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An Improved Modulation Strategy for the Three-Phase Z-Source Inverters (ZSIs)

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***Abstract*—Z-source inverters (ZSIs), compared to the conventional two-stage architecture, embrace some interesting features, like the reduced size and complexity of the entire conversion system. Many research activities have been established to improve the performance of the so-called ZSI since it has been proposed in 2003, and several modifications have been introduced since then. These modifications include the structure of the ZSI, i.e. modifying the topology itself, and its modulation scheme as well. From the modulation perspective, the existing modulation strategies suffer from some demerits, such as the increased number of switch commutations at high current during the entire fundamental period and the utilization of extra reference signals. In this paper, an improved modulation strategy is proposed in order to enhance the performance of the three-phase ZSIs and the equivalent topologies. The proposed modulation strategy, which is called simple-boost modified space vector (SBMSV) modulation, reduces the number of switch commutations for shorter period during the fundamental cycle, simplifies the generation of the gate signals by utilizing only three reference signals, and achieves a single switch commutation at a time. This modulation strategy is analyzed and compared to the conventional equivalent modulation strategy, where a reduced-scale *1 kVA* three-phase ZSI is designed and simulated using MATLAB/PLECS models. Finally, the designed *1 kVA* three-phase ZSI is implemented experimentally in order to verify the proposed modulation strategy, the reported analysis, and the simulation results.**

***Index Terms*—Impedance source inverter, modulation, pulse width modulation (PWM), simple-boost, space vector modulation, Z-source inverter (ZSI).**

I. Introduction

Single-stage dc-ac power converters have undergone a fast evolution during the last few years in order to replace the conventional two-stage architecture, which includes a front-end dc-dc boost converter (BC) and an output voltage source inverter (VSI) [1]–[5]. This evolution has been initiated with the proposal of the three-phase Z-source inverter (ZSI), which is shown in Fig. 1, in order to improve the performance of the equivalent two-stage architecture [6]. Consequently, several research activities have been established on the ZSI in order to improve its performance from many perspectives, such as the overall gain, voltage stresses across the different devices, and continuity of the input current. Hence, many improvements and modifications have been adopted to the topology including its modulation, resulting in several topologies and modulation strategies. Most of these improvements and modifications are reviewed and compared in [1], [7], [8].

The three-phase ZSIs can be modulated using several modulation strategies, where the utilization of two additional reference signals in order to generate an additional switching state to the standard space vector (SV) states is the most common technique [6], [9]. This additional switching state, which is responsible for embracing the boosting capability within the inversion operation, is called shoot-through (ST) state and is generated by comparing those two additional reference signals with the carrier signal. During the ST state, all the six switches of the ZSI are turned ON simultaneously, where the B6-bridge is equivalent to a short circuit. On the other hand, these modulation strategies generate two ST pulses per switching cycle, resulting in an increased number of commutations, i.e. an increased effective switching frequency. Furthermore, these commutations happen during the entire fundamental cycle at one-third the ST current. On the other side, this high effective switching frequency is affecting only the dc side filter, i.e. is reducing the input impedance size, but it is not affecting the output ac filter side, as the ST pulses are inserted within the zero states. Hence, this paper proposes an improved modulation strategy for the three-phase ZSIs, which is called a simple-boost modified space vector (SBMSV) modulation strategy.

As a consequence of using this modulation strategy, several merits are gained as follows:

- effectively reduced number of switch commutations;
- single commutation at a time;
- constant ST duty cycle, i.e. no low frequency component at the input dc side;
- the B6-bridge switches are commutating at the ST current for shorter periods during the fundamental cycle;
- improved converter efficiency as a consequence of the reduced commutations;
- simpler generation of the gate signals due to the utilization of three reference signals only.

