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Maximum Boost Space Vector Pulse-Width Modulation Strategy of Z-Source Inverters

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Abstract

In this paper, maximum boost space vector pulse-width modulation(MBSVPWM) strategy of Z-Source Inverters(ZSIs) is proposed. Conventional space vector pulse-width modulation(SVPWM) method of Voltage Source Inverters(VSIs) is modified to produce unique PWM patterns that realize the maximum boost control of ZSIs. This proposed method minimizes the switching power losses of ZSIs by reducing the numbers of the shoot-through states. Moreover, some switches keep ON state and the switching transitions do not occur during the specific sectors. An experimental system has been built and tested to verify the effectiveness of the proposed strategy.

Key words: Z Source Inverter, SVPWM, Maximum Boost, Switching Losses, Shoot-through states

I. Introduction

Z-source inverters (ZSIs) have advantages of inherent buck-boost characteristics with single stage topology; no worries about short circuits of the inverter legs, better EMI characteristics, and reliabilities. Figure 1 shows the basic structure of a ZSI. As described in [1], the peak inverter input dc voltage($\hat{V}_{inv}$) and the inverter output ac voltage($\hat{v}_{ac}$) can be expressed as

$$\hat{V}_{inv} = 2V_c - V_{dc} = \frac{1}{1-2D_{sh}} V_{dc} = BV_{dc} \tag{1}$$

$$\hat{v}_{ac} = M\frac{\hat{V}_{inv}}{2} = BM\frac{V_{dc}}{2} = \frac{1-D_{sh}}{1-2D_{sh}}\frac{V_{dc}}{2} = G\frac{V_{dc}}{2} \tag{2}$$

where, shoot-through duty ratio is defined as $D_{sh} = T_{sh}/T_s$, T_s, T_{sh} are the switching period and the shoot-through time interval.

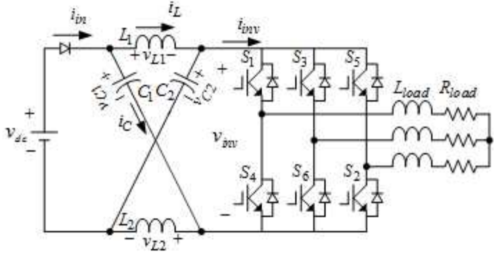

Fig.1 Basic structure of a ZSI

Therefore, ZSI can produce ac output voltage that is greater than the available dc bus voltage. Shoot-through states are inserted within the zero states of the conventional PWM patterns without deteriorating the AC output voltage waveform.

Many conventional PWM methods of VSI have been modified and implemented to ZSI. In [1], a simple PWM control method of ZSI has been

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presented and the basic principles of ZSI have been analyzed. In [2], a maximum boost control of ZSI has been proposed which utilize all zero states of VSI as shoot through states. This method has the advantages of minimum voltage stresses of the IGBTs and high voltage gains. In [3], a maximum constant boost control of ZSI has been proposed to minimize inductor current ripple.

Space vector PWM (SVPWM) has been widely used for the conventional VSI because it has a pretty good performance in utilizing a DC voltage and low current harmonics and it can be easily realized in digital implementation known as digital scalar PWM (DSPWM) or Hybrid PWM [4]. Due to the benefits of SVPWM, there have been a lot of researches to modify SVPWM and implement it to the ZSI [5]. Regardless of the PWM methods, the shoot-through states should be inserted within the zero states of the conventional PWM patterns by short-circuiting at least one phase leg of the inverter simultaneously. The switching power loss reduction in inverters is one of the most important aspects regardless of the PWM strategies and hence lots of research has been reported to decrease the switching power losses [6],[7]. However, there has been no thorough research reported for the ZSI switching power loss reduction.

In this paper, the currents of the ZSI switches during turn-on and turn-off transitions are analyzed in detail with the relation of the switching patterns. Based on the analysis, a maximum boost SVPWM strategy of ZSI is proposed to minimize the switching power losses. An experimental system has been built to test, and the power losses are measured under the variations of the voltage gain (G). The experimental results verify the effectiveness of the proposed maximum boost SVPWM strategy.

Ⅱ. Analysis of Space Vector PWM for the Z-Source Inverter

In the previous researches, conventional SVPWM of VSI is modified and implemented to the ZSI. Figure 2 illustrates how to modify the modulating voltage references of the conventional SVPWM for the ZSI in sector Ⅰ. The voltage references of the conventional SVPWM of VSI are modified to produce the PWM patterns with shoot-through states for the ZSI based on the following equations.

