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SIMO Boost Converter to Obtain Simultaneous AC and DC Output

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Abstract - *This paper presents a novel technique to obtain simultaneous multi stage boost AC and DC output with a single stage input. A single input is applied at the input side of the boost converter and multi state output is obtained. To achieve minimum switching loss, only one power stage works at a high frequency is called as Boost to Boost mode of operation. An Inductor is used in the power loop to reduce the conduction losses during operation. The principle of operation is demonstrated through the analysis on the equivalent circuits of a "half-bridge" single-phase inverter. The theoretical analysis shows that when input dc voltage is larger than the magnitude of the ac voltage, it is a voltage-source inverter, and on the contrary it is current-source inverter in the other mode. Simulations and experiments show that it has a good control and system performance.*

***Key Words*: Boost in boost, buck in buck, CL filter, current-source inverter (CSI), efficiency, LCL filter, voltage-source inverter (VSI)**

1. INTRODUCTION

Vast usage of renewable energy as a global accepted alternative source urges the use of grid-tied inverters [1]–[3]. The converters can be divided into voltage-source inverters (VSI) and current-source inverters (CSI), where the VSI is the dominant converter. One of the reasons is that the VSI does not need a large inductor as the energy storage element, while the CSI should adopt a larger inductor in order to keep the dc current constant for a proper modulation. The research related to CSI mainly focus on the control [4]–[7]. So far, how to decrease the total dc-link inductance for CSI is a challenge, especially in the low voltage and three-phase application area.

Since the VSI is a step-down inverter and the CSI is a kind of step-up inverter, the Z-source inverters (ZSI) was proposed in [8] in order to fully utilize the basic character of VSI and CSI and the minimum semiconductors were used with the combined characters of the step-down and the step-up converters. How-ever, compared to the CSI or the VSI, the ZSI has two extra inductors in the power loop, which may sacrifice the efficiency [9], [10]. The control difficulty is also a demerit in the Z-source impedance.

In the renewable power generation system, the input dc volt-age of the converter may vary greatly. For example, the output dc voltage of a solar panel will change a lot under different temperature conditions. To transfer this kind of dc energy into the grid, a two- or three-stage inverter may be required as the power interface, especially for the VSI-based system. If all power stages work at high frequency, the efficiency of the inverter will be in-evitable affected. In order to decrease the switching frequency, many interesting inverters have been proposed [11]–[13] and the basic idea is to ensure that only one of the power stages of the system works at high frequency. Nevertheless, the main output filter of these inverters should be designed to satisfy the harmonic requirements [14] in the "buck" mode, especially when the dc input voltage is higher than the amplitude of the grid voltage. Thus, when they work in the "boost" mode, an over filtering may take place due to that the output filter is a CL–CL filter. Since the excessive inductance is in the power loop, extra conduction losses will be present and the grid current is not easy to control as well.

A consensus has been reached that the power electronics will take a main role in the future energy area [15]. But which favourite type of grid-tied inverters for the future is still discussed. Dependent on the efficiency evaluation, the smaller inductance in the power loop will cause a higher efficiency, due to the fact that the power loss caused by power device has be-come smaller and smaller. Thus, it may be a good way to achieve high efficiency through decreasing the total inductance in the power loop. It should be pointed out that aiming to minimize the inductance of output filter of VSI, a recently new type of power filter named as the LLCL-filter was proposed and analysed for the grid-tied VSI [16]–[18]. Theoretically, compared with an LCL-filter, an LLCL-filter can save the total inductance. Due to the reason of familiarity, the conventional LCL-filter is still used as the output filter benchmark for the comparison between several classical inverters.

In this paper, typical full-bridge single-phase grid-tied inverters with the different power sources are introduced. Next, a new type of "boost in boost" grid-tied inverter is proposed and the operating principle is illustrated through a half-bridge inverter with the equivalent circuits in the different working stages. Then, the modelling is carried out with a small signal model method. Based on this, an indirect current control method is introduced, when the inverter is working in the "boost" stage. Finally, simulations and experiments are given to verify the theoretical analysis and the principle of operation.