The rest of this paper is organized as follows: Section II reviews the operation and modulation of the ZSI, highlighting the seen demerits behind such modulation strategy. Then, the proposed SBMSV modulation strategy is introduced and analyzed in Section III. This improved modulation strategy and the conventional equivalent one are simulated in Section IV using MATLAB/PLECS models, where a 1 kVA ZSI is utilized as an example. The experimental results of the designed

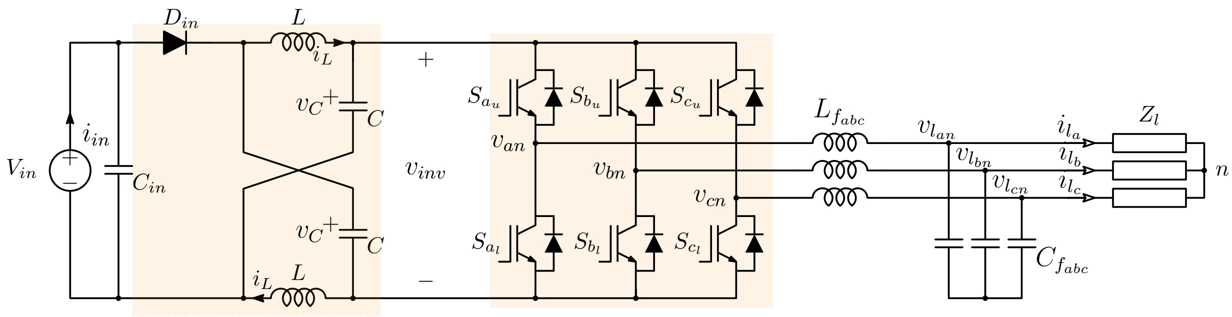


Fig. 1. Three-phase Z-source inverter (ZSI) with an output LC filter.

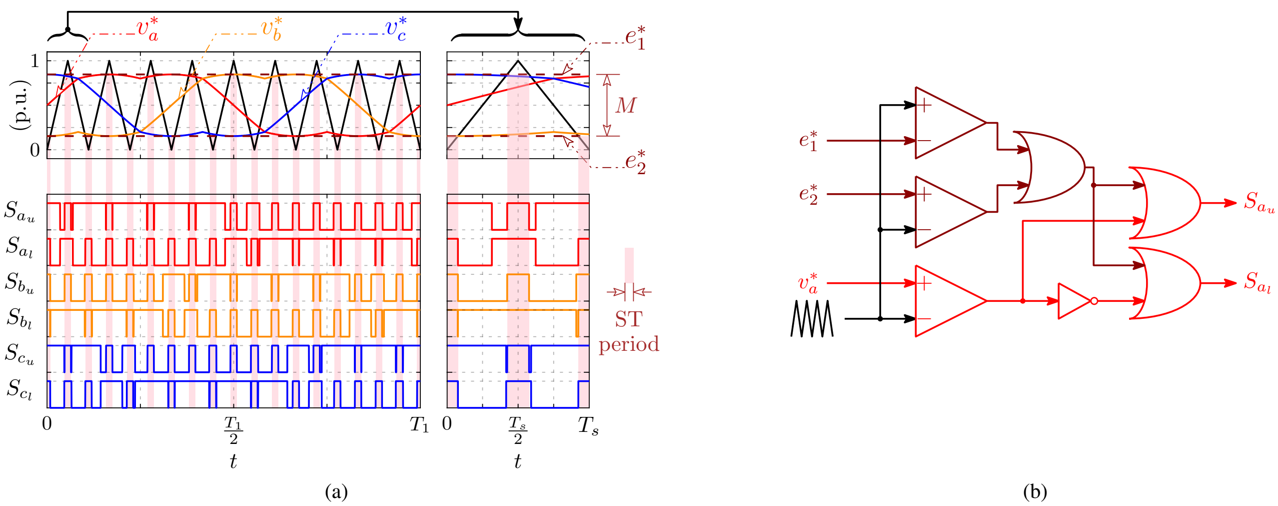


Fig. 2. Three-phase Z-source inverter (ZSI) conventional simple-boost space vector (SBSV) modulation strategy. (a) SBSV modulation strategy reference, carrier, and gate signals for one fundamental cycle, where the modulation index $M = 0.7$, the modulation-to-fundamental frequency ratio $M_f = 9$, T_1 is the fundamental period, and T_s is the switching period; (b) generation of S_{a_u} and S_{a_l} gate signals.

1 kVA ZSI using the proposed SBMSV and the conventional modulation strategies are introduced in Section V. Finally, the conclusion is drawn in Section VI.

