Overview of Space Vector Modulations for Three-Phase Z-Source/Quasi-Z-Source Inverters

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***Abstract*—Three existing and one extended space vector modulations (SVMs) for the three-phase Z-source/quasi-Z-source inverter (ZSI/qZSI) are investigated. The different switching control patterns, the available maximum shoot-through duty ratio, the maximum voltage stress across the switch versus voltage gain, and efficiency are compared in detail. A total average switch device power taking into account the shoot-through current stress is proposed to evaluate the total stress of power switches. Simulation and experimental results of the prototyped qZSI verify the theoretical analysis. The six parts of shoot-through time intervals will reduce the inductor current ripples, and improve the qZSI efficiency. Also, the maximum voltage stress and total average switch power will benefit from the shoot-through division. However, the division method impacts these performances of qZSI.**

***Index Terms*—Power conversion, space vector modulation, Z-source/quasi-Z-source inverters.**

I. Introduction

The three-phase Z-source/quasi-Z-source inverters (ZSI/qZSI) have been increasingly gaining attraction for many years to achieve the power conversion [1], [2] due to the excellent ability to handle the wide voltage variations of dc sources in a single-stage topology. The ZSI/qZSI couples an impedance network, consisting of two inductors and two capacitors, between the dc source and the inverter. A shoot-through zero state is inserted into the inverter's switches to boost the dc input voltages up to a higher voltage level. When the input voltage is high enough to provide the desired ac voltage, the ZSI/qZSI operates as the traditional voltage source inverters (VSIs). Compared with the dc–dc boost circuitry based two-stage inverter, the ZSI/qZSI efficiency can increase and also save the cost. Moreover, the inverter reliability is highly improved since a short circuit of bridge legs no longer destroys the inverter. To date, various studies of ZSI/qZSI focus on: 1) the modeling and switching pattern control [3]–[13]; 2) the applications, such as photovoltaic power conversion, electric and fuel cell vehicles, excitation field driver [14]–[19]; and 3) the extended topologies such as Z-source matrix converters, trans-Z-source inverters, etc. [20]–[23]. Anyway, the shoot-through zero states are essential to make the ZSI/qZSI operate properly at the boost mode.

Up to date, several types of switching control have been proposed to achieve wide modulation range, simple implementation, and low voltage stress on the switches [7]–[13]. Three SPWMs including simple boost control (SBC) [1], maximum boost control [7], and maximum constant boost control [8] were compared in [12], as a result the maximum boost control presents the highest voltage gain. Whereas, the maximum boost control utilizes all possible traditional zero states to achieve the shoot-through states, which causes the variable shoot-through time intervals, so the low-frequency ripple components are produced in the capacitor voltage and inductor current. The maximum constant boost control is more popular because it elaborates the upper and lower shoot-through envelopes to keep the constant shoot-through duty ratio and to achieve the maximum boost factor. However, the drawbacks of high switching frequency and additional switching losses are still inevitable for the three SPWMs.

As the superiority of low current harmonics and high voltage utilization, the traditional space-vector concept has been modified to be applicable for the ZSI/qZSI in [9]–[11]. The two switches' control signals of the same bridge leg are no longer complementary, even though the traditional SVM does. The shoot-through states are inserted at the beginning or the end of active vector's switching moment to avoid the additional switching actions and losses. There are three different existing ways to distribute the shoot-through states: 1) the desired total shoot-through time interval is divided into six parts evenly distributed into six switching times [9]. The six switching times are modified, so called as ZSVM6 in this paper. 2) the divided six-part shoot-through time intervals are also fulfilled in each control cycle, but the four switching times are only modified in [10], so called as ZSVM4 here. 3) The desired total shoot-through time interval is divided into four realizable parts, but two switching times are modified in [11], so called as ZSVM2. The voltage gain, voltage stress across the switch, and ac harmonic

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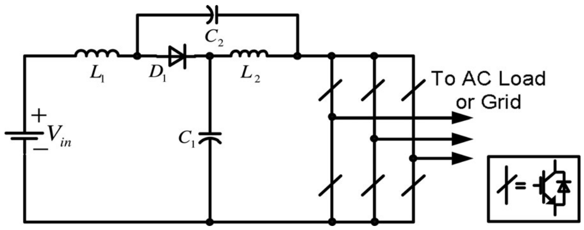


Fig. 1. qZSI topology.

content of the three aforementioned SPWMs and the ZSVM4 are compared in [13], but it does not consider the switch current stress. The total switching device power (SDP) was presented to evaluate both the voltage and current stresses in [18]. However, the deduced formula are not suitable for the aforementioned ZSVMx ($x = 6$, 4, and 2), because they have different current stress and voltage stress when compared to those in [18].