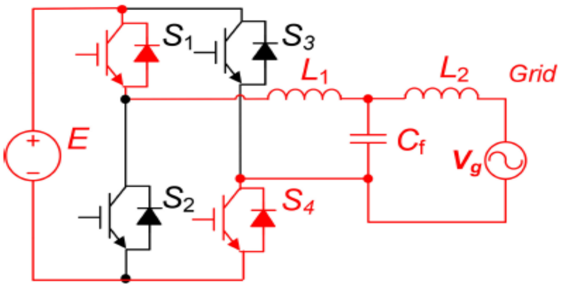


Fig-1: Signle Phase Grid Tied VSI

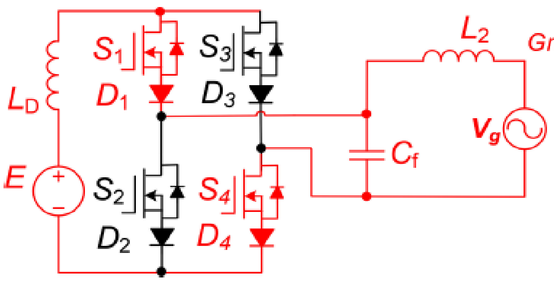


Fig-2: Single Phase Grid Tied CSI

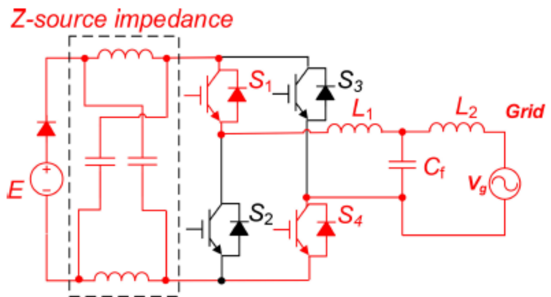


Fig-3: Single Phase Grid tied ZSI

2. TYPICAL FULL-BRIDGE SINGLE-PHASE GRID-TIED CONVERTER WITH THE DIFFERENT POWER SOURCE

2.1 Single-Stage Converters

1. Inverters with the Single Function of Step-Down or Step-Up: Figs. 1 and 2 show the typical VSI with LCL-filter and the typical CSI with CL-filter, respectively. The VSI is buck-type (step-down) inverter, which means its dc voltage should be higher than the amplitude of the grid voltage. The CSI is a boost-type (step-up) inverter, which means that its dc voltage should be lower than the amplitude of the grid voltage [19]. Generally, the output dc voltage of the renewable power source (for example, a PV panel) may vary in a large range, then the VSIs or the CSIs have their own limitations as a renewable power conditioner connected to the grid directly, and after an additional dc/dc converter is used.

2. Inverters With the Function of Both Step-Down and Step-Up:

a) ZSI: Combined with the voltage characters of the VSI and the CSI, a Z-source type inverter was proposed [8]. In theory, ZSI (as shown in Fig. 3) can work in the step-down and the step-up states as required and its reliability can be improved a lot, owing to its immunity to the electromagnetic interference. However, due to the two additional inductors in the power loop, the conduction power loss is high and over filtering may also take place, especially when the input dc voltage is high. It is basically a boost–buck type converter and it is difficult to realize the overall parameter optimization, when the input dc voltage varies in a large range. The efficiency of the ZSI seems not as high as that of the other conventional two-stage inverters [9], [10].

