

AN OVERVIEW AND SIMULATION OF DC-DC-AC AND Z-SOURCE GRID CONNECTED INVERTERS

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Abstract: Energy sources such as batteries, fuel cells, capacitors/ultracapacitors, solar cells etc., produce DC power. In many situations, it is required and advantageous to interface them to the main power grid. The DC voltage generated is stepped up and inverted to the appropriate voltage and frequency for grid integration by power electronic (PE) interface modules employing DC-DC converters and DC-AC inverters. The role of these PE systems are mainly three fold: 1) to invert the DC voltage into line frequency single/three-phase voltages, 2) to boost the low voltage DC into grid voltage, and 3) to provide electrical buffer between the energy source and the main grid lines. This paper presents an overview of two of the possible methods of inversion: a) DC-AC inversion with a DC-DC converter interface, b) single stage Z-source based DC-AC inversion. The two aforementioned systems are designed for a typical 1kW application. The circuit designs are verified with the aid of Saber Sketch simulation software. The first-cut design procedures presented in this work benefits the power supply designers by reducing the design time.

Key Words: Alternative Energy, DC-AC Inverter, Impedance-Source Inverter, Power Conversion, and Z-Source Inverter

I. INTRODUCTION

Alternative energy sources are gradually gaining a strong foothold in the power sector. They are seen as compact, efficient, and cleaner sources which can reduce the burden on the predominantly fossil fuel powered grid [1]. Energy storage elements like batteries, capacitors, and ultracapacitors are used as backup sources for the grid connected systems. They are usually employed to meet dynamic load variations. Both alternative energy sources and energy storage units are DC sources and, irrespective of their energy density, they have relatively low output voltage. This requires a power conditioning interface to modulate the voltage and frequency to grid acceptable standards. Pulse-width modulated (PWM) power electronic DC-DC converters and DC-AC inverters are robust, reliable and high efficiency systems which are used extensively as power conditioning modules between energy sources and the grid [2]-[8].

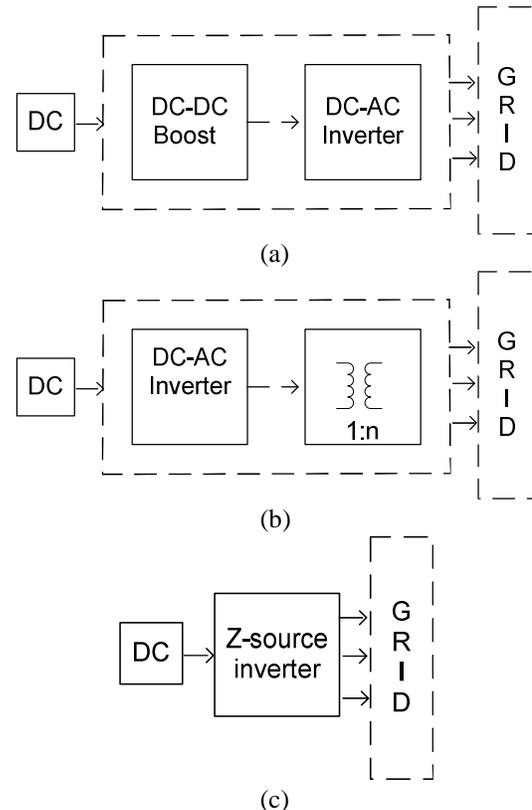


Fig. 1. Block diagram of a DC-AC inverter systems. (a) DC-DC boost converter plus DC-AC inverter system. (b) DC-AC inverter plus a line-frequency step-up transformer system. (c) Z-source DC-AC inverter.

The basic requirement is to step up the voltage level, and to invert from DC to AC. In a majority of the situations, the two requirements have been individually met by two dedicated power converters. The two power converters are then connected to form a two stage voltage step-up, inversion system. This two stage approach has popularly employed a DC-DC converter for voltage step-up and three-leg six-switch voltage source inverter (VSI) or current source inverter (CSI) for DC-AC inversion [9]. A host of DC-DC step-up converters have been developed and used for various applications, an appropriate topology has to be selected based on ones requirements. For inversion, VSIs have been preferred over CSI due to reduced losses and complexity.