II. Review of ZSI Operation and Modulation

The three-phase ZSI shown in Fig. 1 inserts an impedance network, that comprises two inductors, two capacitors, and a diode between the dc input source and the B6-bridge [6]. This combination allows the use of an additional switching state, called the ST state, in which all switches of the B6-bridge are turned ON simultaneously. This ST state or period is inserted inside the zero states, in order not to affect the active states and the output voltage consequently.

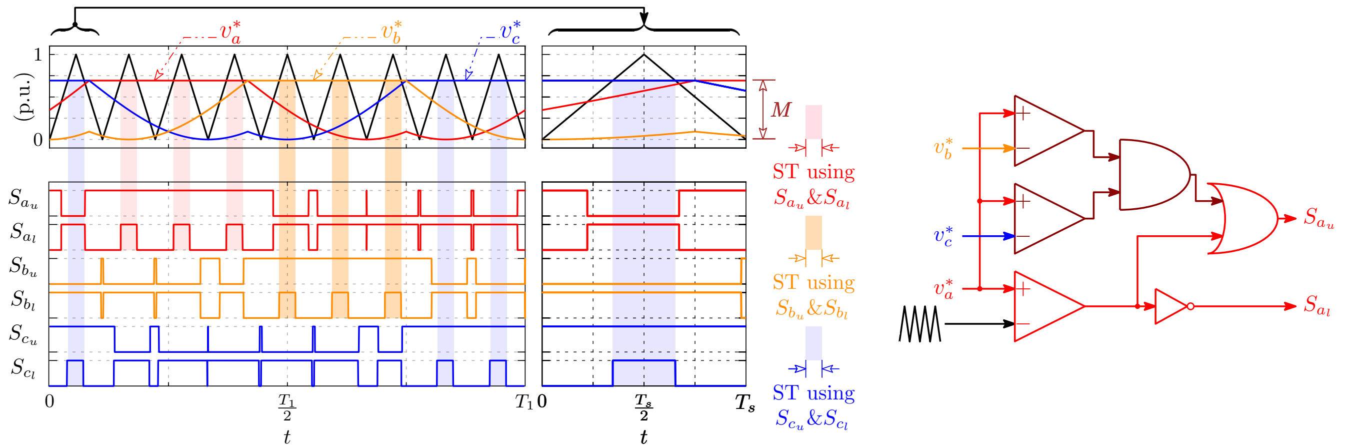
Depending on the method of inserting this ST state, the ZSIs modulation strategies are classified into two categories. The first one is the single-phase-leg ST-based category, in which the ST state is achieved via one phase-leg at a time, while the second one is the three-phase-leg ST-based category, in which the ST state is achieved via the three phase-legs simultaneously [8], [9]. The latter category is the commonly used one and it is classified into three sub-categories as follows:

1) simple-boost (SB) strategies [6], [8];
2) maximum-boost (MB) strategies [8], [10]; and
3) constant-boost (CB) strategies [8], [11],

where these modulation strategies use three standard reference signals (v_a^*, v_b^*, and v_c^*) of any modulation scheme used with the VSI, e.g. the space vector (SV) modulation, in addition to two more reference signals (e_1^* and e_2^*) to modulate the ZSI as shown in Fig. 2(a), considering the simple-boost space vector (SBSV) modulation strategy.

These additional reference signals, i.e. e_1^* and e_2^*, are used to generate the required ST pulses or states. Under this conventional SBSV modulation strategy, the ZSI is modulated in the conventional way like the VSI by comparing v_a^*, v_b^*, and v_c^* with the carrier signal to generate the required pulses for the switches. In addition to that, when the carrier signal is higher than e_1^* or lower than e_2^*, the ZSI goes to the ST state by turning ON all the switches simultaneously as shown in Fig. 2(b). This results in inserting the ST state in the zero states.

Note that using the single-phase-leg ST-based modulation strategies, six reference signals are utilized and the effective switching frequency of the B6-bridge is not affected by the ST state as in the three-phase-leg ST-based ones.