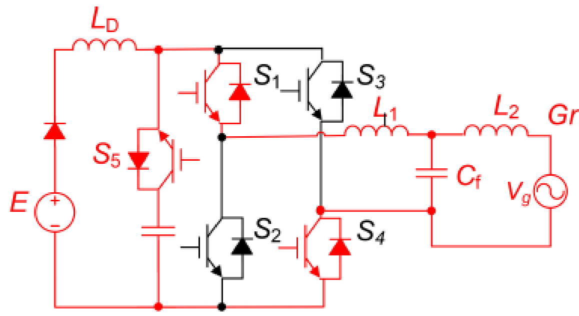


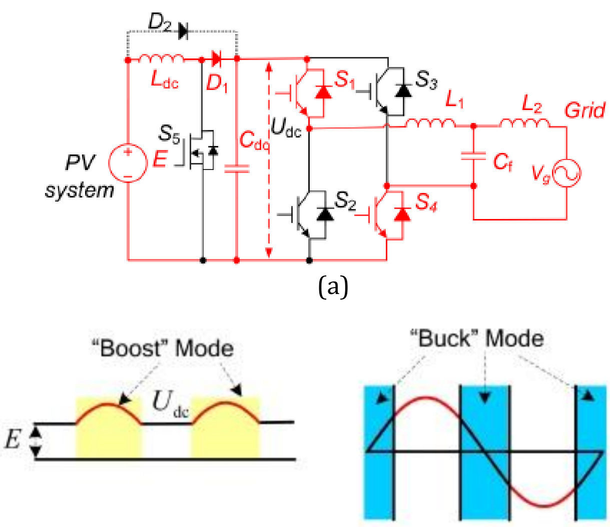
Fig-4: Single phase grid tied natural soft switching inverter

b) Natural Soft-Switching Inverter (NSSI): For a VSI, the reverse recovery power loss and the power losses caused by the tail current of insulated-gate bipolar transistor (IGBT) limit the switching frequency of the VSI [20]. However, the conduction power loss of the VSI is low, compared to the CSI. For the CSI, the high conduction power losses of the devices and the high power losses caused by the dc-link inductor are the main drawbacks related to the efficiency. Nevertheless, the CSI has no reverse recovery power losses. Using the merit of VSI and CSI and avoiding the demerit of them, a high efficiency inverter was proposed [21] as shown in Fig. 4 (For a single-phase application), named as the NSSI. When the additional switch of S5 is ON, the inverter works as a pure VSI with an LC-type dc input filter and an LCL type of ac output filter. While S5 is OFF, it works like a CSI with a clamped voltage and an LCL filter. Thus, this inverter can fit for a wide variation of input dc voltage, especially for the permanent magnet synchronous wind generator with a front-end diode rectifier. An improved NSSI was proposed to increase the efficiency when it is used for the three-phase photovoltaic inverter application [22], whereas an additional boost dc/dc circuit had been inserted. Note that the NSSI may have a higher efficiency than the traditional two-stage VSI, since more switches can work in the soft-switching or quasi-soft-switching state. More efficiency analysis about this inverter is introduced in [23]. However, the inductance in the power loop still seems large.

2.2 Two-Stage "Boost in Boost, Buck in Buck" Converter

The traditional two-stage VSI adopts an input dc/dc boost converter to transfer a variable input dc voltage into a stable dc voltage, and then injects the dc energy into the grid. So, both two stages of the power converter work at high frequency, causing considerable switching losses. Fig. 5 shows a conventional two stage dual-mode time-sharing high efficiency inverter used as a PV inverter [11]. Here, an LCL-filter is used instead of an L-filter to reduce the total inductance. The outstanding character of this inverter is that only one power stage is chopping at high frequency at any time, so the switching power losses can be decreased, compared to other conventional two-stage power converter with the constant dc-link voltage. Its character can be summarized as a "boost in boost, buck in buck" converter, which means that the converter works in the "boost" or "buck" state with the high frequency only when the "boost" or the "buck" is needed to minimize the switching losses. Further, in order to reduce the conduction power loss of the dc inductor, a bypass diode D2 is often used [24].

However, during the "boost" working stage, the over filtering still takes place since the equivalent output filter of the "boost" circuit is a CL–CL filter and the extra conduction loss of the inductor cannot be avoided.