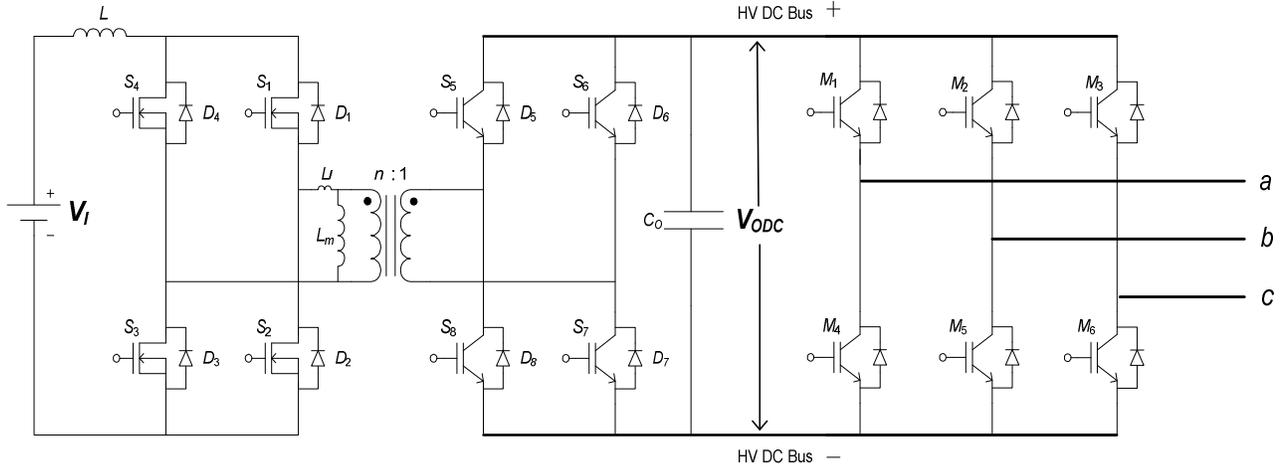


Fig. 2. Current-fed full-bridge voltage source DC-AC inverter.

The Z-source inverter incorporates the boosting and the inversion functions into a single stage [10]. Single stage conversion reduces the system complexity, increases the efficiency and saves cost and volume. This scheme is relatively new, however it has received a lot of attention by the industry and academia.

Section II presents the circuit description and design of a typically rated two stage voltage step-up and inversion technique. A current-fed full-bridge DC-DC voltage converter followed by a three-leg six-switch VSI is considered in this paper. Section III presents a Z-source inverter designed for conditions identical to the ones considered in Section II. Section IV presents the simulation results of the schemes considered in Sections II and III. Section V presents the conclusion.

II. DC-DC-AC INVERTER SYSTEM

Fig. 1 shows a block diagram of the step-up DC-AC inverter systems. Fig. 1(a) shows a conventional DC-AC inverter system. It consists of a DC-DC converter and a DC-AC inverter. PWM inverters are divided into VSI and CSI. VSI is the preferred topology for medium and high power applications. The DC-DC converter is mainly required to step-up the input DC voltage as VSI is inherently a step-down inverter. Additionally, transformer versions of DC-DC converters can be employed to provide electrical isolation and increased boosting range. The stepped-up DC voltage is then inverted to a three-phase ac voltage by a three-leg six-switch VSI. PWM DC-DC converters are divided into voltage-source converters (VSC) and current-source converters (CSC). A voltage-source full-bridge DC-DC converter is widely used in high power applications. In applications wherein high step-up voltage conversion ratio is required, a current-source full-bridge DC-DC converter is preferred over the voltage-source full-bridge

converter as the transformer in the voltage-source full-bridge requires a very low value of primary-to-secondary turns ratio n . For example, if a voltage-source full-bridge converter has to boost a 12 VDC input to 200 VDC, then $n = N_p : N_s = 12 : 200 = 0.06$ i.e., for every turn in the primary winding N_p , there has to be 17 turns in the secondary winding N_s . Designing a well coupled, compact transformer with a low value of n would be highly challenging.

Both VSI and CSI employ a three leg six-switch network as shown in Fig. 2. VSI employs a constant DC voltage source at the input of the switching network and the CSI employs a constant current source at the input of the switching network. Usually a current source is realized by having a large inductance in series with a voltage source. The main attributes of VSI and CSI are:

- VSI – the peak value of the AC voltage at the output can reach a maximum value equal to the DC input voltage. For practical purposes, VSI is considered a voltage step-down operator.
- CSI – the peak value of the AC voltage at the output of the inverter can reach a minimum value equal to the DC input voltage. For practical purposes, CSI is considered a voltage step-up operator. CSI requires a large inductor to realize its operation and suffers from poor efficiency as compared to VSI.

Three-leg six-switch VSI is opted for this paper as it is simpler and more efficient than CSI. Additionally, both PWM VSI and PWM CSI require dead-bands in their gating function in order to avoid a shorting of the DC source.

a. Circuit Description and Operation of Current-fed Full-Bridge DC-DC Converter.

The circuit diagram of the current-fed full-bridge DC-DC converter is shown in Fig. 2. The transformer primary side (low voltage side) consists of power MOSFET's

denoted by S_1 - S_4 along with their body diodes D_1 - D_4 , respectively. The boost inductor L is connected between the input source and the two-leg four-switch bank S_1 - S_4 . The transformer secondary side (high voltage side) consists of rectifier diodes D_5 - D_8 . In bidirectional applications, power IGBT's denoted by S_5 - S_8 are used to transfer power from the high voltage side to the low voltage side. The transformer is modeled as an ideal transformer with its magnetizing inductance L_m and its leakage inductance L_l both referred to primary. The principle of operation of the current-fed full-bridge DC-DC converter during the boost mode is as follows: The boost inductor L is charged by the input source when all the primary side switches S_1 , S_3 , and S_2 , S_4 are turned ON, and discharges when the pair of switches S_1 , S_3 , or S_2 , S_4 are turned OFF. The secondary side IGBT's are always OFF during the boost mode, however, the IGBT's anti-parallel diodes freewheel the output current when only a pair of primary switches are turned ON i.e., D_5 , D_7 are ON when S_1 , S_3 are ON and D_6 , D_8 are ON when S_2 - S_4 are ON.

b. Circuit Description and Operating Principle of Three-Leg Six-Switch PWM DC-AC VSI.