(a) (b)

Fig. 3. Proposed simple-boost modified space vector (SBMSV) modulation strategy. (a) reference, carrier, and gate signals for one fundamental period, where $M = 0.7$ and $M_f = 9$; (b) generation of S_{a_u} and S_{a_l} gate signals.

TABLE I
PARAMETERS OF THE DESIGNED *1-kVA* Z-SOURCE INVERTER (ZSI)

Input dc voltage (V_{in})	200 V
Fundamental output peak phase voltage (V_{φ_1})	$110\sqrt{2}$ V
Fundamental frequency (f_1)	50 Hz
Switching frequency (f_s)	50 kHz
Connected resistive load	36 Ω
Modulation index (M)	0.7951
Average dc-link voltage (V_{inv})	269.3 V
Peak dc-link voltage ($\hat{v}_{inv}$)	338.9 V
L_f	1 mH
C_f	4.7 μF
L	1.3 mH
C	500 μF

Meanwhile, the switches under this single-phase-leg ST-based modulation strategies category are commutating during the entire fundamental period with higher current, which is three times the three phase-legs ST case. Furthermore, due to the time variation of the active states, the impedance network is designed with an effective switching frequency of $2f_s$ as a worst case, but the input diode should be selected for a switching frequency of $6f_s$ [9].

III. Proposed Modulation Strategy

The prior art three-phase-leg ST-based modulation strategies generate two ST pulses per switching cycle, resulting in an increased number of commutations, i.e. an increased switching frequency. Furthermore, all the converter switches are continuously commutating at one-third the ST current during the entire fundamental period. According to Fig. 2(a), which shows the conventional SBSV modulation strategy, each switch is switched ON and OFF four times per switching cycle, resulting in an effective switching frequency of two times the actual one. Such increase in the switching frequency is affecting only the dc side filter, i.e. reducing the input impedance size, but not the output ac filter size, as the added ST pulses are inserted inside the zero states. In other words, the effective switching frequency for the dc side filter is equal to $2f_s$, while for the ac side filter it is equal to f_s.

It is worth to note that during the ST period, the three phase-legs are switched ON simultaneously, resulting in dividing the current equally among the three phase legs, which requires a properly designed gate drive circuit. Meanwhile, from a practical perspective, a delay for a fraction of μs in the gate signals might exist, resulting in having the ST state using one phase-leg for short periods. Hence, it is mandatory to design each switch to carry the highest possible current to protect the inverter, which is the ST current.

A. Principle of Operation

Due to the previous demerits, an improved modulation strategy is proposed in this paper, which is called SBMSV modulation strategy and it is illustrated in Fig. 3(a). The proposed SBMSV modulation strategy utilizes only three reference signals (v_a^*, v_b^*, and v_c^*) in order to modulate the ZSI. These reference signals are obtained by modifying the standard SV modulation reference signals to have a flat positive envelope [2].

Using the proposed SBMSV modulation strategy, the ZSIs are modulated in the traditional manner like the VSI by comparing v_a^*, v_b^*, and v_c^* with the carrier signal to generate the required gate signals. In addition to that, the ST states are obtained as follows: S_{a_u} is maintained ON when v_a^* is larger than v_b^* and v_c^*, S_{b_u} is maintained ON when v_b^* is larger than v_a^* and v_c^*, and finally S_{c_u} is maintained ON when v_c^* is larger than v_a^* and v_b^*. In other words, S_{a_u} is turned ON when v_a^* is larger than the carrier signal or larger than v_b^* and v_c^*, while S_{a_l} is turned ON when v_a^* is smaller than the carrier signal as depicted in Fig. 3(b).