(a)

(b)

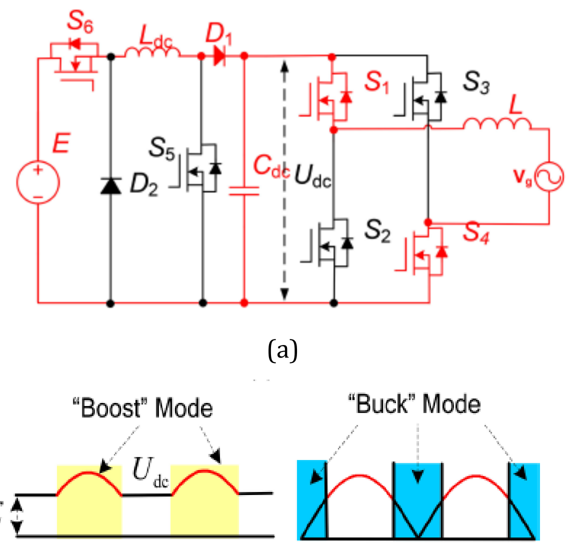
Fig -5: Conventional two stages dual-mode time-sharing converter with LCL-filter: (a) topology and (b) operating principle [11].

3. PROPOSED CONVERTER

3.1 Topologies of "Full-Bridge" and "Half-Bridge" converter

A three-stage inverter was adopted in order to achieve higher efficiency with devices of MOSFET. One merit of the inverter is that with the input LC-filter, the current ripple of dc input source is smaller than that of the conventional VSI. Note that due to the energy balance, a large input smoothing capacitor should be inserted and its capacitance is mainly dependent on the ripple current at the double line frequency, so this LC filter has less help to decrease the total input capacitance.

Since the input dc LC-filter of the conventional three-stage dual-mode time-sharing inverter may not be so necessary, a new family "boost in boost" inverter is proposed and abbreviated as the Aalborg Inverter. A "full-bridge" three-stage inverter is proposed and shown in Fig. 6. Similar to the conventional three-stage dual-mode time-sharing inverter, only one power stage works at high frequency and the output power stage works at the line frequency. Compared with the inverter in [13], the main difference is that the physical position of "boost" stage and "buck" stage has been exchanged and one inductor can be saved. So, in theory, the related conduction power loss is also reduced and a higher efficiency can be achieved.



(a)

(b)

Fig -6: Proposed "full-bridge" converter: (a) topology and (b) Operating principle.

Fig. 7 shows the proposed "half-bridge" SIMO converter. In some applications, if the common mode electromagnetic interference is not an important issue, the inverter can be further simplified as shown in Fig. 8 and the dc inductor can be fully utilized. The operation of the proposed "half-bridge" converter will be introduced to illustrate the basic principle of the circuit in detail.