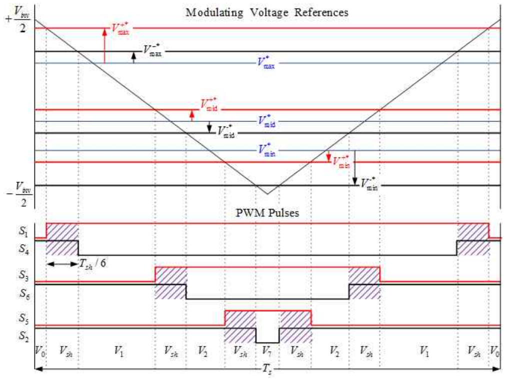


Fig. 2 Modified voltage references and PWM pulses of Z-source inverter in sector Ⅰ.

$$\begin{cases} V_{\max}^{+*} = V_{\max}^{*} + \dfrac{T_{sh}}{2T_s}\hat{V}_{inv} \\ V_{\max}^{-*} = V_{\max}^{*} + \dfrac{T_{sh}}{6T_s}\hat{V}_{inv} \end{cases} \quad \begin{cases} V_{mid}^{+*} = V_{mid}^{*} + \dfrac{T_{sh}}{6T_s}\hat{V}_{inv} \\ V_{mid}^{-*} = V_{mid}^{*} - \dfrac{T_{sh}}{6T_s}\hat{V}_{inv} \end{cases}$$

$$\begin{cases} V_{\min}^{+*} = V_{\min}^{*} - \dfrac{T_{sh}}{6T_s}\hat{V}_{inv} \\ V_{\min}^{-*} = V_{\min}^{*} - \dfrac{T_{sh}}{6T_s}\hat{V}_{inv} \end{cases} \tag{3}$$

where, $\hat{V}_{inv}$ is the peak voltage of the Z-source inverter input, $V_{\max,\,mid,\,\min}^{+*}$, $V_{\max,\,mid,\,\min}^{-*}$ are the modified voltage references for the upper and the lower switches in the Z-source inverter and $V_{\max,\,mid,\,\min}^{*}$ are the voltage references of the conventional SVPWM, respectively.

In this previous SVPWM for the ZSI, the shoot-through state intervals are divided equally into six parts and inserted between the state transitions of the conventional SVPWM.

The switching power losses of the conventional VSI with continuous PWM are a function of switching frequency, voltage, and current [6],[7].

$$P_{sw} = \frac{1}{2\pi}\frac{V_{dc}(t_{on}+t_{off})}{2T_s}\int_0^{2\pi} f_i(\theta)d\theta \tag{4}$$

where t_{on}, t_{off} are the turn-on and turn-off times of the switches, V_{dc} is the voltage across the inverter bridge and $f_i(\theta)$ is a switching current function which is usually a sinusoidal waveform in the conventional VSI.

However, for the ZSI, there are unique shoot-through states which make it possible to boost the DC input voltage. In addition, the inverter switch currents must carry the Z-network currents during the shoot-through states. Therefore, the switching current function is not sinusoidal in the ZSI. Instead, it depends on the Z-network currents and the switching state transitions.

The state transitions of the SVPWM in the sector Ⅰ are as follows: $V_0 \to V_{sh} \to V_1 \to V_{sh} \to V_2 \to V_{sh} \to V_7$ (during the half of the switching period). The turn-on and turn-off transitions are occurred only at the shoot-through states, hence, every switches has one transition per every half switching period. By analyzing the equivalent circuit of ZSI for the each state, the variations of the switching current during transitions with the previous SVPWM are obtained as the table Ⅰ. As shown in Table Ⅰ, the variations of the switching current in the ZSI are larger than those in the conventional VSI which results increased switching power losses.