The three phase VSI consists of three legs with two switches in each leg. The three legs are in parallel with the DC input source. The three phase voltages are taken at the midpoints of the three legs as shown in Fig. 2. For bidirectional operation, the switches must have anti-parallel diodes for AC-DC rectification. The input to the VSI is assumed to be ideal DC, the ensuing output is three phase symmetrical sinusoidal wave. The DC voltage is synthesized to obtain the required sine wave by employing six switches and a switching pattern generated by an appropriate modulation technique.

The sine-triangle modulation technique is a simple and an effective way to synthesize single phase or multi-phase sinusoidal outputs. In sine-triangle modulation, high frequency carrier triangle wave is continually compared with a three phase command or reference sinusoidal signal. The switching frequency of the six inverter switches is determined by the carrier frequency and the output voltage frequency is determined by the reference signal frequency.

Fig. 3 shows the sine-triangle modulation scheme. In Fig. 3, waveforms *sine1*, *sine2*, and *sine3*, are compared with the *Triangle* waveform to obtain the gating sequences *M1*, *M2*, and *M3*, respectively. The upper side switches of the inverter are M_1 , M_2 , and M_3 and the lower side switches are M_4 , M_5 , and M_6 , respectively. The phase and the line voltages of the inverter are a function of the switches and their respective states (ON or OFF). In a VSI, no two switches of the same leg can be in the ON state simultaneously as it would short the DC source.

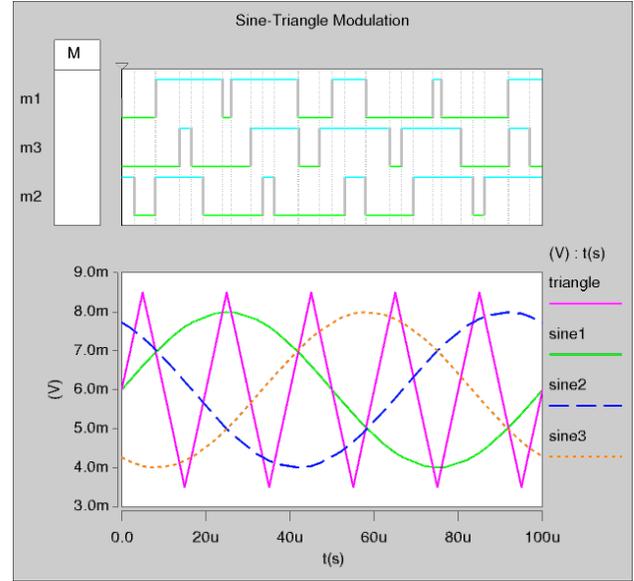


Fig. 3. Sine-triangle modulation technique.

TABLE I
ALLOWABLE SWITCHING STATES OF A SIX-SWITCH VSI

| State | Switches ON | State | V_{ab} | V_{bc} | V_{ca} |
|-------|-------------|--------|-----------|-----------|-----------|
| 100 | 1, 5, 6 | Active | V_{dc} | 0 | $-V_{dc}$ |
| 110 | 1, 2, 6 | Active | 0 | V_{dc} | $-V_{dc}$ |
| 010 | 2, 4, 6 | Active | $-V_{dc}$ | V_{dc} | 0 |
| 011 | 2, 3, 4 | Active | $-V_{dc}$ | 0 | V_{dc} |
| 001 | 3, 4, 5 | Active | 0 | $-V_{dc}$ | V_{dc} |
| 101 | 2, 3, 5 | Active | V_{dc} | $-V_{dc}$ | 0 |
| 111 | 1, 2, 3 | Zero | 0 | 0 | 0 |
| 000 | 4, 5, 6 | Zero | 0 | 0 | 0 |

For a conventional VSI, the possible allowed switching states and their respective state voltages are given in Table. I. In Table I, V_{ab} , V_{bc} , and V_{ca} are the line voltages and V_{dc} is the input DC voltage. The numbers 1, 2, and 3 represent the top switches and 4, 5, and 6 represent the bottom switches, respectively. The switches in any one leg are switched complementarily.

c. Design of DC-AC Inverter System

For the first-cut design, the values of the boost inductor L , the transformer turns ratio n , and the devices stresses of the switches and diodes are required.