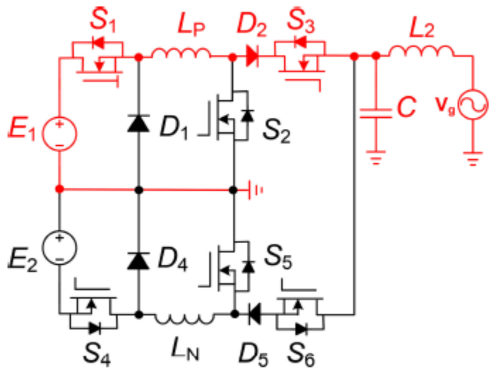


Fig -7: Proposed Half Bridge converter A

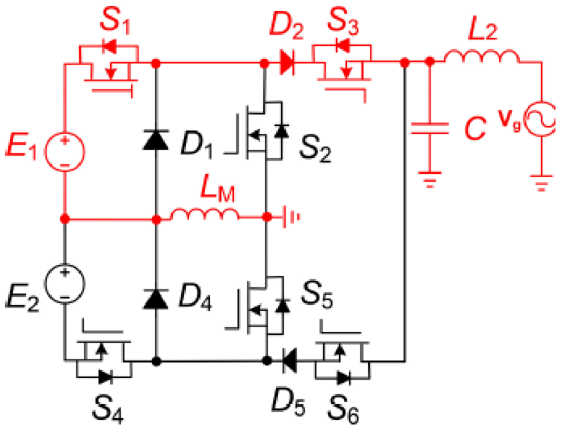
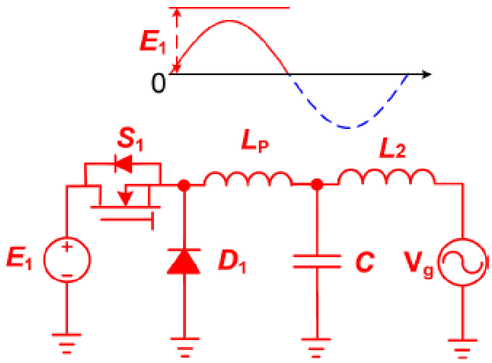
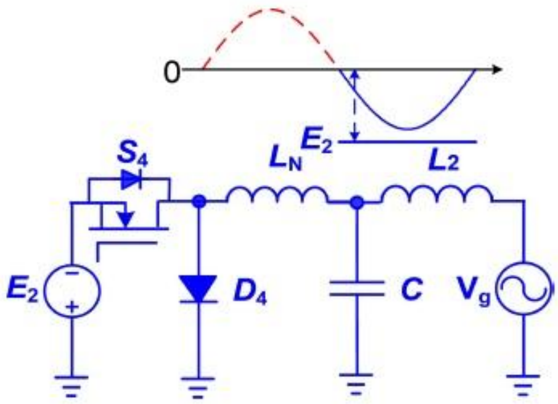


Fig-8: Proposed Half Bridge converter B



(a)



(b)

Fig-9: Equivalent circuits when E_1 and E_2 are higher than the amplitude of the grid voltage: a) during positive period, b) during negative period

3.2 Operating Modes of the Proposed "Half-Bridge" Inverter-A

1) $|E_1|$ or $|E_2| \geq$ Vg A : When the input dc voltage (E_1 , E_2) is larger than V_g A , the amplitude value of grid voltage, the equivalent circuits are as shown in Fig. 9. As shown in Fig. 9(a), during the positive period of the grid voltage, S_3 is ON, S_2 is OFF, S_1 works at high frequency in order to achieve a sinusoidal grid-injected current, and E_1 provides the total energy. In the same way, as shown in Fig. 9(b), during the negative period of V_g , S_6 is ON, S_5 is OFF, S_4 works in the high frequency mode in order to keep the grid-injected current sinusoidal, and E_2 delivers the total energy. The inverter works as a VSI connected to the grid through an LCL-filter.
2) $|E_1|$ and $|E_2| < V_g$ A: When the input dc voltage (E_1 , E_2) is lower than the amplitude of grid voltage (V_g A), the control becomes a little bit more complicated. Fig. 10 shows the working sequence of the proposed "half-bridge" inverter-A, when the amplitude of the input dc voltage is lower than the ac grid voltage, where the sequence can be separated into six parts during a full line frequency period.

During T_1 and T_3, S_3 is ON, S_1 works at high frequency, and the rest of the switches are OFF. The equivalent circuits are shown in Fig. 11(a) and it can be seen that it works like a pure buck converter with an LCL-filter connected to the grid. In this case, the buck converter is a classical VSI.
During T_2 , S_1 and S_3 are ON, S_2 works with high frequency, and the rest of the switches are OFF. The equivalent circuit is shown in Fig. 11(b) and it can be seen that it works like a pure boost converter with a CL-filter connected to the grid. If the current of the boost inductor can be fully controlled, this equivalent circuit can be seen as a CSI.
Similarly, during T_4 and T_6 , S_6 is ON, S_4 works at high frequency, and the rest of the switches are OFF. The equivalent circuit is shown in Fig. 13(a) and it can be seen that it also works like a pure buck circuit with an LCL-filter connected to the grid.

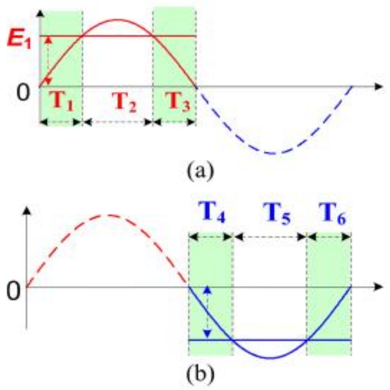


Fig-10: Working sequence when E_1 and E_2 are lower than the amplitude of the grid voltage: (a) during the positive period and (b) during the negative period.