Table Ⅰ. The variations of the switching current during transitions with the previous SVPWM of ZSI

Sector		Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ
phase A	Δi_{s1}	$2i_L$	$2i_L - i_b$	$2i_L + i_a$	$2i_L + i_a$	$2i_L - i_c$	$2i_L$
	Δi_{s4}	$2i_L - i_a$	$2i_L + i_c$	$2i_L$	$2i_L$	$2i_L + i_b$	$2i_L - i_a$
phase B	Δi_{s3}	$2i_L - i_a$	$2i_L$	$2i_L$	$2i_L - i_c$	$2i_L + i_b$	$2i_L + i_b$
	Δi_{s6}	$2i_L + i_c$	$2i_L - i_b$	$2i_L - i_b$	$2i_L + i_a$	$2i_L$	$2i_L$
phase C	Δi_{s5}	$2i_L + i_c$	$2i_L + i_c$	$2i_L - i_b$	$2i_L$	$2i_L$	$2i_L - i_a$
	Δi_{s2}	$2i_L$	$2i_L$	$2i_L + i_a$	$2i_L - i_c$	$2i_L - i_c$	$2i_L + i_b$

Assuming that the input power and output power are equal, the inductor current is derived as

$$i_L = \frac{3}{4}\frac{M}{\sqrt{3}M-1}\hat{I}_{ac}\cos\phi \tag{5}$$

where M is modulation index and $\hat{I}_{ac}$ is peak inverter output phase current.

Ⅲ. Proposed Maximum Boost SVPWM of a ZSI

Feng proposed a maximum boost control of ZSI which utilize all zero states of VSI as shoot through states [2]. This method has the advantages of minimum voltage stresses of the IGBTs and high voltage gains. However, this strategy is an analogous method and all the switches on the three inverter legs made short circuit during the shoot-through states. As mentioned before, the currents flowing through the inverter switches during the shoot-through states are larger than the phase currents which results increased switching power losses. To reduce the switching losses in a ZSI, the total number of shoot-through switching actions should be reduced keeping the same shoot-through duty ratio. In this paper, maximum boost SVPWM strategy is proposed which has good performance of SVPWM and reduced switching power losses. Figure 3 illustrates the modulating voltage references and PWM pulses of the proposed maximum boost SVPWM(MBSVPWM).

New modulating voltage references for the proposed MBSVPWM are produced easily, based on the following equations to create PWM pulses.

$$\begin{cases} V_{\max}^{+*} = 1/2\,\hat{V}_{inv} \\ V_{\max}^{-*} = V_{\max}^{*} \end{cases} \quad \begin{cases} V_{mid}^{+*} = V_{mid}^{*} \\ V_{mid}^{-*} = V_{mid}^{*} \end{cases} \quad \begin{cases} V_{\min}^{+*} = V_{\min}^{*} \\ V_{\min}^{-*} = -1/2\,\hat{V}_{inv} \end{cases} \tag{6}$$

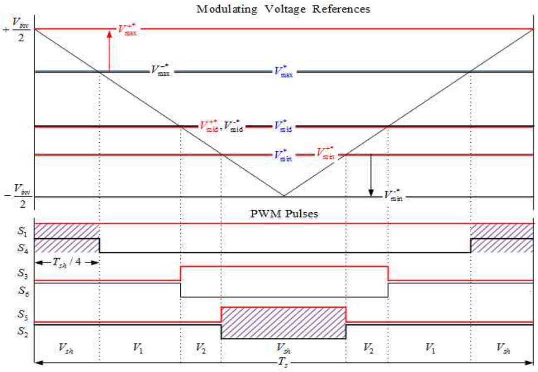


Fig. 3 Modulating voltage references and PWM pulses for the proposed MBSVPWM

In the proposed MBSVPWM strategy, the shoot-through states are inserted only two times within the single switching period. In addition, the upper switch for the maximum modulating reference and the lower switch for the minimum modulating reference keep ON state during the corresponding sectors. Table Ⅱ is obtained which shows the variations of the switching current during turn-on and turn-off transitions with the proposed MBSVPWM.

Table Ⅱ. The variations of the switching current during transitions with the proposed MBSVPWM

Sector		Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ
phase A	Δi_{s1}	0	i_a	$2i_L+i_a$	$2i_L+i_a$	i_a	0
	Δi_{s4}	$2i_L-i_a$	i_a	0	0	i_a	$2i_L-i_a$
phase B	Δi_{s3}	i_b	0	0	i_b	$2i_L+i_b$	$2i_L+i_b$
	Δi_{s6}	i_b	$2i_L-i_b$	$2i_L-i_b$	i_b	0	0
phase C	Δi_{s5}	$2i_L+i_c$	$2i_L+i_c$	i_c	0	0	i_c
	Δi_{s2}	0	0	i_c	$2i_L-i_c$	$2i_L-i_c$	i_c

Figure 4 shows the variations of the switching current for each PWM strategy during the whole electrical cycle. The variations of the switching current of the proposed MBSVPWM are smaller than those of the previous SVPWM and the integrations of them are directly proportional to the switching power losses. Thus, the total switching power losses can be reduced.