The DC-AC inverter system is designed for the following specifications:

- Nominal DC input voltage: V_I 50 VDC
- Line-to-neutral output voltage: v_a 120 Vrms
- Output power: P_O 1 kW
- Switching frequency: f_s 50 kHz

- Inverter output frequency: $f = 60 \text{ Hz}$

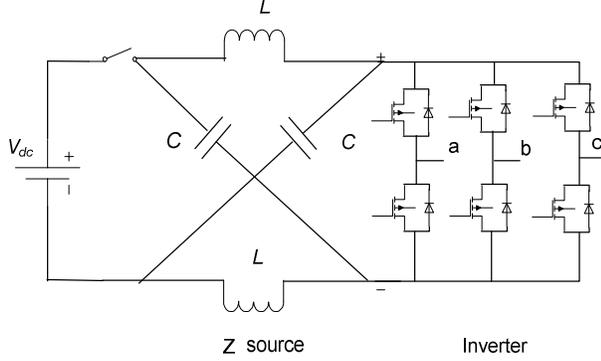


Fig. 4. Z-source DC-AC inverter.

Assuming that the sine-triangle modulation index m_a of the DC-AC inverter is 0.8, the output voltage of the DC-DC converter is

$$V_{ODC} = \frac{2\sqrt{2}v_a}{m_a} = \frac{2 \times \sqrt{2} \times 120}{0.8} = 424.26 \text{ V.} \quad (1)$$

The peak voltage V_{Speak} of the secondary winding of the transformer is equal to the DC output voltage V_{ODC} . Assuming that $n = 1:4 = 0.25$, the peak voltage V_{Ppeak} of the primary winding of the transformer is

$$V_{Ppeak} = nV_{Speak} = nV_{ODC} = 0.25 \times 424.26 = 106.06 \text{ V.} \quad (2)$$

The boost inductor is designed for continuous-conduction mode (CCM). The charging and the discharging periods of the boost inductor are assumed to be equal i.e., the duty cycle of the switches $S_1 - S_4$ is $D = 0.5$. Assuming that the DC-DC converter efficiency η is 85% and the peak-to-peak value of the boost inductor current Δi_L is 10% of the input current I_I , the ripple current in the boost inductor is

$$\Delta i_L = 0.1I_I = \frac{0.1\eta I_O}{n(1-D)} = \frac{0.1 \times 0.85 \times 2.35}{0.25 \times (1-0.5)} = 1.598 \text{ A} \quad (3)$$

The minimum inductance that ensures CCM operation is [2]

$$L_{min} = \frac{nV_{ODC}D(1-D)}{\Delta i_L f_s} = \frac{0.25 \times 424.26 \times 0.5 \times (1-0.5)}{1.6 \times 50 \times 10^3} = 331.45 \mu\text{H} \quad (4)$$

Select $L = 350 \mu\text{H}$.

The maximum drain-to-source voltage of the switches S_1-S_4 is

$$V_{DSmax} = V_I. \quad (5)$$

Since the boost inductor is in series with the switches, high voltage transients appear across the switches due to the resonance between the boost inductor and the parasitic output capacitance of the switches when the switches are turned OFF. Therefore, a snubber or a transient voltage suppressor (TVS) must be used to

clamp this additional voltage across the switches. The maximum drain current of the switches S_1-S_4 is

$$I_{DSmax} = I_I + \frac{\Delta i_L}{2} = \frac{I_O}{n(1-D)} + \frac{nV_{ODC}D(1-D)}{2f_s L} \quad (6)$$

The maximum reverse voltage of the rectifier diodes D_5-D_8 is

$$V_{Dmax} = \frac{V_I}{n}. \quad (7)$$

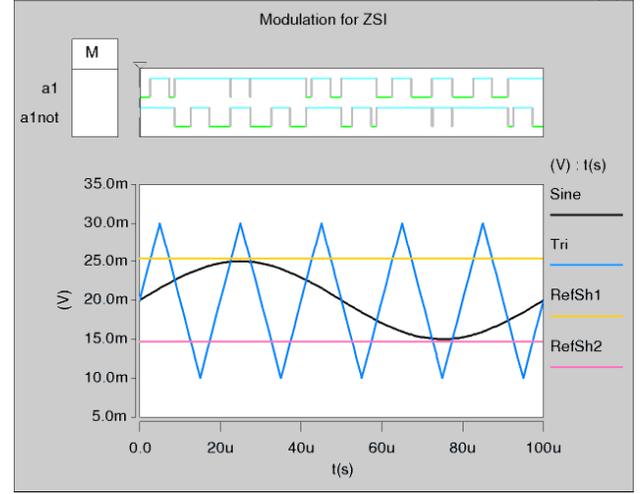


Fig. 5. Maximum-boost sine-triangle modulation technique.

The maximum current stress of the rectifier diodes D_5-D_8 is

$$I_{Dmax} = I_O + \frac{n\Delta i_L}{2} = I_O + \frac{n^2 V_{ODC} D(1-D)}{2f_s L} \quad (8)$$

The minimum value of the output filter capacitor is

$$C_{Omin} = \frac{D_{max} I_O}{f_s V_{Cpp}}, \quad (9)$$

where, V_{Cpp} is the peak-to-peak value of the voltage across the capacitor C_O . Let V_{rCpp} be the peak-to-peak voltage across the equivalent series resistance r_C of C_O . Assuming that the total ripple voltage across both r_C and C_O is 1% of V_{ODC} and $V_{rCpp} = V_{Cpp}$, C_{Omin} can be found. Consequently, the maximum value of $r_C = V_{rCpp}/I_{Dmax}$.