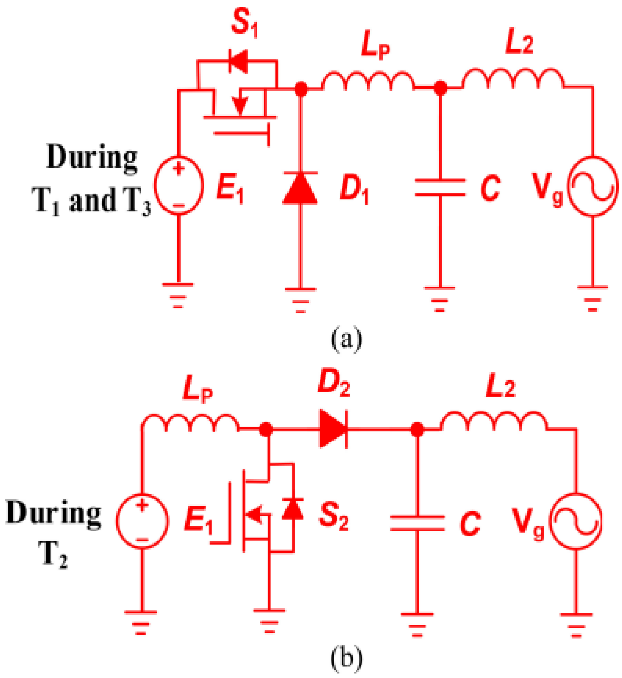


Fig-11: Equivalent Circuits during positive period of the converter a) During T_1 and T_3 b) During T_2

During T_5 , S_4 and S_6 are ON, S_5 works at high frequency, and the rest of the switches are OFF. The equivalent circuit is shown in Fig. 12(b) and it can also be seen as a CSI with a CL-filter connected to the grid, if the current of the boost inductor can be fully controlled.

From the previous analysis, it can be seen that the proposed inverter cannot simply be identified as a conventional VSI or CSI. The most outstanding character of this type inverter is that the minimum filtering inductance in the power loop is adopted and over filtering will not take place; so, theoretically, the pro-posed inverter has the merit to achieve higher efficiency than other inverters under the same condition of the input dc voltage.

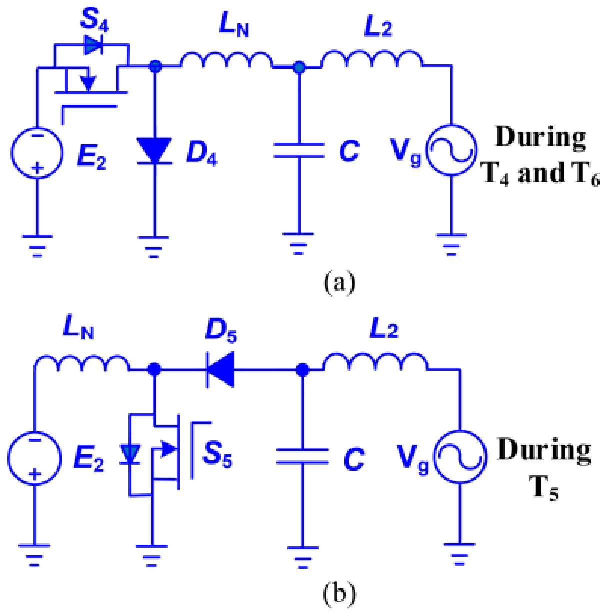


Fig-12: Equivalent circuits during the negative period for the converter. (a) During T_4 and T_6. (b) During T_5

4. SIMULATIONS AND EXPERIMENTAL RESULTS

Simulations on the proposed "Half-bridge" Inverter-A as shown in Fig. 7 are carried out with the PSIM software. The parameters are listed in Table I. During the simulation, the delay is considered as 0.75 T_s , and the grid voltage is set to 220 V. The simulation results are shown in Figs. 13–16 respectively.