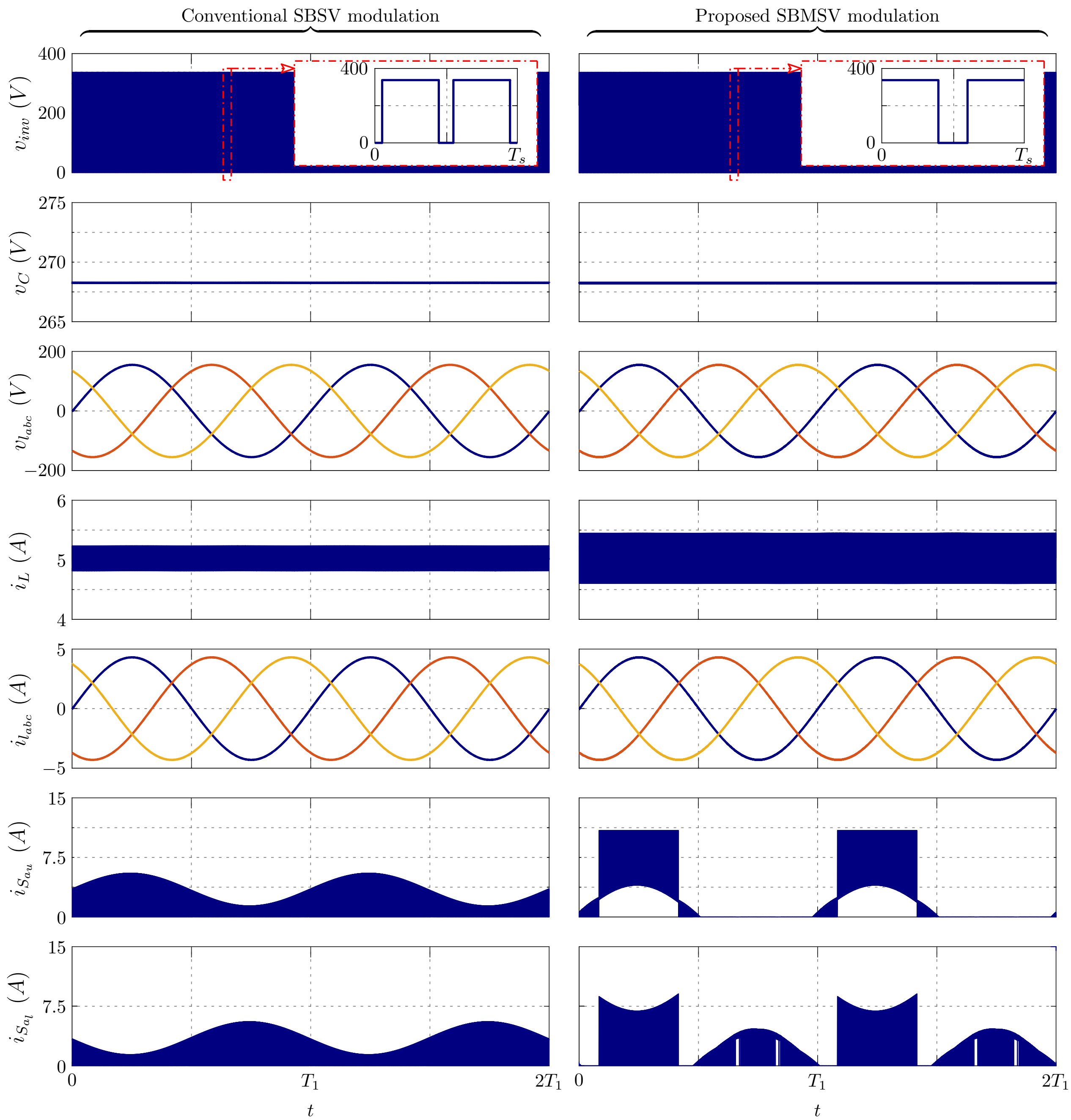


Fig. 4. Obtained simulation results of the 1 kVA ZSI using the conventional SBSV and the proposed SBMSV modulation strategies, where the the dc-link voltage (v_{inv}), the capacitor voltage (v_c), the load phase voltages ($v_{l_{abc}}$), the inductor current (i_L), the load phase currents ($i_{l_{abc}}$), the current in S_{a_u} ($i_{S_{a_u}}$), and the current in S_{a_l} ($i_{S_{a_l}}$) are shown from top to bottom.

It is worth noting that, as a consequence of using the proposed SBMSV modulation strategy, each switch of the upper switches (i.e. S_{a_u}, S_{b_u}, and S_{c_u}) is continuously conducting for one-third the fundamental period, resulting in less number of commutations. Furthermore, it is obvious that the ST state is achieved through one phase-leg at a time, where only one switch is commutating at the ST current each one-third of the fundamental period.

