rectifying capacitors C_{rec1} and C_{rec2} , and standby capacitor C_{stby} . The inductor L_{aux} is coupled to the boost inductor L , and the inductor L_{aux} defines a secondary winding. The rectifying capacitors C_{rec1} and C_{rec2} are connected in series, and a node between the rectifying capacitors C_{rec1} and C_{rec2} is connected to a first terminal of inductor L_{aux} . Diode D_1 is connected between the inductor L_{aux} and the rectifying capacitor C_{rec1} such that positive voltage (i.e., the voltage V_{in}) applied across inductor L charges the rectifying capacitor C_{rec1} . Diode D_2 is connected between the inductor L_{aux} and the rectifying capacitor C_{rec2} such that negative voltage (i.e., the

voltage V_{in} - V_{out}) applied across the boost inductor L charges the rectifying capacitor C_{rec2} . The diodes D_1 and D_2 rectify the voltage across the secondary winding (i.e., the inductor L_{aux}). The standby capacitor C_{stby} is connected in parallel with the rectifying capacitors C_{rec1} and C_{rec2} , and an output of the integrated auxiliary power supply 120 can be connected across the standby capacitor C_{stby} .

[0035] Fig. 4 shows voltage waveform V_L and current waveforms I_L of boost inductor L and voltage waveforms V_{rec1} and V_{rec2} of rectifying capacitors C_{rec1} and C_{rec2} shown in Fig. 3 at high-line input and light load for two switching cycles. An example of a high-line input is greater than about 220 V, and an example of light load is less than about 10% of a rated power.

[0036] In contrast to the known unidirectional PFC boost converter 110 shown in Fig. 1, the totem-pole PFC boost converter 210 includes synchronous rectifiers Q_3 and Q_4 in place of diode D_3 . By including synchronous rectifiers Q_3 and Q_4 instead of diode D_3 , current flow through the boost inductor L does not stop upon reaching zero, but instead continues flowing in the opposite direction towards the AC voltage V_{AC} , as shown at time T_2 in Fig. 4. That is, current can flow bidirectionally in the boost inductor L .

[0037] With the totem-pole PFC boost converter 210 shown in Fig. 3, a reflected voltage is provided across inductor L_{aux} over an entire switching cycle, unlike the unidirectional PFC boost converter 110 shown in Fig. 1. Thus, the totem-pole PFC boost converter 210 can provide a sustained power flow between the AC voltage V_{AC} and the auxiliary output for the entirety of each switching cycle of the totem-pole PFC boost converter 210.

[0038] The totem-pole PFC boost converter 210 shown in Fig. 3 can provide a longer duty cycle from time T_0 to time T_1 than a duty cycle of the PFC boost converter 110 shown in Fig. 1 to compensate for the negative current that flows from the DC bulk capacitor. Thus, with the totem-pole PFC boost converter 210 shown in Fig. 3, the integrated auxiliary power supply 120 can operate properly at high line and light output conditions.

[0039] According to the operation of the totem-pole PFC boost converter 210 shown in Fig. 3, the inductor current I_L can flow in both directions to provide a switching voltage across the boost inductor L for the entire duration of the pulse width modulation (PWM) period. Thus, the

totem-pole PFC boost converter 210 shown in Fig. 3 provides a bi-directional current flow that enhances the performance of the integrated auxiliary power supply 120.

[0040] Since the boost switch Q_1 remains on when the inductor current I_L reaches zero, the capacitor C_{DC} begins charging the inductor L with negative current through the boost switch Q_1 . However, the average current of each switching cycle is the component that results in power transfer from the AC side to the DC side of the totem-pole PFC boost converter 210. In other words, whether conduction of the boost switch Q_1 stops when the inductor current I_L reaches zero or continues, the net average current of the switching cycle remains the same. Therefore, by allowing negative current to flow through the boost switch Q_1 , more positive current is required in the charging period, when the boost switch Q_2 is on and the boost switch Q_1 is off, to maintain the average current at the same level as in the case when the boost switch Q_1 ceases conduction when I_L reaches zero (similar to the unidirectional PFC boost converter 110 shown in Fig. 1 stopping conduction due to the diode D_3). Thus, the totem-pole PFC boost converter 210 provides longer duty cycles when compared with the PFC boost converter 110, which means that very narrow pulses are also avoided. Narrow pulses can interrupt power delivery to the voltage V_{stby} as soon as a volt-sec balance of the inductor L is completed, after which no power is transferred to the voltage V_{stby} due to resonance between the inductor L and any parasitic capacitances, for example, junction capacitor(s), where energy is only exchanged between the reactive elements (inductors and capacitors).

[0041] Fig. 5 shows a two-phase interleaved totem-pole converter 330 according to a second preferred embodiment of the present invention. The two-phase interleaved totem-pole converter 330 shown in Fig. 5 can provide increased auxiliary output power compared with the PFC boost converter 110 shown in Fig. 1, but with much less ripple in the input current and without the need of much negative current in the boost inductor, in contrast to the totem-pole PFC boost converter 210 shown in Fig. 3.

[0042] The two-phase totem-pole PFC boost converter 330 includes an AC voltage V_{AC} as an input voltage connected to a first phase with a first inductor L_1 (also referred to as the first boost inductor) and connected to a second phase with second inductor L_2 (also referred to as the second boost inductor), an integrated auxiliary power supply 120 coupled to the first

inductor L_1 , two series-connected synchronous rectifiers Q_5 and Q_6 connected to the first and second phases, and an output capacitor C_{DC} connected in parallel with the synchronous rectifiers Q_5 and Q_6 . The first phase also includes two series-connected boost switches Q_1 and Q_2 connected to the first inductor L_1 , and the second phase also includes two series-connected boost switches Q_3 and Q_4 connected to the second inductor L_2 . The two series-connected synchronous rectifiers Q_5 and Q_6 are connected in parallel with the boost switches Q_1 and Q_2 and in parallel with the boost switches Q_3 and Q_4 . The output capacitor C_{DC} can be connected to a load, shown as DC voltage V_{DC} as the output voltage. A first node between the boost switches Q_1 and Q_2 is connected to a first terminal of the AC voltage V_{AC} via the first inductor L_1 , a second node between the boost switches Q_3 and Q_4 is connected to the first terminal of the AC voltage V_{AC} via the second inductor L_2 , and a third node between the synchronous rectifiers Q_5 and Q_6 is connected to a second terminal of the AC voltage V_{AC} .