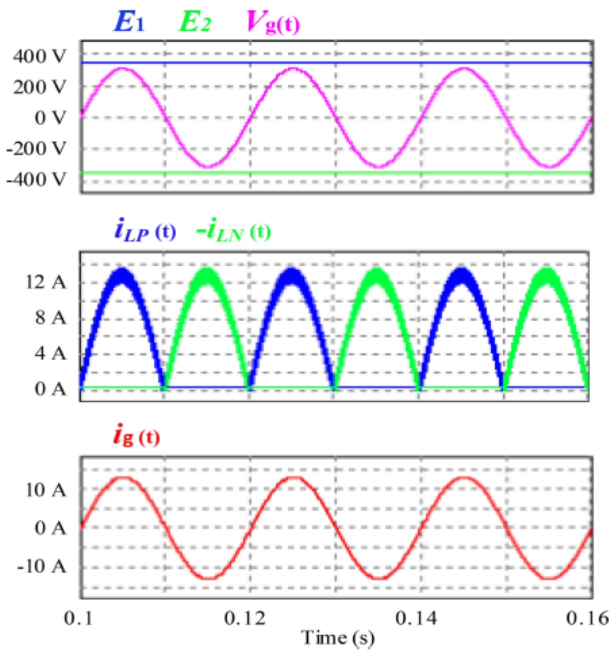


Fig-13: Simulated input dc voltages (E_1, E_2), grid voltage (V_g (t)), dc currents of dc inductor (i_{LN} (t), i_{LP} (t)), and grid injected current (i_g (t)) while E_1 = E_2 = 350 V and 2000 W operation (full load).

Fig. 13 shows the simulation results of the input dc voltages (E1 , E2), the grid voltage (Vg (t)), the dc currents of the dc inductor (iL N (t), iL P (t)), and the grid-injected current (ig (t)) while E1 = E2 = 350 V. It can be seen that the inverter works as a pure VSI and the current of the dc inductor is a rectified sinusoidal waveform, which is set according to (6).

Table 1: Design Parameters of 2 KW Converter

Parameters	L_2	C	L_N, L_P	f_s (S_1-S_5)
Units	600 µH	2µF	600 µH	40 kHz

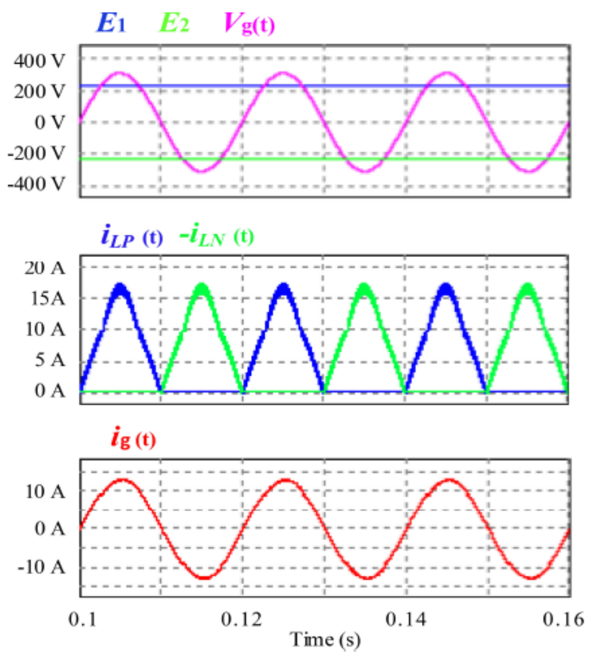


Fig-14: Simulated input dc voltages (E_1 , E_2), grid voltage (V_g (t)), dc cur-rents of dc inductor ($i_{L\,N}$ (t), $i_{L\,P}$ (t)), and grid-injected current (i_g (t)) when E_1 = E_2 = 240 V and 2000 W operation (full load).