B. Mathematical Derivation

The mathematical derivation of the ZSI under the proposed SBMSV modulation strategy can be obtained using the same procedure followed in [6]. The ST duty cycle (D_0) is constant and it can be calculated as a function of the modulation index (M), which is defined in Fig. 3(a), by

$$D_0 = 1 - M. \tag{1}$$

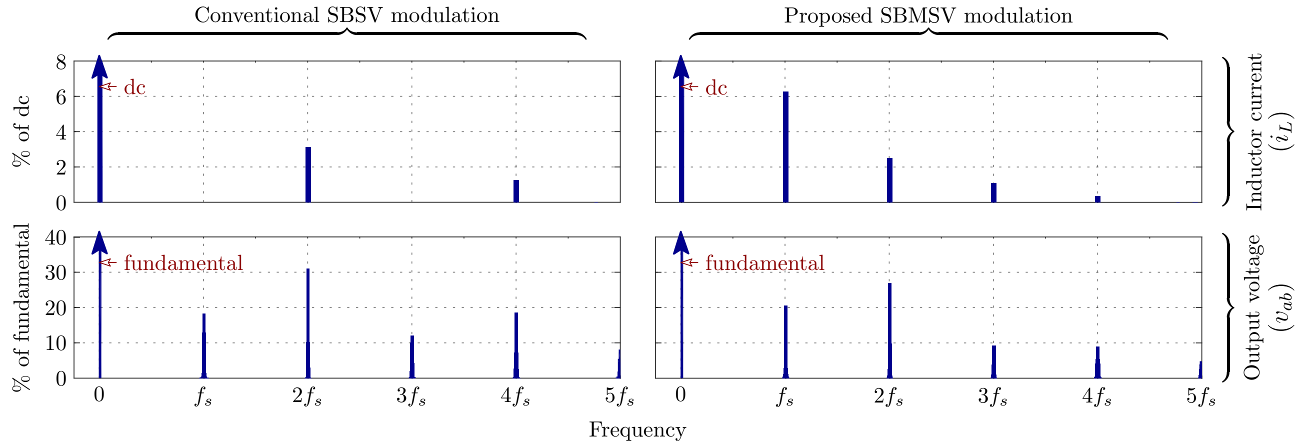


Fig. 5. Simulated spectrum of the inductor current (i_L) and the output line voltage (v_{ab}) of the three-phase ZSI under the conventional and the proposed modulation strategies using the parameters given in Table I.

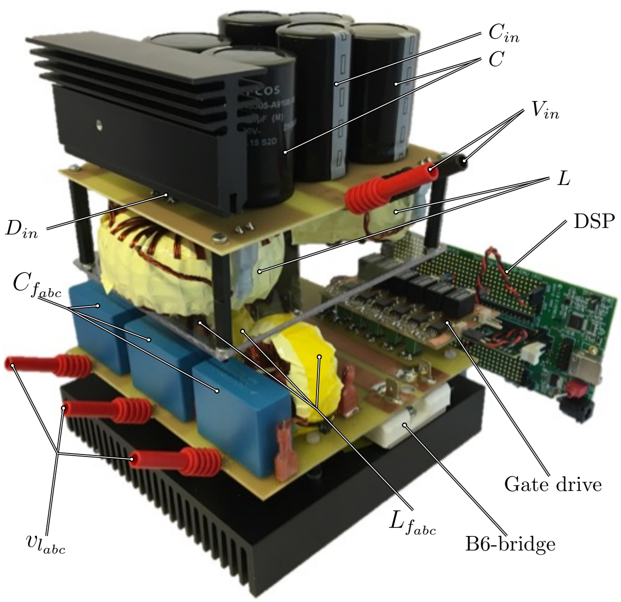


Fig. 6. Experimental prototype of the Z-source inverter (ZSI).

