Buck-Boost Inverter Functionality of Two-Phase Semi-Z-Source Converter

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***Abstract*— A two-phase semi-Z-source (SZS) inverter capable of generating sinusoidal output voltage up to two times the input voltage is discussed in this paper. The two-phase SZS inverter consists of four switches and two Z-source networks. The buck-boost functionality achieved without the presence of shoot-through phenomenon is the major advantage of the two-phase SZS inverter. In the two-phase SZS inverter structure, there are two blocks of single-phase SZS circuits. Each single-phase SZS inverter block consists of two switches and one Z-source network. In each SZS inverter block, the switches are operated complementarily. The voltage gain of the single-phase SZS circuit block is non-linear in nature and a Modified Sinusoidal Pulse Width Modulation (MSPWM) technique is employed for generating the switching pulses. The MATLAB/Simulink results are presented to demonstrate the characteristics of the two-phase SZS inverter.**

Keywords—Renewable Energy Sources (RES), Full-Bridge (FB) Inverter, Semi-Z-Source (SZS) inverter, Modified Sinusoidal Pulse Width Modulation (MSPWM)

I. INTRODUCTION

The depleting fossil fuels are demanding the integration of renewable energy sources (RES) in to the grid. The demand for quality power and concern regarding environmentally sustainable solutions to the problem of power shortage welcomes the application of RES such as solar, wind, fuel cells etc in to the power system network. These RES require power electronic interfaces like ac-ac converters, ac-dc-ac converters or dc-ac converters depending on their type of power output. The percentage of solar power utilization is more when it comes to RES. The solar energy sources supply dc power output. The dc-ac converter or inverter is required to interface these solar sources to the grid.

In the literature, numerous inverter topologies are proposed for grid integration of RES [1]. The most commonly used inverter topology in single-phase and three-phase grid-tied systems is FB inverter and three-leg inverter respectively. Both these inverters are capable of giving sinusoidal output voltage up to a maximum peak equal to the dc input voltage. The unity gain characteristic of FB inverter and three-leg inverter categorizes them into buck inverters. Most of the commonly used inverter topologies such as half-bridge, FB, three-leg inverters offer voltage gain less than or equal to unity[2]. The line frequency step-up transformers can be utilized for boosting the output sinusoidal voltage from the inverters[3]. However, this increases the size and cost of the system. The inclusion of dc-dc converters of high gain and efficiency between the RES and inverter to enhance the magnitude of the output sinusoidal voltage is an alternative [4]–[8]. A more promising solution is interfacing the RES to the grid using single-stage buck-boost inverters with less number of switching devices[9]–[13]. Several multilevel and cascaded inverters are reported in the literature. This indeed increases the complexity of the inverter circuit and also the number of switches[14]–[18].

Cao.et.al proposed a two-phase SZS inverter which is capable of generating a sinusoidal output voltage up to two times greater than its single phase counterpart [19]. There is no detailed description of the two-phase SZS inverter in the literature.

This paper intends to present two-phase SZS converter as a buck-boost inverter. The two-phase SZS inverter finds applicability in RES-grid integration and custom power devices. Compared to its single-phase counterpart and FB inverter, two-phase SZS inverter gives two times bigger output voltage with the same input voltage. The dc input voltage utilization of the two-phase SZS inverter is more compared to the FB inverter. The two-phase SZS inverter achieves twice the voltage gain of the conventional FB inverter with the same number of switches as the latter. The switches in the two-phase SZS inverter are positioned in four different legs. There

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is no risk of short-circuiting of the dc power supply or shoot-through condition in the two-phase SZS inverter.

In FB inverter, to avoid the shoot-through condition, dead-time control is employed which in turn causes fifth and seventh harmonics in the voltage [20]. There is no requirement of dead-time control in two-phase SZS inverter. The filtering scheme is inevitable to remove the unwanted harmonics from the output sinusoidal voltage of the FB inverter. However, in two-phase SZS filtering scheme is not required.

The count of passive components is a limitation of the two-phase SZS inverter. However, the size of the two Z-source networks is small as they are placed in the ac-side of the two-phase SZS inverter circuit [19]. This, in turn, reduces the overall size of the two-phase SZS inverter and makes it compact. The absence of the shoot-through condition, elimination of dead-time control, the Z-source network in the ac-side and reduced size are the benefits of the two-phase SZS inverter. The non-linear voltage gain of the two-phase SZS inverter demands a non-linear modulation technique to generate the sinusoidal voltage. This paper gives the circuit description, operation and modulation strategy of the two-phase SZS inverter. The simulation results from MATLAB/Simulink environment are also presented to validate the feasibility of the two-phase SZS inverter.