[0043] The boost switches Q_1 , Q_2 , Q_3 , and Q_4 of the totem-pole PFC boost converter 20 can be gallium nitride (GaN) transistors, for example, GaN high-electron-mobility transistors (HEMTs) or can be other suitable devices, including, for example, silicon carbide metal-oxide-semiconductor field-effect transistors (MOSFETs) and insulated-gate bipolar transistors (IGBTs) with anti-parallel connected diodes. The synchronous rectifiers Q_5 and Q_6 can be MOSFETs, silicon carbide MOSFETs, or other suitable devices. The boost switches Q_1 , Q_2 , Q_3 , and Q_4 can be switched at a higher frequency than the synchronous rectifiers Q_5 and Q_6 . The boost switches Q_1 , Q_2 , Q_3 , and Q_4 and the synchronous rectifiers Q_5 and Q_6 can be operated in a similar manner as discussed above, but the switching of the first and second phases can be out of phase with each other. For example, the switching of boost switches Q_1 and Q_2 and the switching of boost switches Q_3 and Q_4 can be out phase by 180° with each other.

[0044] The integrated auxiliary power supply 120 used in the two-phase interleaved totem-pole converter 330 of Fig. 5 can be the same as the integrated auxiliary power supply 120 discussed above with respect to Fig. 3.

[0045] Each phase of the two-phase interleaved totem-pole converter 330 can be operated as a boost converter or a buck converter. At light load (for example, less than about 10% of a rated load), the first phase that is coupled to the integrated auxiliary power supply 120 can be

operated as a boost converter. Therefore, the second phase can be operated as a buck converter to provide a circulating current to the boost inductor L_1 of the first phase operating as a boost converter. Fig. 5 shows an example of the two-phase interleaved totem-pole PFC converter 330 operating when a positive phase is provided by the AC voltage V_{AC} . During the positive phase of the AC voltage V_{AC} , inductor L_1 operates as a main boost inductor and supplies current to DC voltage V_{DC} plus the circulating current. Accordingly, more current flows through the inductor L_1 , which prevents the inductor current from becoming discontinuous. Therefore, power flow between the AC voltage V_{AC} and the auxiliary output is not interrupted. During a negative phase of the AC voltage V_{AC} , the current directions and voltage polarities described above are reversed. That is, the operation of the two-phase interleaved totem-pole PFC boost converter 330 during the negative phase is symmetric to the operation during the positive phase.

[0046] The buck operation of the two-phase interleaved totem-pole PFC converter 330 has a complementary duty cycle with respect to the boost operation to maintain the same input and output voltage levels. The main switch in the boost phase is the opposite of the main switch in the buck phase. For example, if the switch Q_2 is the main switch in the boost phase, then the switch Q_3 is the main switch in the buck phase. Accordingly, switches Q_1 to Q_4 can receive the same control signals as a typical 2-phase interleaved totem-pole PFC. To transition one phase from the boost operation to buck operation, the one of the switches Q_1 to Q_4 that operates as a free-wheeling switch is disabled for a predetermined number of switching cycles to build up the negative current in the inductor L , and then this switch can be re-activated to reduce conduction losses.

[0047] As discussed above, Fig. 5 shows an example of the two-phase interleaved totem-pole PFC converter 330 operating when a positive phase is provided by the AC voltage V_{AC} . Accordingly, the current I_{L1} through the inductor L_1 is the boost current, while the current I_{L2} through the inductor L_2 is the circulating current generated by the other phase of the AC voltage V_{AC} . The switches Q_3 and Q_4 of the second phase reverse their roles, and switch Q_3 operates as the main switch and switch Q_4 operates as a free-wheeling switch. Fig. 5 shows the directions of the currents I_{L1} , I_{L2} , and I_{IN} during the positive phase of the AC voltage V_{AC} . By

applying Kirchhoff's Current Law at node A, the boost current I_{L1} of the inductor L_1 is the sum of the current I_{IN} from the AC voltage V_{AC} and the circulating current I_{L2} . Thus, instead of the current I_{L1} being half of the current I_{IN} , the current I_{L1} is now the sum of the currents I_{IN} and I_{L2} .

[0048] Fig. 6 shows inductor switching timing and voltage and inductor current waveforms of two switching cycles of the two-phase interleaved totem-pole PFC boost converter 330 shown in Fig. 5. Assuming the direction of the inductor current in the inductor L_1 is positive, the current flow described above for the two-phase interleaved totem-pole PFC boost converter 330 is illustrated in Fig. 6. The current level in the inductor L_1 , which operates as the boost inductor, can be increased, which extends the power delivery duration from the AC voltage V_{AC} to the auxiliary output and reduces a dependence on auxiliary capacitors, including standby capacitor C_{stby} and rectifying capacitors C_{rec1} and C_{rec2} . By interleaving the two phases, the ripple of the input current can be reduced, and the frequency can be doubled, as shown in Fig. 6, and thus the ripple component in the input current is more easily filtered. During a negative phase of the AC voltage V_{AC} , the current directions and voltage polarities described above are reversed. That is, the operation of the two-phase interleaved totem-pole PFC boost converter 330 during the negative phase is symmetric to the operation during the positive phase.

[0049] Fig. 7 shows a synchronous boost converter 430 according to a third preferred embodiment of the present invention, in which diode D3 of Fig. 1 is replaced by synchronous rectifier Q2, which is connected between the inductor L and an output terminal and the capacitor C_{DC} . The inductor L is connected between a first terminal of the input voltage V_{in} and the synchronous rectifier Q2. The boost switch Q1, which can also be referred to as a power switch, is connected to the inductor L and a second terminal of the input voltage. In particular, when reverse recovery losses are not a design concern, the synchronous rectifier Q2 can be used instead of a diode. The synchronous rectifier Q2 can provide negative current flow through the inductor L. The integrated auxiliary power supply 120 is coupled to the inductor L in a similar manner as discussed above with respect to the first and second preferred embodiments of the present invention. Accordingly, the integrated auxiliary power supply 120 described above can provide a reliable auxiliary output during all input voltage and load conditions, including high-line and light-load conditions.

[0050] In automotive and industrial applications, a single-stage non-isolated synchronous buck converter, an example of which is shown Fig. 8 as the fourth preferred embodiment of the present invention, can be used. The integrated auxiliary power supply 120 can be used with negative current flow in a similar manner as the first, second, third preferred embodiments of the present invention described above. The synchronous buck converter 530 includes a buck switch Q1, which can also be referred to as a power switch, connected between a first terminal of the input voltage V_{in} and the inductor L and includes a synchronous rectifier Q2 connected between a second terminal of the input voltage and a node between the buck switch Q1 and the inductor L. The inductor L is also connected to an output terminal and to the capacitor C_{DC} . The integrated auxiliary power supply 120 is coupled to the inductor L in a similar manner as discussed above with respect to the first, second, and third preferred embodiments of the present invention. When current in the inductor L becomes discontinuous for the majority of a PWM cycle, the synchronous rectifier Q2 of Fig. 8 can conduct negative current, which allows the integrated auxiliary power supply 120 to provide a stable auxiliary output voltage.

[0051] The synchronous boost converter 430 shown in Fig. 7 can also be implemented as an interleaved totem-pole PFC boost converter, for example, as described above with respect to Fig. 5.