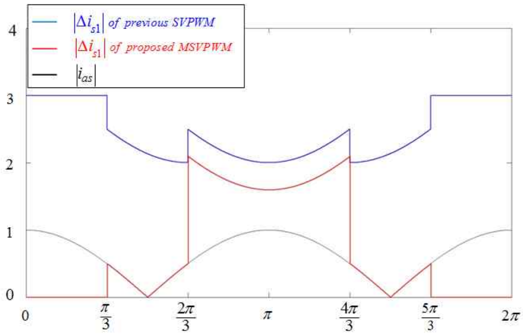


Fig. 4 The variations of the switching current for each PWM during whole electrical cycle.

Ⅳ. Experimental Results

Experimental system shown in Fig. 5 has been built and tested to verify the effectiveness of the proposed PWM strategy. The ZSI structure shown in figure 1 is constructed with the following parameters. The inductances of Z network(L_1, L_2) are 2mH and the capacitors(C_1, C_2) are 470uF. The 3 Phase RL loads(R_{load} 9.5Ω, L_{load} 4mH) are connected to the output of the ZSI. And the DC input voltage of the ZSI has been set to 20V. The ZSI has been operated at 10kHz switching frequency with the variation of voltage gain G. The proposed and the previous PWM strategy for the ZSI have been realized with the TI DSP (TMS320F28335) control board. The total efficiency of the ZSI has been measured with the power analyzer (YOKOGAWA WT500).

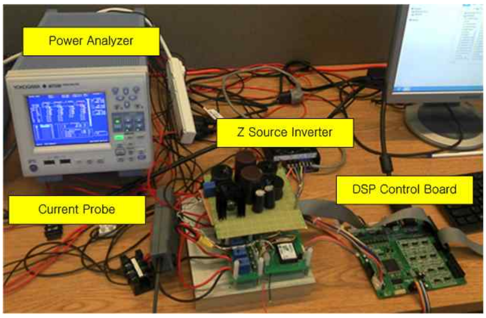
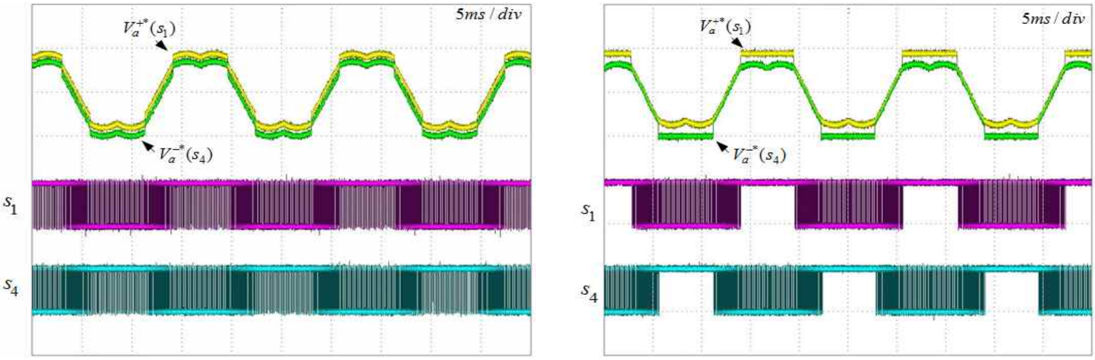