II. Two-Phase SZS inverter

Basically, the two-phase SZS inverter is a buck-boost dc-dc converter which is capable of producing both positive and negative output voltages. The ability to output both positive and negative voltages transforms the two-phase SZS converter to a two-phase SZS inverter. Fig.1 shows the two-phase SZS inverter. The two-phase SZS inverter is the extension of single-phase SZS inverter (shown inside the dashed boxes) to generate the next phase voltage of a two-phase power system and hence the name [19].

The two-phase SZS inverter consists of two single-phase SZS inverters namely inverter A and B connected to a common dc voltage source V_{dc_Z}. Each of the single-phase SZS inverter present in the two SZS inverter circuit generates output voltages of equal magnitude, but 180^o phase shifted from each other for forming the two-phase power system. For achieving the buck-boost inverter, the two output voltages of the single-phase SZS inverter blocks are connected in series aided fashion to form the amplified output. When series aided, the two-phase SZS inverter gives a sinusoidal output voltage of magnitude twice that of the single phase output.

III. Operation of The Two-Phase SZS inverter

In this paper, more focus is given on achieving a single phase ac output voltage, V_o from the two-phase SZS inverter rather than the two voltages V_A and V_B. The voltage gain of single-phase SZS inverter is given by equation (1) where X can be A or B representing inverter A and B respectively.

$$\frac{v_X}{V_{dc\_Z}} = \frac{1-2D_X}{1-D_X} \qquad (1)$$

Here, in this paper the SZS inverter A gives a sinusoidal output voltage V_A which is in-phase with the required output voltage V_o. The SZS inverter B output voltage V_B is out-of

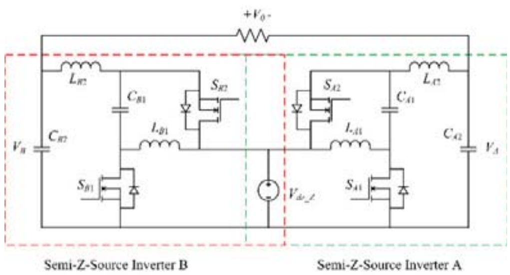

Fig.1. Two-Phase SZS inverter

phase with the required voltage V_o. However, the magnitude of V_B is equal to V_A which is half of the required output voltage V_o. Both the single-phase SZS inverter blocks A and B are operated with same voltage gain.

The instantaneous output voltage v_o of the two-phase SZS inverter is given by equation (2).

$$v_0 = v_A - v_B \qquad (2)$$

where v_A and v_B gives the instantaneous voltages of SZS inverter A and B respectively.

The SZS inverter A and B are modulated using Modified Sinusoidal Pulse Width Modulation (MSPWM) technique which requires a non-linear reference signal as the inverter voltage gain given by equation (1) is non-linear in nature [19]. As per equation (2), the voltage gain of the two-phase SZS inverter is two times the voltage gain of inverter A or B, provided the SZS inverter blocks have equal voltage gain.

The single-phase SZS inverter block gives the positive cycle and negative half cycle of its output sinusoidal voltage (range -V_{dc_Z} to +V_{dc_Z}) when the duty cycle D_A/ D_B of the switch S_{A1}/S_{B1} are varied from (0-0.5) and (0.5-0.6667) respectively. In two-phase SZS inverter, whenever inverter A outputs positive half cycle, inverter B gives negative half cycle and vice versa. The two-phase SZS inverter output voltage follows the phase of inverter A. Fig 2(a) and 2(b) gives the operating modes of the two-phase SZS inverter where the switch combination of (S_{A1}, S_{B1}) and (S_{A1},S_{B2}) are turned on respectively.