When E_1 = E_2 = 240 V, the simulated results are shown in Figs. 14–16. From Fig. 14, it can be seen that when the instantaneously ac grid voltage is higher than the input dc voltage, the boost circuit works quite well according to the proposed control strategy. Fig. 15 shows the simulated voltage V_g(t) and the grid-injected current i_g (t) when the given output power changes from the half load to the full load at the time of 0.084 s, and back to the half load again at 0.124 s. Fig. 16 also shows the simulated voltage V_g (t) and the grid-injected current i_g (t), when a volt-age sag of 50% appears in the grid voltage between 0.074 and 0.124 s. From Figs. 15 and 16, it can be seen that the converter has good control performance, which is due to the fact that the minimum filtering inductance in the power loop has been used, especially during the "boost" working stage.

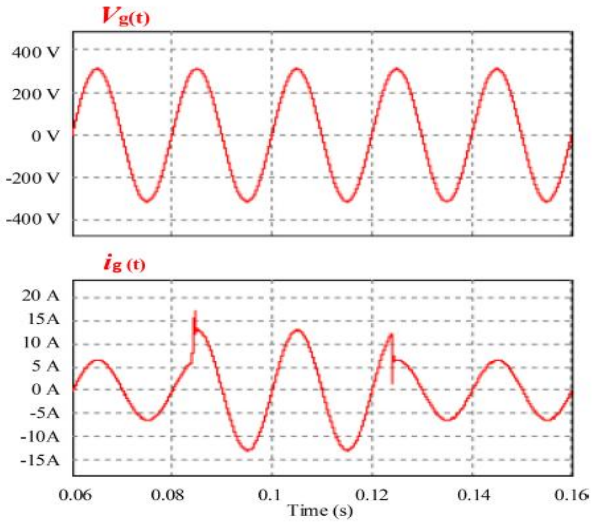


Fig-15: Simulated grid voltage (V_g (t)) and grid-injected current (i_g (t)) when the given power changes at 0.084 and 0.124 s (from the half-load to the full load, then back to the half-load).

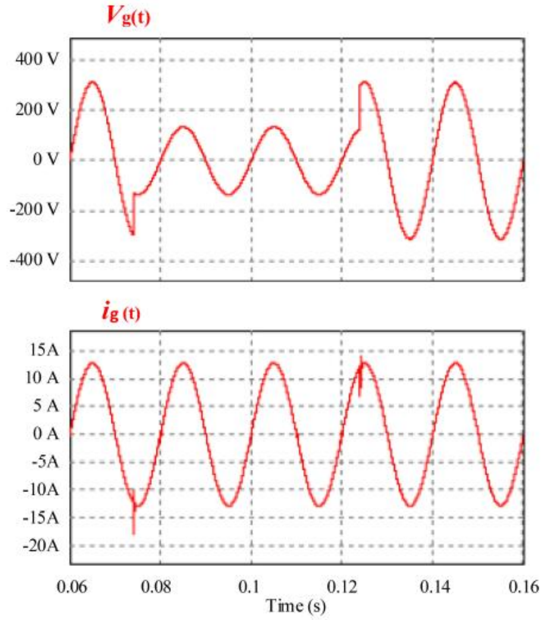


Fig-16: Simulated grid voltage (V_g (t)) and grid-injected current (i_g (t)) when the grid has a voltage sag between 0.074 and 0.124 s.

5. CONCLUSION

In this paper, a new family of "boost in boost" inverter is proposed. The working modes of a "half-bridge" single-phase inverter are introduced in detail through equivalent circuits. For this type of inverter, when the input dc voltage is lower than the amplitude of grid voltage, it combines the characters of VSI and CSI during the different working stages. If the input dc voltage is higher than the amplitude of the grid voltage, it is a pure VSI. Similar to the traditional "boost in boost" inverter, only one power stage works in the high frequency stage at any time, which results in minimum switching losses. Different from the traditional "boost in boost" inverter, the inverter has a minimum voltage drop of the filtering inductors in the power loop at any time.

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