Then, due to the capacitor ampere-second and the inductor volt-second balances, the normalized average capacitor voltage (V_C/V_{in}) and the normalized average dc-link voltage (V_{inv}/V_{in}) are given by

$$\frac{V_C}{V_{in}} = \frac{V_{inv}}{V_{in}} = \frac{1-D_0}{1-2D_0} = \frac{M}{2M-1}, \tag{2}$$

while the normalized peak dc-link voltage ($\hat{v}_{inv}/V_{in}$) is given by

$$\frac{\hat{v}_{inv}}{V_{in}} = \frac{1}{1-2D_0} = \frac{1}{2M-1}. \tag{3}$$

The normalized fundamental output peak phase voltage (V_{φ_1}/V_{in}) can be calculated by

$$\frac{V_{\varphi_1}}{V_{in}} = M \cdot \frac{\hat{v}_{inv}}{\sqrt{3}V_{in}} = \frac{M}{2\sqrt{3}M-\sqrt{3}}. \tag{4}$$

Finally, the required inductance and capacitance can be calculated from

$$L = \frac{M \cdot (1-M) \cdot V_{in}}{(2M-1) \cdot f_s \cdot \Delta I_L}, \tag{5}$$

$$C = \frac{(1-M) \cdot I_{in}}{f_s \cdot \Delta V_C}, \tag{6}$$

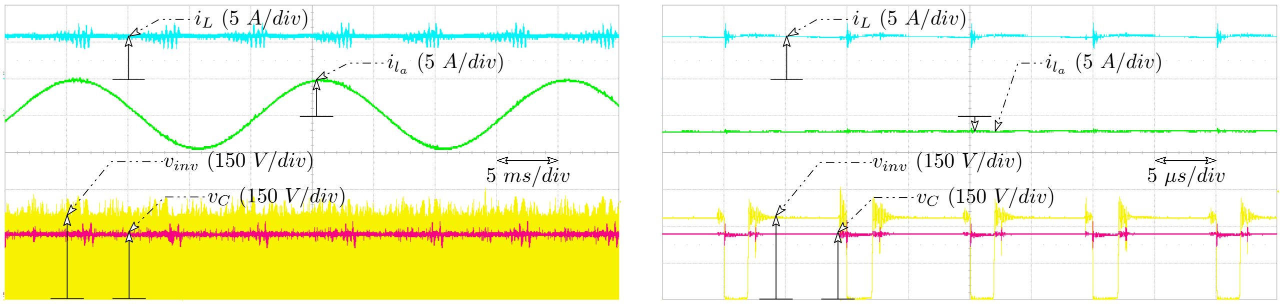
where f_s is the switching frequency, I_{in} is the average input dc current, and ΔI_L and ΔV_C are the peak-to-peak inductor current and capacitor voltage ripples respectively.

IV. Simulation Results

In order to examine the performance of the proposed modulation scheme and verify the reported analysis, a $1\ kVA$ ZSI is designed and simulated in this section. Table I introduces a summary of the designed parameters of the three-phase ZSI. Note that the values of the ZSI impedance network passive elements have been designed in order to have a peak-to-peak current ripple of 17% and to have a peak-to-peak voltage ripple of 0.015% of their average values.

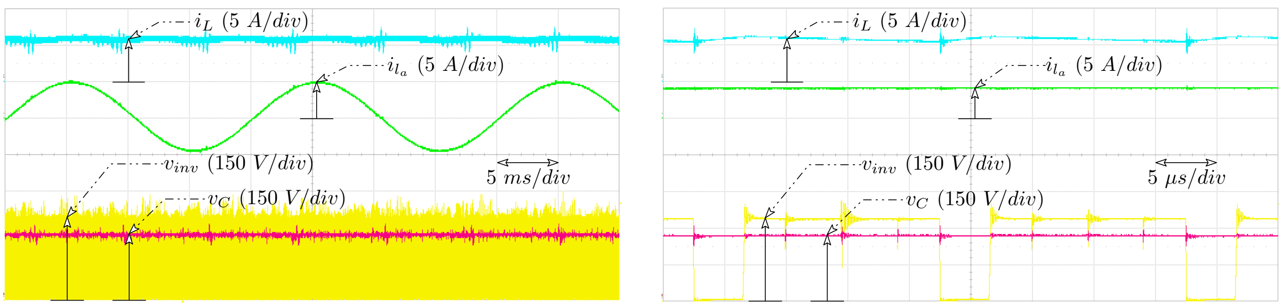
The obtained simulation results are reported in Fig. 4, in which the dc-link voltage (v_{inv}), the capacitor voltage (v_c), the load phase voltages ($v_{l_{abc}}$), the inductor current (i_L), the load phase currents ($i_{l_{abc}}$), the current in S_{a_u} ($i_{S_{a_u}}$), and the current in S_{a_l} ($i_{S_{a_l}}$) are shown using the conventional SBSV and the proposed SBMSV modulation strategies. These simulation results confirm the functionality of the proposed SBMSV modulation strategy and verifies the reported analysis. As it is shown in Fig. 4, the upper devices commutate for a partial time of the fundamental cycle under the proposed modulation strategy. This commutation happens with a frequency equal to f_s. On the other hand, the upper devices commutate during the entire fundamental cycle with a frequency equal to $2f_s$.