In Fig.2a the switch S_{A1} and S_{B1} are operated to obtain the positive half cycle of the two-phase SZS output voltage. The duty cycle of switch S_{A1} is varied from 0 to 0.5 whereas that of switch S_{B1} is varied from 0.5 to 0.6667 to get the positive half cycle of the two-phase SZS output voltage V_o with the maximum positive peak equal to V_{dc_Z}. When the switch S_{A1} is turned on with duty cycle varying in the range (0-0.5) as shown in Fig.2a, the two inductors L_{A1} and L_{A2} gets charged from the input dc supply and the capacitor C_{A1}. At the same time, switch S_{B1} is conducting with duty cycle varying from (0.5-0.6667). The two inductors L_{B1} and L_{B2} discharges. For obtaining the positive half cycle of V_o, the other switch combinations are (S_{A2}, S_{B1}) and (S_{A2}, S_{B2}) where the duty cycle range of S_{A2} , S_{B1} and S_{B2} is varied from (1-0.5), (0.6667-0.5) and (0.333-0.5) respectively [19], [21], [22].

In Fig.2b the switch S_{A1} and S_{B2} are operated to obtain the negative half cycle of the two-phase SZS output voltage. The duty cycle of switch S_{A1} is varied from 0.5 to 0.6667 whereas that of switch S_{B2} is varied from 0 to 0.5 to get the negative half cycle of the two-phase SZS output voltage V_o with maximum negative peak equal to -V_{dc_Z} . When the switch S_{A1} is turned on with duty cycle varying in the range (0.5-0.6667) as shown in Fig.2b, the two inductors L_{A1} and L_{A2} behave as two sources. At the same time, switch S_{B2} is conducting with duty cycle varying from (0-0.5). The currents of inductors L_{B1} and L_{B2} start decreasing. For obtaining the negative half cycle of V_o, the other switch combinations are (S_{A1}, S_{B1}) and (S_{A2}, S_{B2}) where the duty cycle range of S_{A1} , S_{B1} and S_{B2} is varied from (0.5-0.6667), (0.5-0) and (0.5-1) respectively [19], [21], [22].

The detailed description of the SZS inverter operation for different duty cycle ranges is given in [19], [21] and [22]. The switches in the single-phase SZS inverter A and B are operated complementarily.

The sinusoidal output voltages from SZS inverter A and B can be represented by $v_A = V_{A,p}\sin\omega t$ and $v_B = V_{B,p}\sin(\omega t - \pi)$ respectively where $V_{A,p}$ and $V_{B,p}$ are the peak value of the output voltages v_A and v_B respectively. The output voltage V_A is taken as the reference for writing the equations. The modulation index M of both the inverters A and B are given by equation (3) and are equal.

$$M = \frac{V_{A,p}}{V_{dc\_Z}} = \frac{V_{B,p}}{V_{dc\_Z}} \qquad (3)$$

Representing SZS inverter A and SZS inverter B outputs in terms of equation (1) and plugging to equation (2) gives the voltage gain of two-phase SZS inverter given by equation (4)

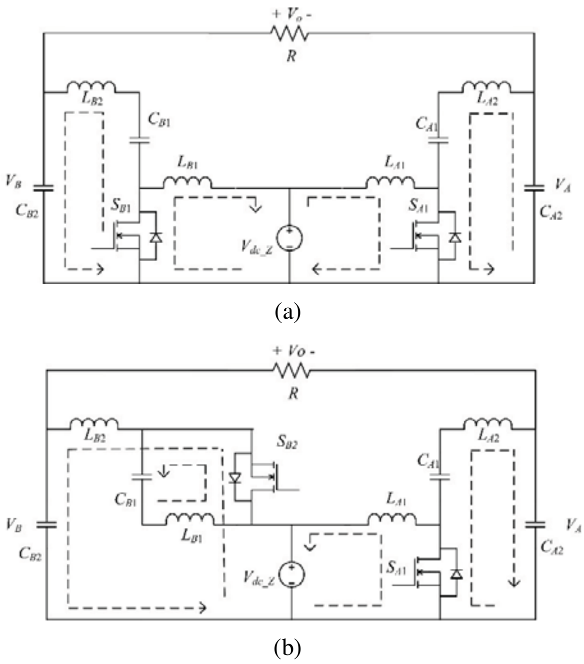

Fig.2. Operating Modes (a) $S_{A1}$and S_{B1} on (b) $S_{A1}$and S_{B2} on

$$\frac{v_o}{V_{dc\_Z}} = \frac{D_B - D_A}{(1-D_A)(1-D_B)} \qquad (4)$$

Rewriting equation (2) in terms of modulation index M gives equation (5). This shows that the buck-boost characteristic is determined by the selection of M value.

$$v_o = 2MV_{dc\_Z}\sin\omega t \qquad (5)$$

The range of M value variation is from 0 to 1. For the M values up to 0.5, the two-phase semi-Z source inverter operates as buck converter. The M value above 0.5 makes the two-phase SZS inverter to operate in boost mode. The maximum possible M value of 1 offers the two-phase SZS inverter with the maximum voltage gain of 2.