[0052] Fig. 9 shows voltage and current waveforms for two switching cycles of the synchronous buck converter 530 shown in Fig. 8. Similar to the totem-pole PFC boost converter 210, the two-phase interleaved totem-pole converter 330, and the synchronous boost converter 430 described above, at time T2, the switch Q2 of the synchronous buck converter 530 remains on to provide negative current flow. In the case of buck operation, the inductor L of the synchronous buck converter 530 is always connected to the DC voltage V_{DC} , unlike boost operation where the inductor L is always connected to the input voltage V_{IN} . Accordingly, when switch Q2 is on and the inductor L is detached from the input voltage V_{IN} , the output capacitor C_{DC} of the synchronous buck converter 530 provides power to the bias output. Therefore, the capacitor C_{DC} is sized to provide sufficient power to the auxiliary output voltage when the synchronous rectifier Q2 is on and the inductor L is detached from the input voltage V_{IN} .

[0053] The synchronous boost converter 430 shown in Fig. 9 can also be implemented as an interleaved totem-pole PFC boost converter, for example, as described above with respect to Fig. 5.

[0054] Although the integrated auxiliary power supply 120 is described with respect to a single secondary inductor L_{AUX} , the integrated auxiliary power supply 120 may include one or more additional secondary inductors coupled to the boost inductor L , and the one or more additional secondary inductors may provide voltages that are different from a voltage provided by the secondary inductor (L_{AUX}).

[0055] For example, the overall power supply can include two stages. A first stage can provide AC-DC conversion with power factor correction, in which the input voltage can be boosted to about 400 V. A second stage can provide DC-DC conversion, for example, by an LLC converter, which can provide a regulated output voltage of about 12 V.

[0056] It should be understood that the foregoing description is only illustrative of the present invention. Various alternatives and modifications can be devised by those skilled in the art without departing from the present invention. Accordingly, the present invention is intended to embrace all such alternatives, modifications, and variances that fall within the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A converter comprising:
a first inductor;
a first power switch connected to the first inductor; and
an auxiliary power supply coupled to the first inductor to provide an auxiliary voltage from bi-directional current flow in the first inductor; wherein
in response to negative current flowing in the first inductor, a duty cycle of the first power switch is increased.
2. The converter of claim 1, further comprising an output capacitor, wherein
the negative current is provided by the output capacitor.
3. The converter of claim 2, wherein there are no discrete diodes between the first inductor and the output capacitor.
4. The converter of one of claims 1–3, wherein the negative current flows in the first inductor under high-line and light-load conditions.
5. The converter of one of claims 1–4, wherein:
the auxiliary power supply includes a second inductor coupled to the first inductor to provide the auxiliary voltage, and
the auxiliary power supply includes a third inductor coupled to the first inductor to provide a second auxiliary voltage.
6. The converter of one of claims 1–5, further comprising:
a second power switch connected in series with the first power switch; wherein
a first node between the first and the second power switches is connected to the first inductor; and
the converter defines a totem-pole power-factor-correction (PFC) boost converter.

7. The converter of claim 6, further comprising first and second synchronous rectifiers connected in series with each other and connected in parallel with the first and the second power switches.

8. The converter of claim 7, wherein the first and the second synchronous rectifiers are field-effect transistors.

9. The converter of claim 7 or 8, wherein the output capacitor is connected in parallel with the first and the second synchronous rectifiers.

10. The converter of one of claims 6–9, wherein the first and the second power switches are GaN high-electron-mobility transistors, silicon carbide metal-oxide-semiconductor field-effect transistors, or insulated-gate bipolar transistors with anti-parallel diodes.

11. The converter of one of claims 1–5, further comprising a synchronous rectifier connected between the first inductor and an output terminal of the converter; wherein the converter defines a synchronous boost converter.

12. The converter of one of claims 1–5, further comprising a synchronous rectifier; wherein

the first power switch is connected between a first input terminal of the converter and the first inductor;

the synchronous rectifier is connected between a second input terminal of the converter and a node between the first power switch and the first inductor; and

the converter defines a synchronous buck converter.

13. The converter of one of claims 1–12, wherein:
the auxiliary power supply includes:

a second inductor coupled to the first inductor;

a first capacitor and a second capacitor connected in series with each other such that a node between the first and the second capacitors is connected to a first terminal of the second inductor; and

a first diode and a second diode connected in series with each other such that a node between the first and second diodes is connected to a second terminal of the second inductor; and

the first and second capacitors are collectively connected in parallel with the first and second diodes.

14. A totem-pole power-factor-correction (PFC) boost converter comprising:

a first phase including a first boost inductor;

a second phase including a second boost inductor; and

an auxiliary power supply coupled to the first boost inductor; wherein

the first phase is operated as a boost converter to provide a DC output voltage; and

the second phase is operated as a buck converter to provide a circulating current to the first boost inductor.

15. The totem-pole PFC boost converter of claim 14, wherein the second phase is operated as the buck converter to provide the circulating current to the first boost inductor only under light-load conditions.

16. The totem-pole PFC boost converter of claim 14 or 15, wherein

the first phase includes first and second boost switches connected in series;

a first node between the first and the second boost switches is connected to the first boost inductor;

the second phase includes third and fourth boost switches connected in series;

a second node between the third and the fourth boost switches is connected to the second boost inductor.

17. The totem-pole PFC boost converter of claim 16, further comprising first and second synchronous rectifiers connected in series with each other, connected in parallel with the first and the second boost switches, and connected in parallel with the third and the fourth boost switches.

18. The totem-pole PFC boost converter of claim 17, wherein the first and the second synchronous rectifiers are field-effect transistors.

19. The totem-pole PFC boost converter of claim 17 or 18, further comprising an output capacitor connected in parallel with the first and the second synchronous rectifiers.

20. The totem-pole PFC boost converter of one of claims 16-19, wherein the first, the second, the third, and the fourth boost switches are GaN high-electron-mobility transistors, silicon carbide metal-oxide-semiconductor field-effect transistors, and insulated-gate bipolar transistors with anti-parallel diodes.

21. The totem-pole PFC boost converter of one of claims 14-20, wherein:

the auxiliary power supply includes:

a third inductor coupled to the first boost inductor;

a first capacitor and a second capacitor connected in series with each other such that a node between the first and the second rectifying capacitors is connected to a first terminal of the third inductor;

a first diode and a second diode connected in series with each other such that a node between the first and the second diodes is connected to a second terminal of the third inductor; and

a standby capacitor connected in parallel with the first and the second capacitors; and

the first and second capacitors are collectively connected in parallel with the first and second diodes.