The aim of this paper is to present an overview of SVMs for three-phase ZSI/qZSI and compare their boost capacity, voltage stress, efficiency, etc., especially to propose the SDP for the aforementioned ZSVMx ($x = 6$, 4, and 2). The paper is organized as follows. The qZSI operation is illustrated in Section II, and the different ZSVMs are addressed in Section III. The total average SDP is proposed in Section IV. Simulation and experiment are carried out in Section V. Finally, Section VI concludes this study. In the following description, the qZSI is used for illustration. All PWMs can be applied to the ZSI.

Symbol list is as follows:

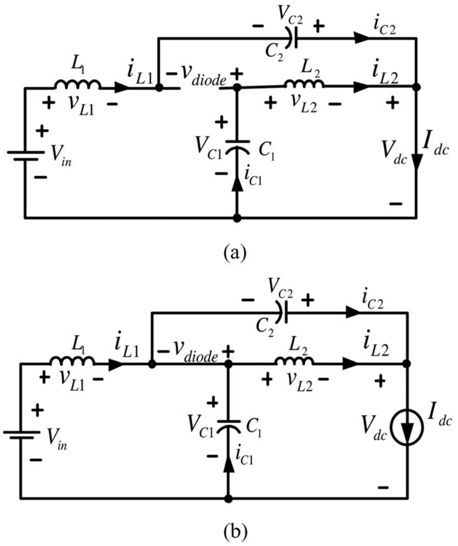
$V_{\rm in}$	DC source voltage.
$v_{\rm dc}$	DC-link peak voltage.
$I_{\rm dc}$	DC-side current of inverter.
$P_{\rm out}$	AC output power.
$\cos\varphi$	AC load power factor.
$V_{\rm ac}, v_{\rm ac}$	AC phase-to-neutral RMS and peak voltage.
$I_{\rm ac}, i_{\rm ac}$	AC RMS and peak current.
D	Shoot-through duty ratio.
M	Modulation index.
B	Boost factor.
G	Voltage gain.

II. qZSI PRINCIPLE

Figs. 1 and 2 show the topology and equivalent circuits of the basic qZSI, respectively. As shown in Fig. 2, the qZSI has two working states. One is the shoot-through state in Fig. 2(a), where at least one bridge leg turns on. The other is the nonshoot-through state in Fig. 2(b), and the qZSI operates as a traditional VSI. The shoot-through state alternates with the nonshoot-through state by using the partial or entire conventional zero states to boost the dc source voltage

$$\begin{cases} V_{C1} = \dfrac{1-D}{1-2D}V_{\rm in} \\ V_{C2} = \dfrac{D}{1-2D}V_{\rm in} \end{cases} \tag{1}$$

$$I_{L1} = I_{L2} = \frac{1-D}{1-2D}I_{\rm dc} \tag{2}$$



(a)

(b)

Fig. 2. Equivalent circuits of qZSI in (a) shoot-through state and (b) nonshoot-through state.

$$v_{\rm dc} = \frac{1}{1-2D}V_{\rm in} = BV_{\rm in} \tag{3}$$

$$v_{\rm ac} = M \cdot B \cdot \frac{V_{\rm in}}{2} \tag{4}$$

$$B = \frac{1}{1-2D} \tag{5}$$

$$G = M \cdot B \tag{6}$$

where V_{C1} and V_{C2} are the average voltages of capacitors C_1 and C_2, I_{L1} and I_{L2} are the average currents of inductors L_1 and L_2, D is the shoot-through duty ratio, $D = T_{\rm sh}/T_s$; $T_{\rm sh}$ is the total shoot-through time interval, T_s is the control cycle.

III. SVMs FOR qZSI

A. Traditional SVM

As shown in Fig. 3(a), the traditional SVM technique for three-phase VSIs generates eight voltage space vectors, and there are six sectors I, II, III, . . ., VI. The well-known algorithm can be defined as [24]

$$\begin{cases} T_1 = T_s M \sin\left[\dfrac{\pi}{3} - \theta + \dfrac{\pi}{3}(i-1)\right] \\ T_2 = T_s M \sin\left[\theta - \dfrac{\pi}{3}(i-1)\right] \\ T_0 = T_s - T_1 - T_2 \end{cases} \tag{7}$$

$$U_{\rm ref} = U_1 \frac{T_1}{T_s} + U_2 \frac{T_2}{T_s} \tag{8}$$

where $i \in \{1, 2, \ldots, 6\}$ denotes the ith sector; T_0 is the time interval of traditional zero vector U_0; T_1 and T_2 are the time intervals of active vectors U_1 and U_2, respectively; θ is the inclined angle of voltage reference vector $U_{\rm ref}$ and U_1. The modulation index M is defined as $M = \sqrt{3}U_{\rm ref}/V_{\rm dc}$, and $V_{\rm dc}$ is the dc-link voltage.

Fig. 3(b) shows the three-phase VSI switching time sequence in the sector I, where $T_{\rm max}, T_{\rm mid}$, and $T_{\rm min}$ are the maximum,