The duty cycles D_A and D_B of the SZS inverters A and B respectively need to be represented in sine terms to develop the reference signal required for the MSPWM technique.

Rewriting equation (1) in terms of M for single-phase SZS inverter gives equation (6) where X can be A or B representing SZS inverter A or B respectively.

$$M\sin\omega t = \frac{1-2D_X}{1-D_X} \qquad (6)$$

From equation (6), the duty cycles D_A and D_B of switches S_{A1} and S_{B1} can be expressed by equations (7) and (8) respectively which forms the non-linear reference waveform for the MSPWM of SZS inverter A and B respectively [2]–[4].

$$D_A = \frac{1-M\sin\omega t}{2-M\sin\omega t} \qquad (7)$$

$$D_B = \frac{1+M\sin\omega t}{2+M\sin\omega t} \qquad (8)$$

The switches S_{A2} and S_{B2} are operated complementary to the switches S_{A1} and S_{B1} respectively. The duty cycles (1-D_A) and (1-D_B) of the switches S_{A2} and S_{B2} are given in equations (9) and (10) respectively.

$$1 - D_A = \frac{1}{2-M\sin\omega t} \qquad (9)$$

$$1 - D_B = \frac{1}{2+M\sin\omega t} \qquad (10)$$

Fig.3 shows the MSPWM technique and the switching pulses generated. The variation of the duty cycle D_A and D_B of the SZS inverter A and B respectively are given in Fig.4 for a modulation index of 1.

IV. Simulation Results

A 40 W two-phase SZS inverter giving an output sinusoidal voltage of 28 V is simulated in MATLAB/Simulink software. The input dc voltage is 40 V. A triangular carrier wave of 50 kHz switching frequency is used in the MSPWM. MOSFET switches are selected and the Z-source networks of the single-phase SZS inverters are designed as per the design details given in [2]. The capacitor and inductor in the Z-source networks are of value 4μF and 400μH respectively. A modulation index of 0.5 and load resistance of about 19 Ω is used in the simulation. The simulation results are shown in Fig.5. The SZS inverter operates as buck inverter for the

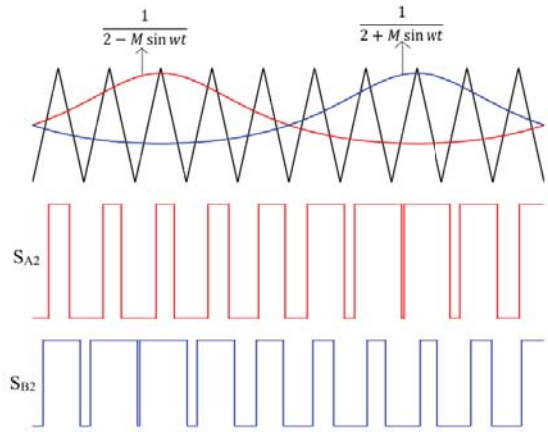

Fig.3.MSPWM Technique

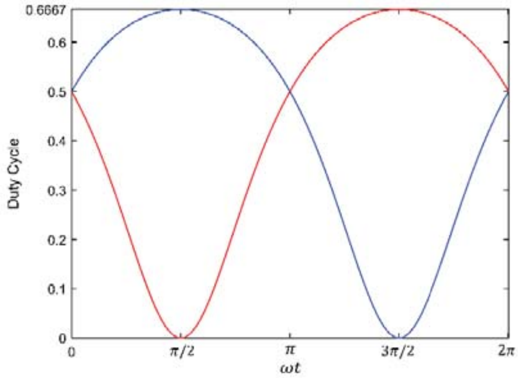

Fig.4. Variation of duty cycle D_A (red) and D_B (blue)