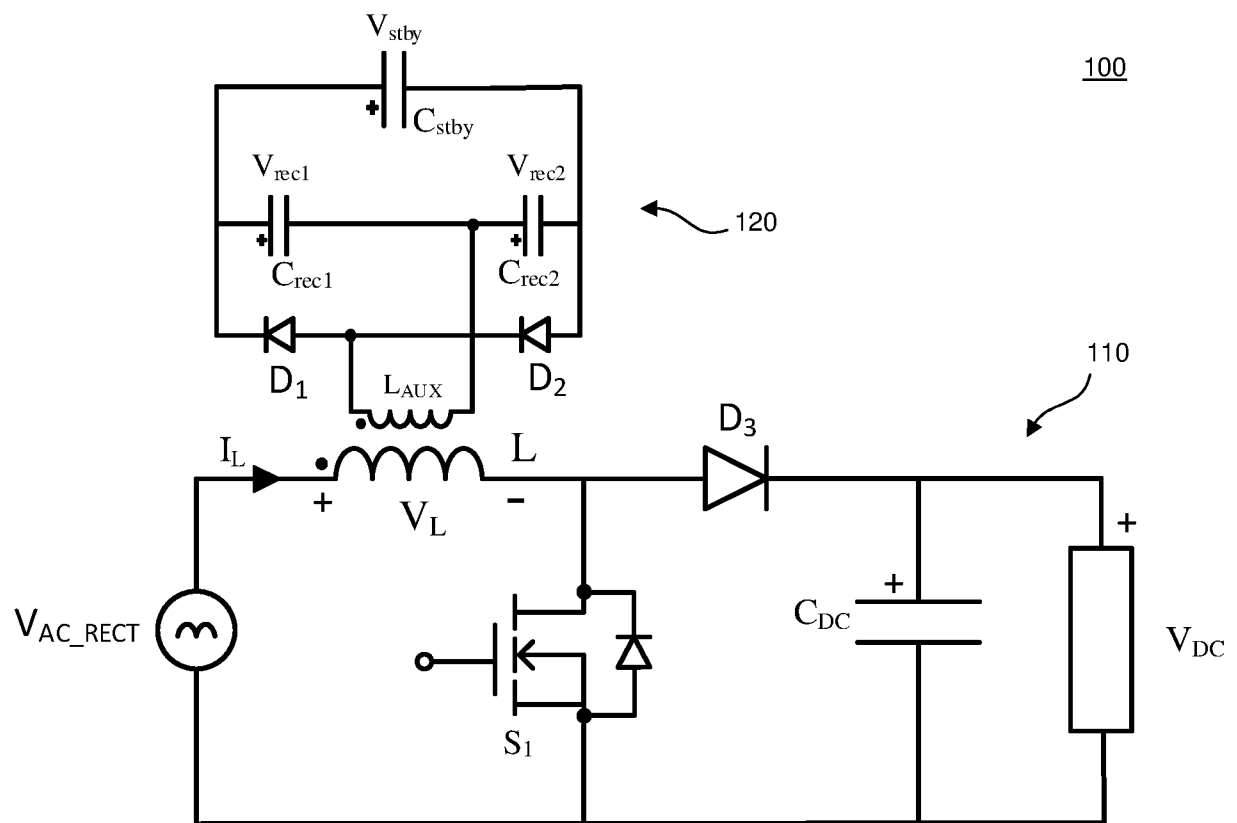


Fig. 1
PRIOR ART

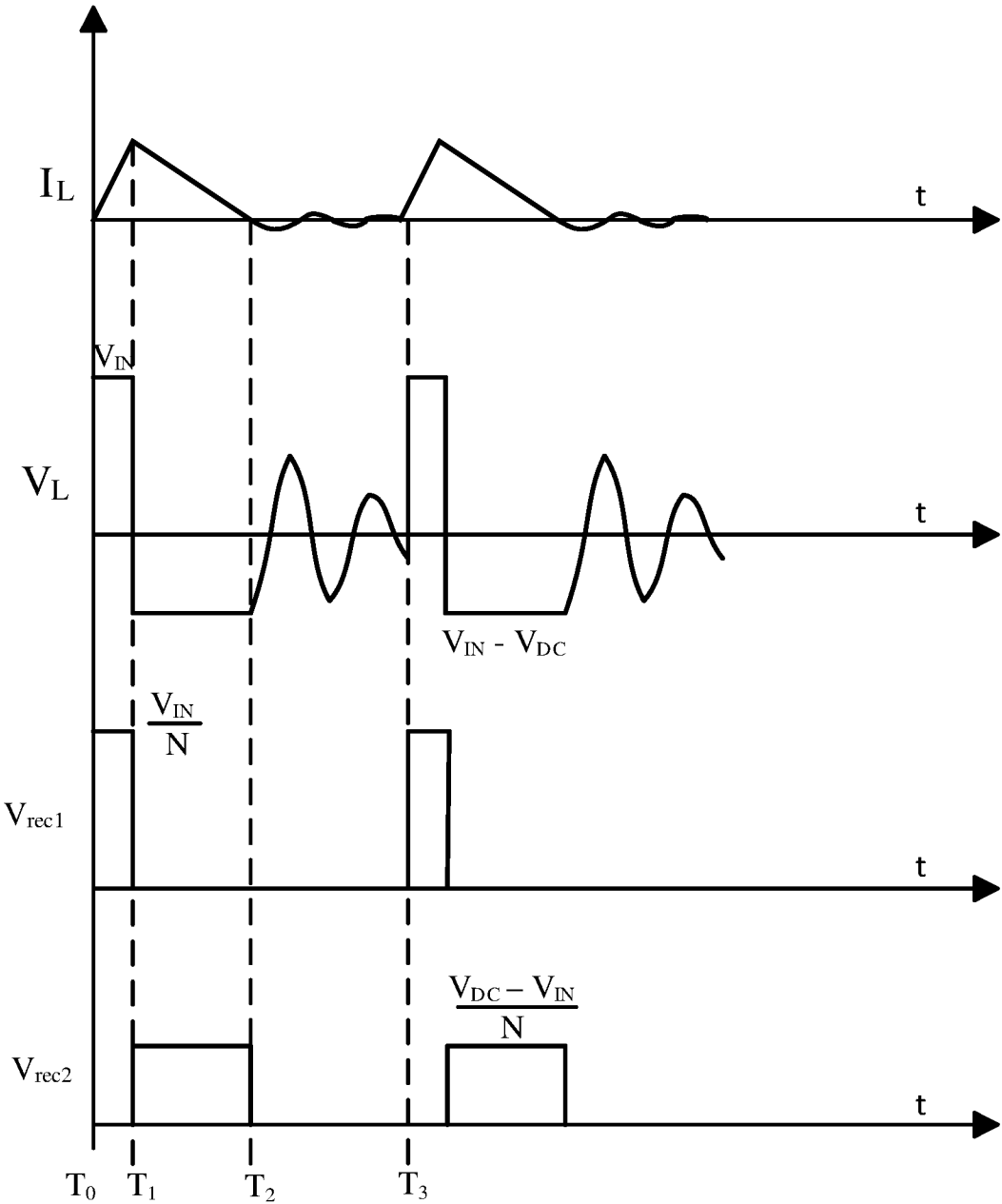


Fig. 2
PRIOR ART

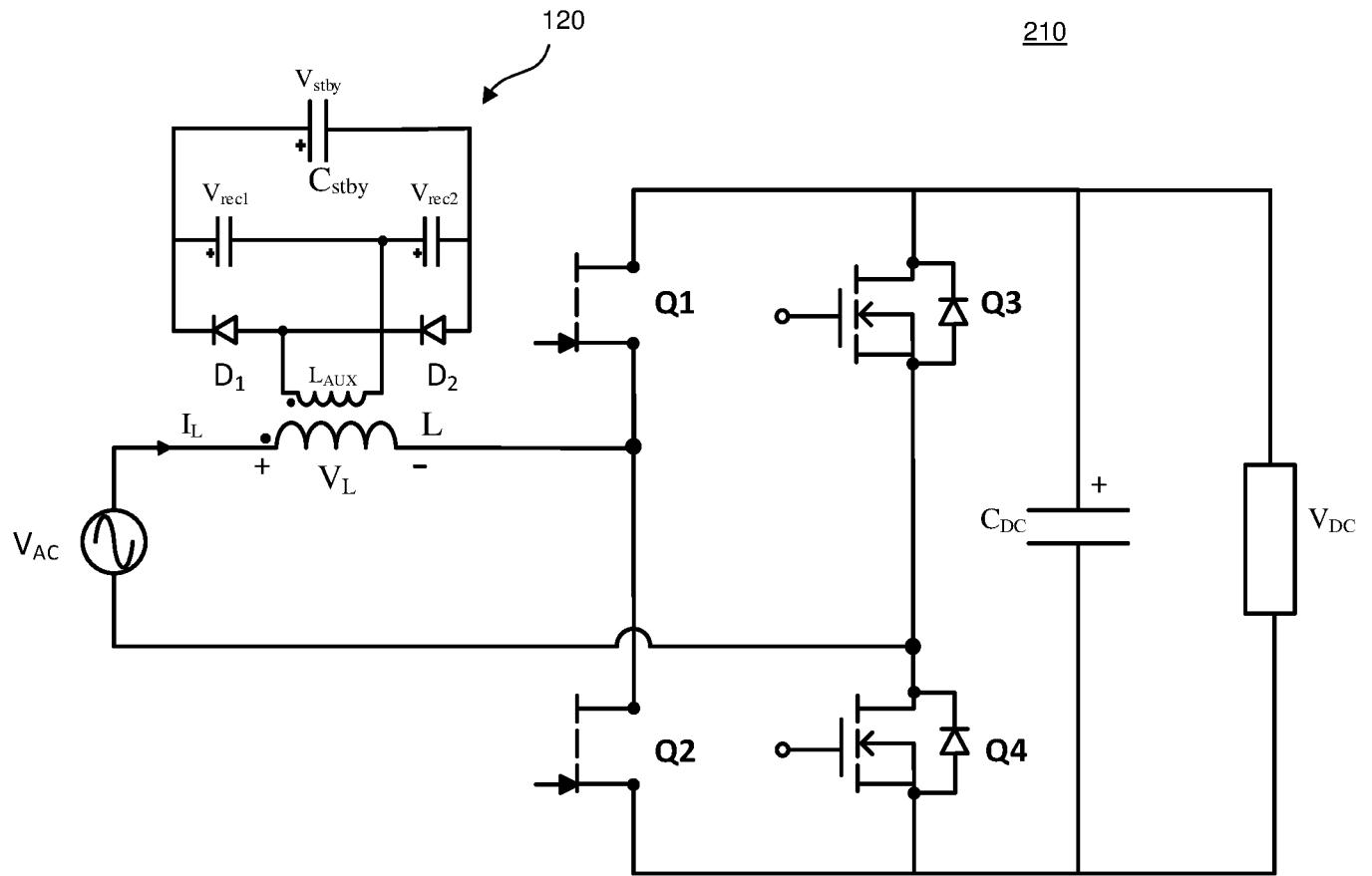


Fig. 3

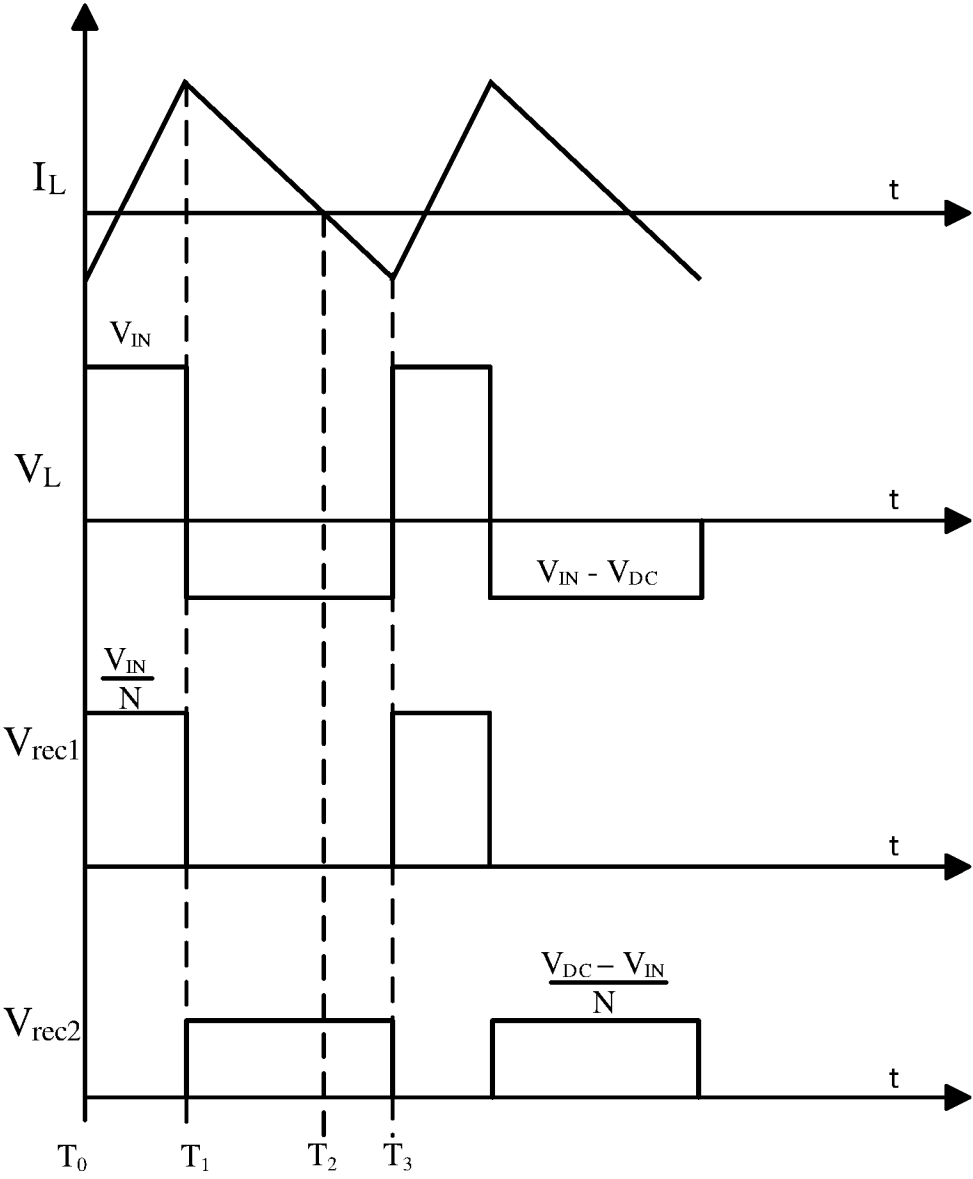


Fig. 4

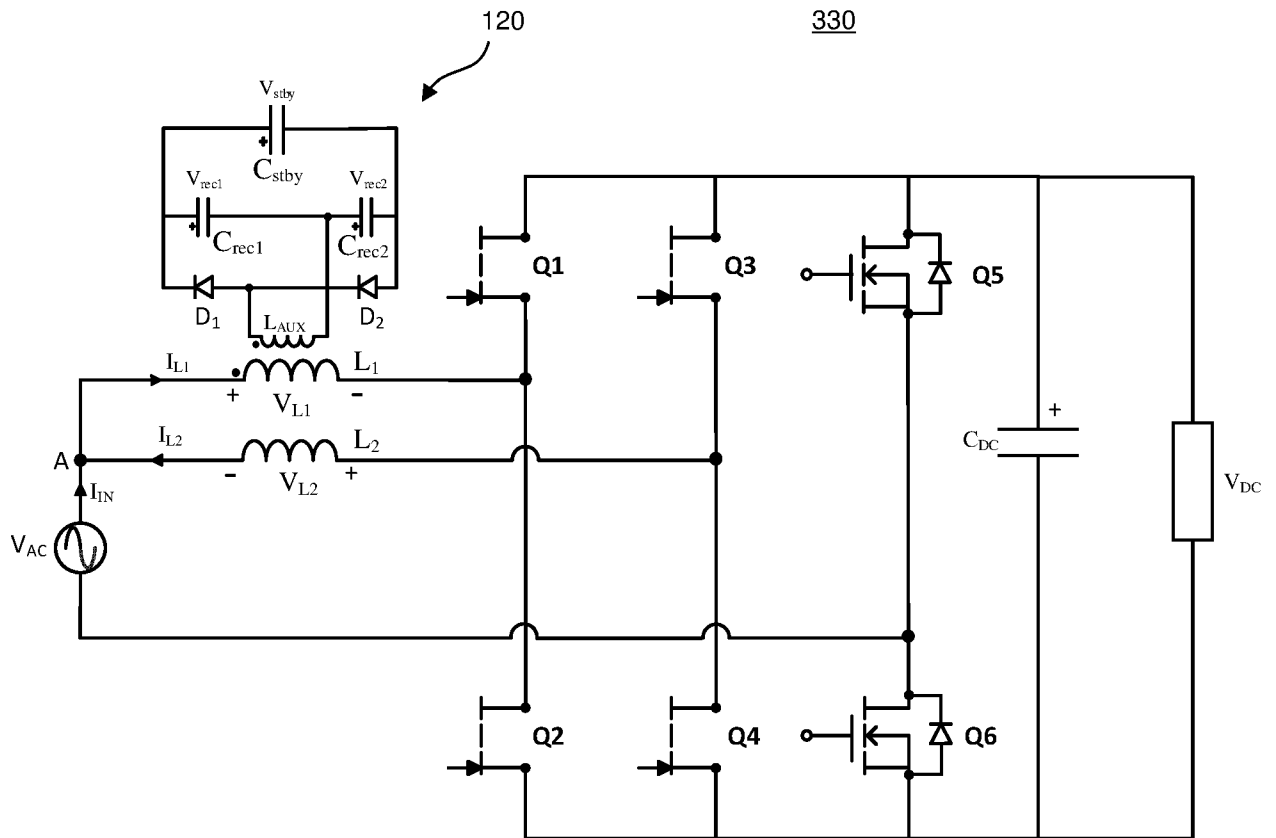


Fig. 5

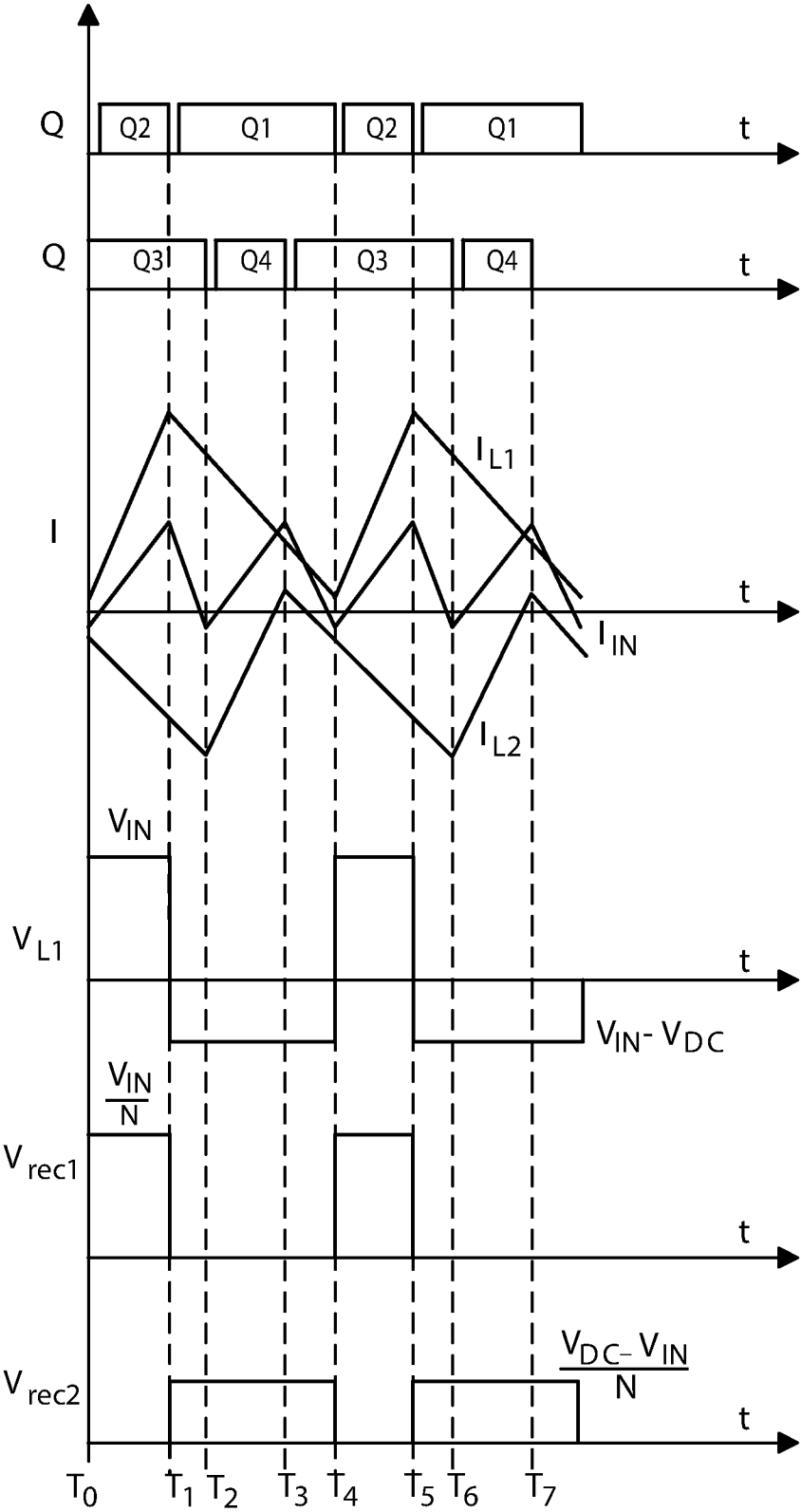


Fig. 6

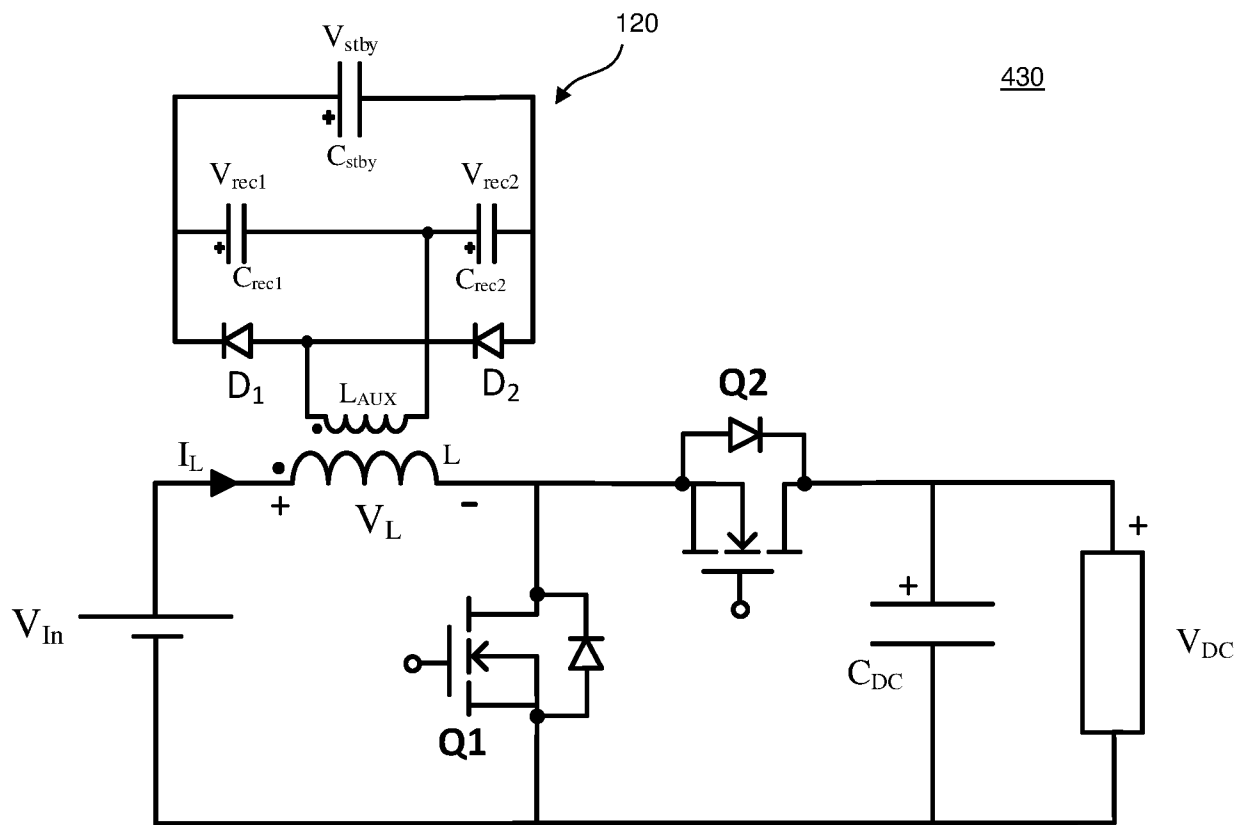


Fig. 7

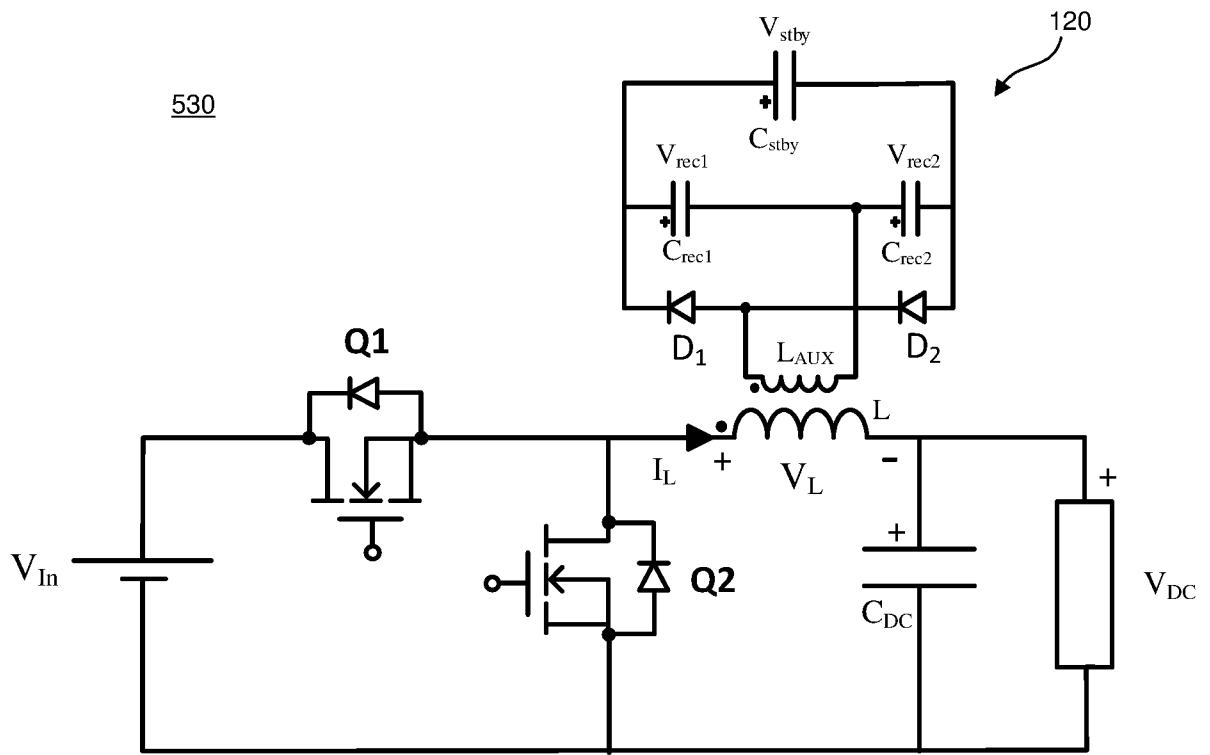


Fig. 8

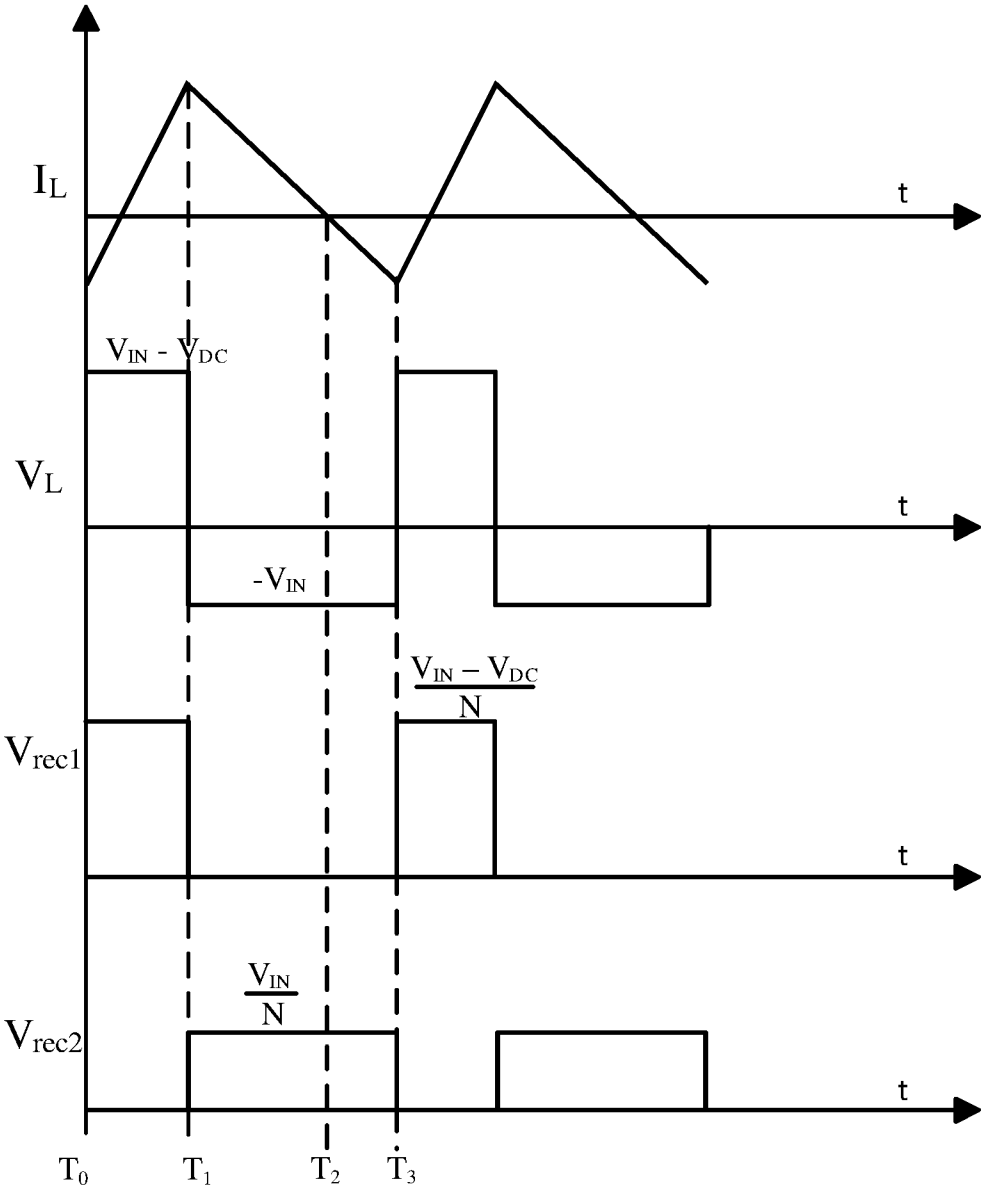


Fig. 9

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2022/039240