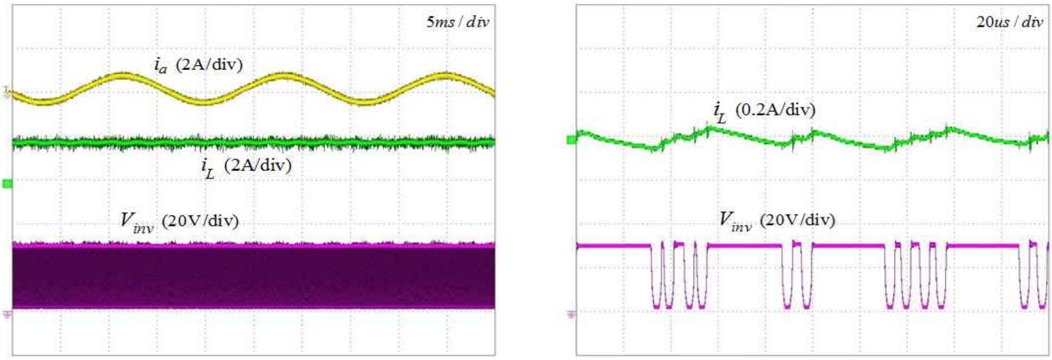
Fig. 5 Experimental Systems

Figure 6 illustrates the modulating voltage references of phase A and the gate signals of the each PWM strategy. In the proposed strategy, the switching transitions on the switches do not occur during the specific sectors. However, in the previous strategy, all of the switches make transitions during the whole cycle. Figure 7 and 8 represent the waveform of the phase current, Z-Source inductor current and the inverter input voltage for both PWM strategies when the voltage gain G is 1.5. Both strategies show almost the same results except the shoot-through state times.



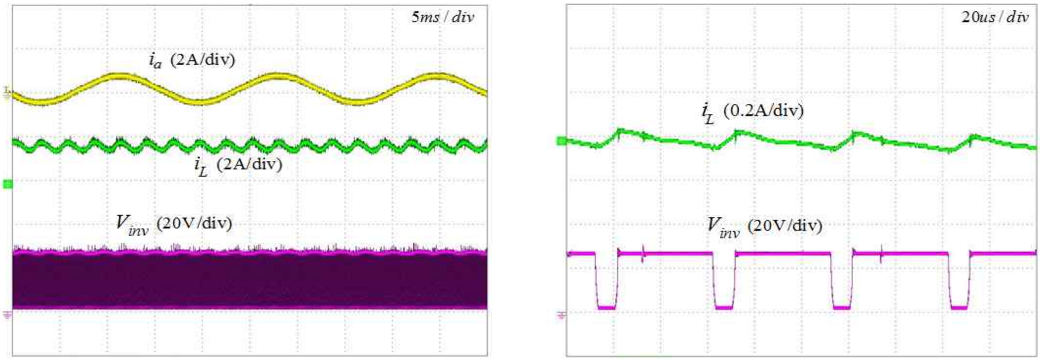
(a) previous SVPWM strategy (b) proposed MBSVPWM strategy

Fig. 6 Modulating voltage references and PWM pulses



(a) 5ms scale waveforms (b) magnified waveforms (20μs/div)

Fig. 7 Waveforms of the ZSI with previous SVPWM strategy when G is 1.5



(a) 5ms scale waveforms (b) magnified waveforms (20μs/div)

Fig. 8 Waveforms of the ZSI with proposed MBSVPWM strategy when G is 1.5

In the proposed strategy, the shoot-through states occur only two times during the single switching period compared to the six times of the previous strategy. As a result, the proposed strategy has lower switching losses than the previous one.

The total power losses have been measured with the various voltage gains. The resultant experimental data are presented in Fig. 9.

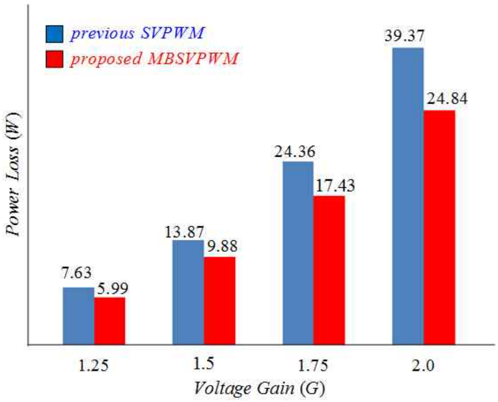


Fig. 9 Total power losses of the ZSI

For all of the voltage gains, the power losses of the proposed strategy are smaller than those of the previous one while keeping the same voltage boosting operation and the same output inverter current. From the experimental results, it is well verified that the proposed approach can minimize the switching losses of the ZSI.

Ⅴ. Conclusion

In this paper, a maximum boost SVPWM strategy to minimize the switching losses for a ZSI has been proposed. In the proposed MBSVPWM strategy, the total numbers of the shoot-through transition are reduced while keeping the same voltage boosting function and the same output inverter current. In addition, with the proposed approach, the upper and lower switches of the ZSI do not make transitions in the specific sectors. The experimental results verified that the proposed MBSVPWM strategy can minimize the switching losses of the ZSI.

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