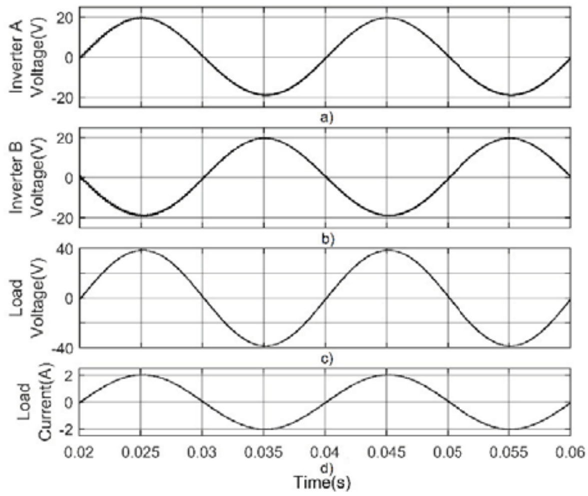

Fig.5 a) SZS inverter A output voltage b) SZS inverter B output voltage c) Two phase SZS inverter output voltage d) Output current

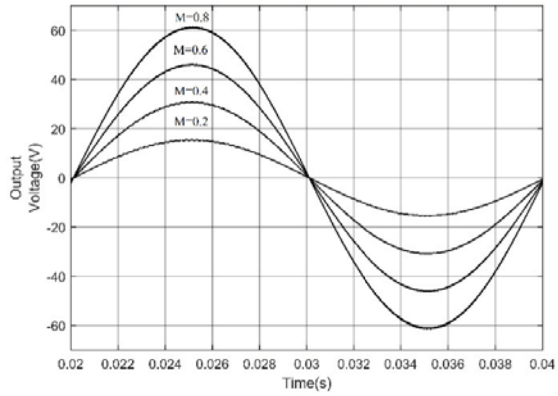

Fig.6. Buck-boost characteristics of two-phase SZS inverter

modulation index below 0.5 and as boost inverter for modulation index above 0.5 and is shown in Fig.6.

According to the wave shape of the reference voltage, the two-phase SZS inverter is capable of generating output voltage of any arbitrary shape as given in Fig.7. This merit of arbitrary wave shape generation allows the utilization of the two-phase SZS inverter in active filtering application. The two-phase SZS inverters can be utilized for supplying the harmonic compensating voltage waveforms in active filters.

Compared to the FB inverter, the two-phase SZS inverter utilizes four switches to give up to twice the FB inverter output for the given input dc voltage. The THD of the two-phase SZS inverter is less; hence it finds application in direct grid connection. The reduced size and reduction in switches with improved harmonic spectra of the output voltage makes SZS inverter superior to FB inverter.

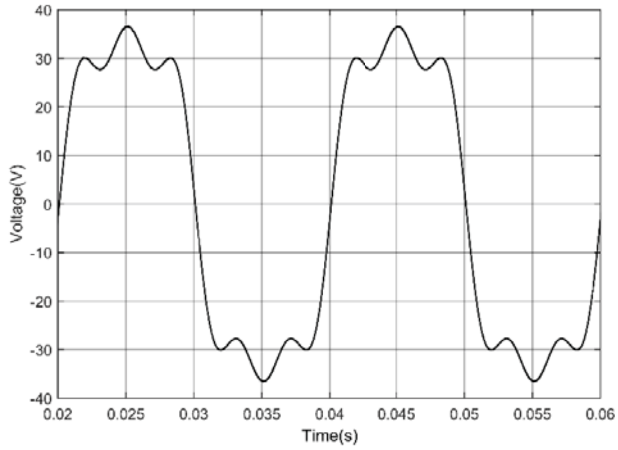

Fig.7. Arbitrary wave shape generation

V. Conclusion

In this paper, two-phase SZS inverter is discussed in detail. The two-phase SZS inverter is suitable for isolated and non-isolated grid integration of solar cells, fuel cells etc. With only four switches, the two-phase SZS inverter is capable of generating two times bigger output than the FB inverter for the given input dc voltage. There is no shoot-through condition as the switches are present in separate legs. A modified PWM is required for obtaining the output voltage of buck-boost nature from the two-phase SZS inverter.

Acknowledgment

This publication is an outcome of the R&D work undertaken project under the Visvesvaraya PhD Scheme of Ministry of Electronics & Information Technology, Government of India, being implemented by Digital India Corporation.

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