A. CLASSIFICATION OF SUBJECT MATTER H02M 1/42(2007.01)i; H02M 7/219(2006.01)i; H02M 7/23(2006.01)i According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H02M 1/42(2007.01); G05F 1/613(2006.01); G05F 3/16(2006.01); H02M 7/06(2006.01); H02M 7/162(2006.01) Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Korean utility models and applications for utility models Japanese utility models and applications for utility models Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) eKOMPASS(KIPO internal) & Keywords: converter, inductor, power switch, auxiliary power supply, auxiliary voltage, negative, current, duty cycle		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2012-0069615 A1 (TOMIOKA, SATOSHI) 22 March 2012 (2012-03-22) paragraphs [0035]-[0117]; and figures 2, 5C, 6, 13	1-4,14-18
Y	US 8222872 B1 (MELANSON, JOHN L. et al.) 17 July 2012 (2012-07-17) column 3, lines 1-21; and figure 1	1-4,14-18
Y	US 2004-0264214 A1 (XU, MING et al.) 30 December 2004 (2004-12-30) paragraph [0031]; and figure 2	3
A	US 2006-0208711 A1 (SOLDANO, MARCO et al.) 21 September 2006 (2006-09-21) paragraphs [0031]-[0034]; and figures 9A-9B	1-4,14-18
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☐ 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 28 November 2022		Date of mailing of the international search report 28 November 2022
Name and mailing address of the ISA/KR Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon 35208, Republic of Korea Facsimile No. +82-42-481-8578		Authorized officer JANG, Gi Jeong Telephone No. +82-42-481-8364

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2022/039240

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☒ Claims Nos.: **7-8**
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

Claims 7-8 are not clear because they refer to multiple dependent claims, which do not comply with PCT Rule 6.4(a).
3. ☒ Claims Nos.: **5-6, 9-13, 19-21**
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/US2022/039240

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Information on patent family members

International application No.

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