The maximum drain-to-source voltage of the switches M_1-M_6 is

$$V_{MDSmax} = V_{ODC}. \quad (10)$$

The peak value of the current of the switches M_1-M_6 is equal to the amplitude of the load current.

III. Z-SOURCE INVERTER

Section II describes a two stage DC to AC step-up inversion. Typical two-stage inversion schemes include a DC-DC converter and a DC-AC inverter or a DC-AC inverter and a line-frequency step-up transformer. Line-

frequency transformers are bulky and hence hamper the energy density of the system. The drawbacks of the two stage DC-AC inversion employing a VSI are:

- Higher part count – leads to additional losses, bulky, and more expensive.

- Complex control – since it is a two stage approach, the control strategy is complex.

The Z-source inverter enables single-stage step-up DC-AC conversion. As opposed to VSI and CSI, the Z-source inverter has an impedance network interfacing the switching network, and the DC source as shown in Fig. 4.

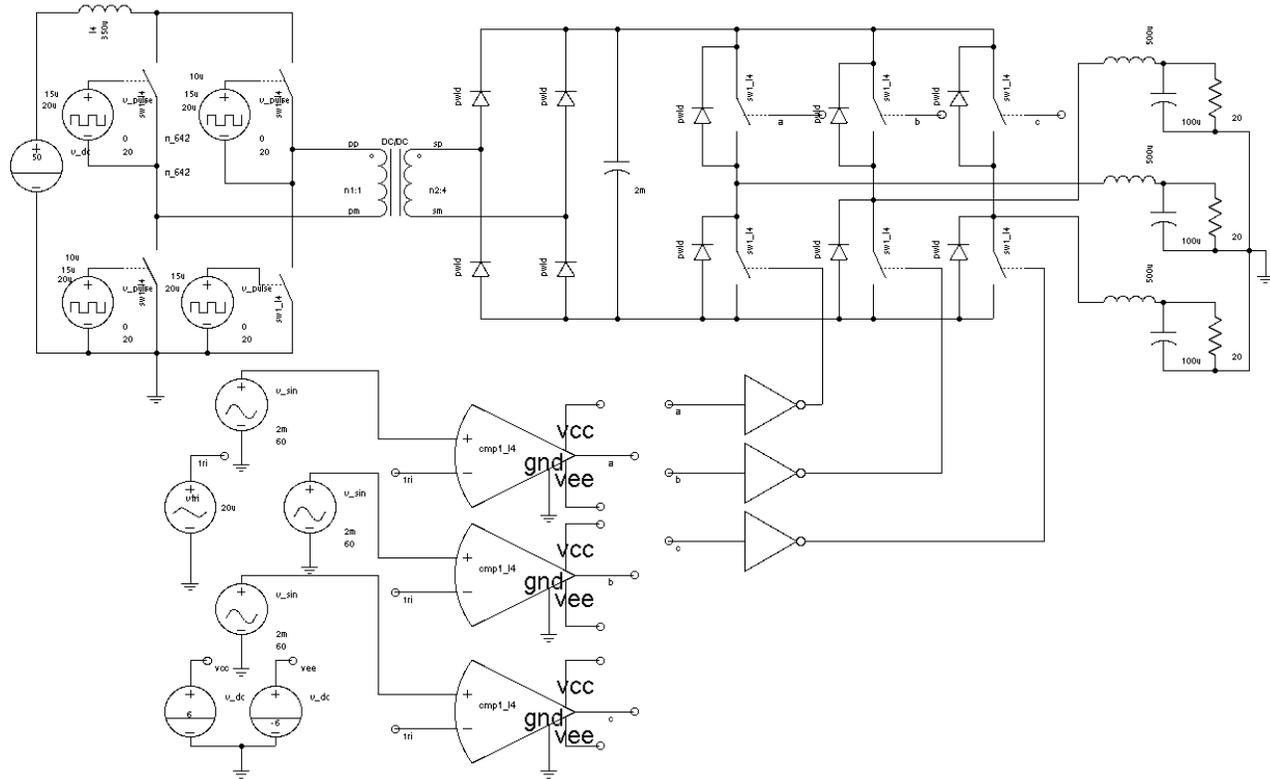


Fig. 6. Circuit of the current-fed full-bridge voltage-source DC-AC inverter system used in Saber Sketch simulation.