In order to highlight the main merits between the proposed modulation strategy and the conventional one, the spectrum of the inductor current (i_L) and the output line voltage (v_{ab}) are shown in Fig. 5 using both modulation strategies. Fig. 5 shows that the effective switching frequency for the dc side filter is equal to $2f_s$, while for the ac side filter is equal to f_s.



(a) (b)

Fig. 7. Experimental results of the Z-source inverter (ZSI) using the conventional SBSV modulation strategy, in which the dc-link voltage (v_{inv}), the capacitor voltage (v_C), the inductor current (i_L), and the load current (i_{l_a}) are shown, and (b) is zoom of (a).



(a) (b)

Fig. 8. Experimental results of the Z-source inverter (ZSI) using the proposed SBMSV modulation strategy, in which the dc-link voltage (v_{inv}), the capacitor voltage (v_C), the inductor current (i_L), and the load current (i_{l_a}) are shown, and (b) is zoom of (a).

V. Experimental Results

In order to validate the functionality of the proposed modulation strategy and verify the prior simulation results, an experimental prototype of 1 kVA three-phase ZSI has been implemented as shown in Fig. 6. The parameters of this prototype are the same as the parameters used in the simulation results, which have been summarized in Table I.

This prototype is tested first using the conventional SBSV and the obtained results are as shown in Fig. 7(a), in which the dc-link voltage (v_{inv}), the capacitor voltage (v_C), the inductor current (i_L), and the load current (i_{l_a}) are shown. Moreover, Fig. 7(b) shows a zoom of these results for four switching cycles. Then, the same prototype has been tested again using the proposed SBMSV modulation strategy and the same results, as introduced before, are shown in Fig. 8(a) and Fig. 8(b). These figures verify the functionality of the proposed modulation strategy. Furthermore, comparing between Fig. 7(b) and Fig. 8(b) confirms that the proposed modulation strategy uses one ST pulse per switching cycle, unlike the conventional modulation strategy, which uses two ST pulses per switching cycle.

Finally, the prototype efficiency has been measured at full-load using both modulation strategies, where the measured efficiency under the conventional SBSV modulation strategy is equal to 94%. Meanwhile, the measured efficiency under the proposed SBMSV modulation strategy is equal to 95.4%, which shows that the efficiency has been improved using the proposed modulation strategy.

VI. Conclusion

An improved modulation strategy, called simple-boost modified space vector (SBMSV) modulation strategy is proposed in this paper in order to enhance the performance of the three-phase Z-source inverters (ZSIs). It has been seen that the conventional modulation strategies make the ZSI to suffer from several demerits, such as a high number of commutations, high effective switching frequency with no effect on reducing the output filter size, and complicated generation of the firing signals due to the utilization of several reference signals. On the other hand, the proposed modulation strategy benefits from the following merits: single ST pulse per switching cycle, constant ST duty cycle during the fundamental period, less number of switch commutations, and the improved converter efficiency.

The proposed SBMSV modulation strategy has been analyzed and simulated using MATLAB/PLECS model, where 1 kVA ZSI has been designed and utilized. Furthermore, it has been compared to the conventional equivalent modulation strategy. Finally, experimental results have been introduced for the proposed and the conventional modulation strategies, showing higher efficiency under the proposed modulation strategy.

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