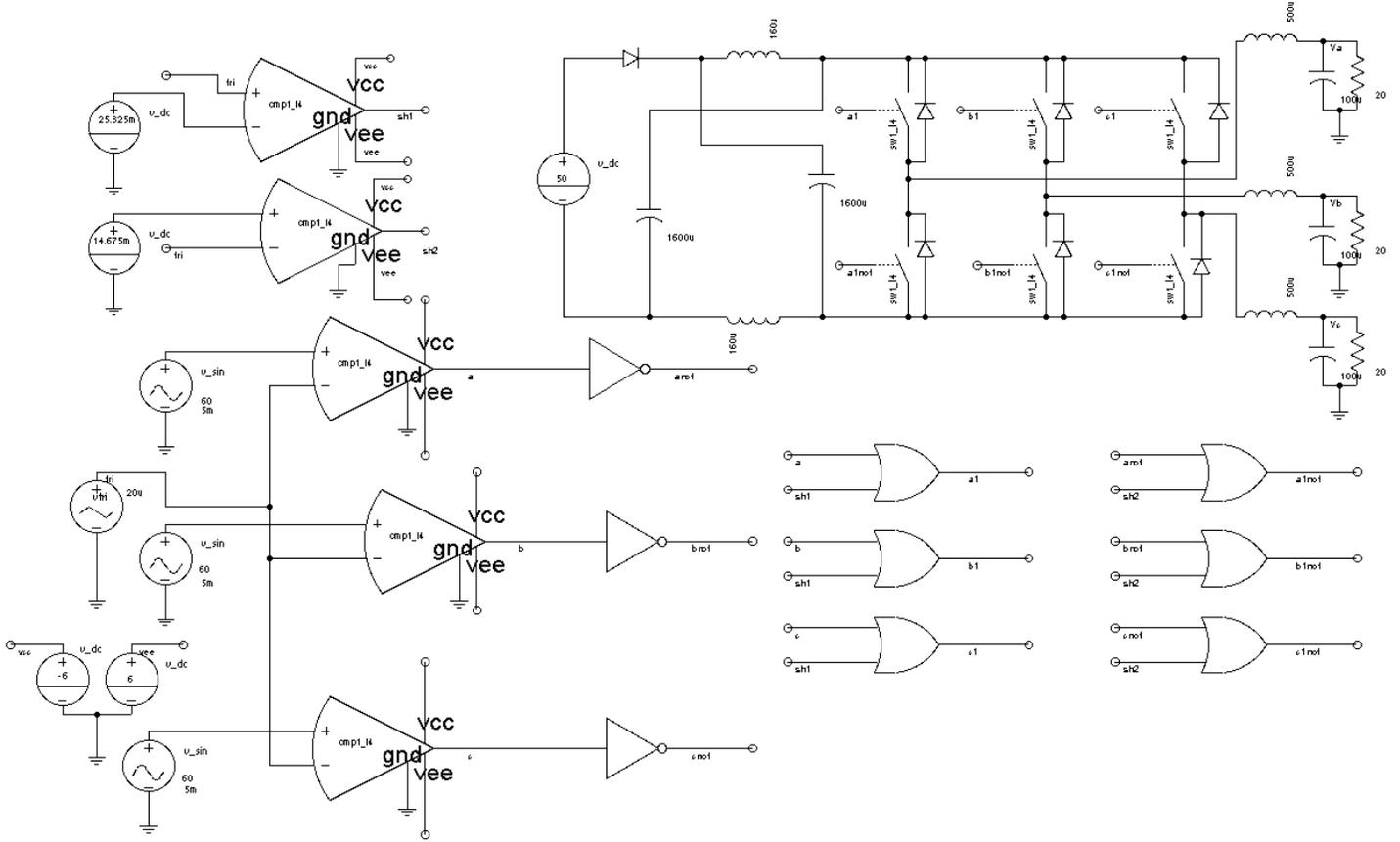


Fig. 7. Circuit of the Z-source DC-AC inverter system used in Saber Sketch simulation. The impedance network incorporates buck-boost feature, provides inherent short circuit protection, and facilitates single stage buck or boost DC-AC inversion.

As mentioned in Section II, VSI has six active states and two zero states, however Z-source inverter has an additional zero state when one or more of the phase leg shorts the impedance network. This state is called the shoot-through state, and this state enables the voltage boosting ability. The shoot-through state is an effective zero state as it is resulted by shorting the input terminals of the six-switch network. The shoot-through state can be generated by seven different combinations of the six switches. The features of the Z-source inverter are [10]:

- Incorporates voltage boost feature to VSI
- Boosting is enabled by shoot-through state. Since no active states are introduced or altered, all the PWM methods and relations existing for VSI are still applicable to Z-source inverter.
- The frequency as seen from the Z-network is six times the inverter switching frequency. This reduces the inductance requirement.
- Additionally provides short circuit protection.

The peak phase voltage at the output of the inverter is given by

$$v_{a(peak)} = M_a B \frac{V_{dc}}{2}, \quad (11)$$

where M_a is the modulation index and B is the boost ratio given by

$$M_a = \frac{v_{carrier}}{v_{ref}} \quad (12)$$

and

$$B = \frac{1}{1 - 2\frac{T_o}{T}}. \quad (13)$$

In (13), T_o is the shoot-through time duration in time period T .

A Z-source inverter is designed for the same specifications as the DC-AC inverter system designed in Section II. c. Based on the inverter switching frequency and the output power rating, typical values of inductance and capacitances for the Z-network are selected in accordance with relevant literature [10]. The component values of the Z-network are: $L = 160 \mu\text{H}$ and $C = 1600 \mu\text{F}$.

For the gating sequence, the maximum boost modulation scheme is chosen [11] as shown in Fig. 5. This technique is a simple extension of sine-triangle modulation. Since a high single-stage boost is required, M_a of 0.5 is selected to accommodate for sufficient boost ratio B . From (11), the required boost ratio is $B = 13.6$. Based on (13), the shoot-through time required per switching time period of $20 \mu s$ is found to be $9.2 \mu s$.

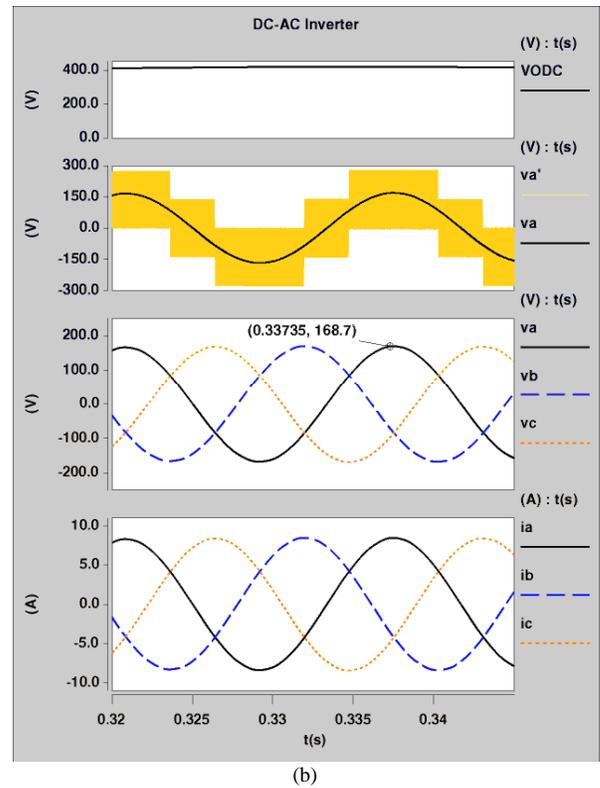
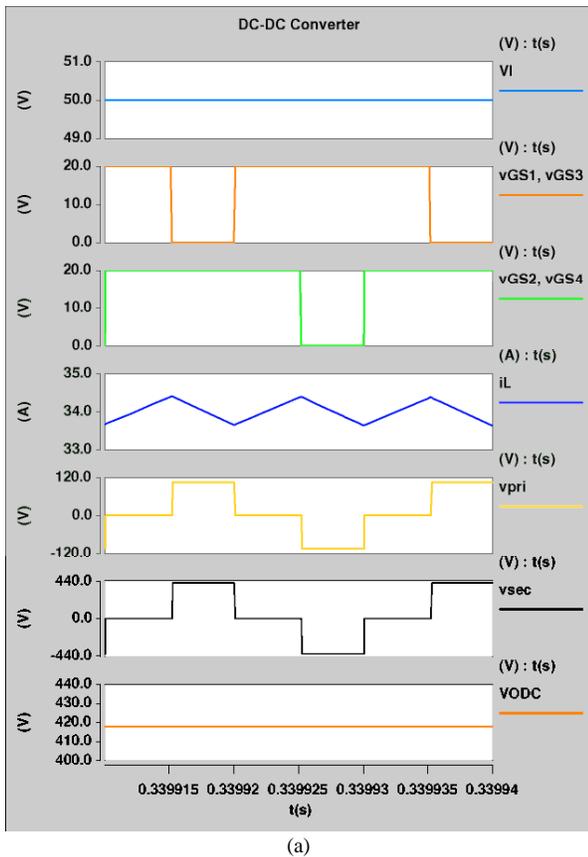


Fig. 8. Simulation results of the current-fed full-bridge VSI DC-AC inverter system. (a) Simulation results of the current-fed full-bridge DC-DC converter. (b) Simulation results of the three-leg six-switch VSI.

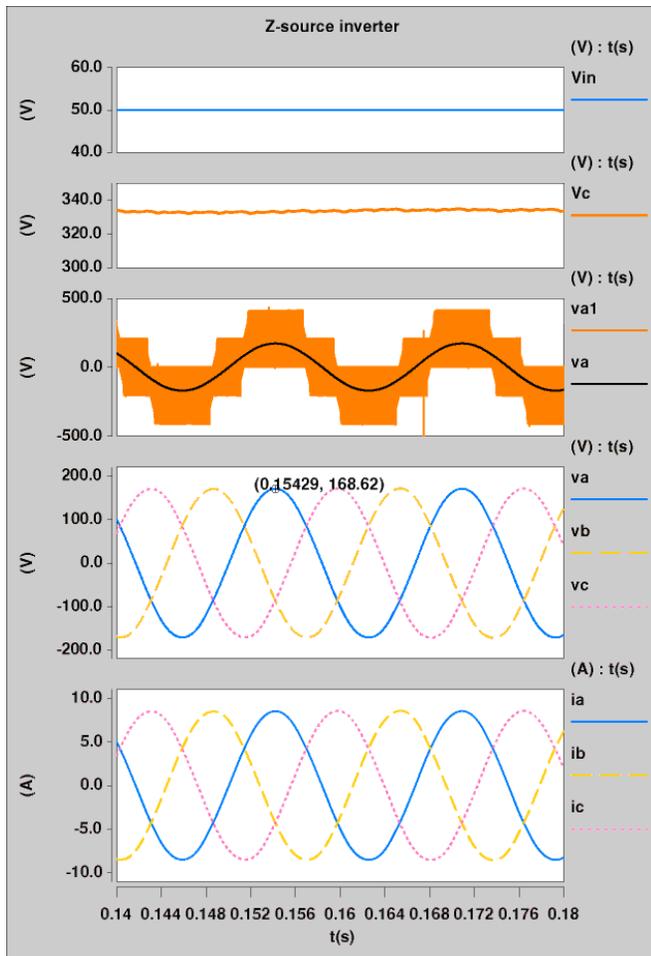


Fig. 9. Simulation results of the Z-source DC-AC inverter system.

IV. SIMULATION RESULTS

The circuits of the DC-AC inverter system and the Z-source inverter used in Saber Sketch simulation are shown in Figs. 6 and 7, respectively. The simulated waveforms of the inverters shown in Figs. 6 and 7 are shown in Figs. 8 and 9, respectively. From the simulation results, it can be clearly seen that the required design specifications are met.

V. CONCLUSIONS

The role of DC-AC inversion systems with respect to alternative energy sources and energy storage elements are described. The basic features and principles of the two-stage DC-AC step-up inverter and the single-stage Z-source converter are highlighted. Operating principle of a current-fed full-bridge DC-DC converter, a VSI, and ZSI are presented. Simplified design of a current-fed full-bridge DC-DC converter and a six-switch three-leg VSI which forms the DC-AC inversion system has been

presented. Design of a single-stage Z-source DC-AC inverter has been given. Simulated circuits and the results are shown. The Z-source inverter offers a simple and an effective alternative over the two-stage DC-AC inverter system. The advantages of the Z-source inverter are:

- Single-stage DC-AC step-up conversion.
- Reduced number of semiconductor switches.
- Inherent short circuit protection.
- All the PWM techniques applicable to VSI are also applicable to Z-source inverter.

In applications wherein the required voltage boost is outside the boosting ability of the Z-source inverter, a line frequency transformer will have to be employed. However, in the case of two-stage DC-DC-AC system, a high frequency transformer can be employed. For a given power rating, line frequency transformers are bulkier than the high frequency transformers.

REFERENCES

1. Frede Blaabjerg, Zhe Chen, and Soren Baekhoej Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1184-1194, Sep. 2004.
2. Marian K. Kazimerczuk, "Pulse-Width Modulated DC-DC Power Converters," John Wiley & Sons, New York, NY, 2008.
3. M. H. Rashid, *Power Electronics Handbook*, Elsevier Press, 2007.
4. N. Mohan, T. M. Undeland, and W. P. Robbins *Power Electronics: Converters, Applications, and Design*, 3rd Ed., John Wiley & Sons, 2003.
5. B. K. Bose, *Power Electronics and Variable Frequency Drives: Technology and Applications*, IEEE Press, Piscataway, NJ, 1997.
6. R. Watson and F. C. Lee, "A soft-switched full-bridge boost converter employing an active-clamp circuit," *Proceedings of IEEE PESC'96 Conference*, 1996, pp. 1948-1954.
7. K. Wang, F. C. Lee, and J. Lai, "Bidirectional full-bridge dc/dc converter with unified soft-switching scheme, Part I: Principles of operation," *Proceedings of VPEC Annual Seminar*, 1998, pp. 143-149.
8. K. Wang, F. C. Lee, and J. Lai, "Bidirectional full-bridge dc/dc converter with unified soft-switching

scheme, Part II: Design, implementation, and experimental results," *Proceedings 31st IEEE PESC'00 Conference*, 2000, pp. 1058-1063.

9. Juan Manuel Carrasco, Leopoldo Garcia Franquelo, Jan T. Bialasiewicz, Eduardo Galvan, Ramon C. Portillo Guisado, Ma. Angeles Martin Prats, Jose Ignacio Leon, and Narciso Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002-1016, Aug. 2006.
10. F. Z. Peng, "Z-source inverter," *Industry Applications, IEEE Transactions on*, vol. 39, pp. 504-510, 2003.
11. Fang Zheng Peng, Miaosen Shen, and Zhaoming Qian, "Maximum boost control of the Z-source inverter," *IEEE Trans. Power, Electron.*, vol. 20, no. 4, pp. 833-838, July 2005.

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