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Research Paper / Makale

Performance Analysis of Z-Source Inverter Control Techniques

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Abstract: This study presents the different control techniques of the Z-Source inverter (ZSI) and compares them for the same modulation index. Different from the traditional inverters, in ZSI circuit configurations simple boost, maximum boost, and maximum constant boost control techniques can be utilized to perform DC-AC voltage conversion with shoot-through states. The operation principles of the control techniques are explained in detail. The shoot-through duty ratio, the boost factor, and the voltage gain for each control technique of the ZSI are calculated using the related equations. The ZSI circuit model and the simulations of the DC-link and the AC output voltage are performed in Matlab/Simulink environment. According to the related equations used in the different control techniques and the obtained simulation results, the maximum boost control technique has the highest boost factor and voltage gain for a determined modulation index. For that reason, the maximum boost control technique offers the greatest equivalent DC-link voltage and AC output voltage under the same conditions. This control technique can be employed for inverter applications where the highest gain is required.

Keywords: Z-Source inverter, control, shoot-through duty ratio, boost factor, voltage gain

Z-Kaynak İnverter Kontrol Tekniklerinin Performans Analizi

Öz: Bu çalışma, Z-Kaynak inverter (ZSI) devresi için kullanılan farklı kontrol tekniklerini aynı modülasyon indeksi altında karşılaştırmalı olarak incelemektedir. Geleneksel inverterlerden farklı olarak ZSI devrelerinde DC-AC güç dönüşümünde; kısa devre ilaveli basit yükseltici, maksimum yükseltici ve maksimum sabit yükseltici kontrol teknikleri kullanılmaktadır. Kontrol tekniklerinin çalışma prensipleri detaylı olarak anlatılmıştır. ZSI için her bir kontrol tekniğinde kısa devre görev oranı, yükseltme faktörü ve gerilim kazancı ilgili denklemler kullanılarak hesaplanmıştır. ZSI devre modeli ile DC-hat gerilimi ve AC çıkış gerilimlerinin benzetim çalışmaları Matlab/Simulink ortamında gerçekleştirilmiştir. Farklı kontrol tekniklerinde kullanılan ilgili denklemlere ve elde edilen benzetim sonuçlarına göre, maksimum yükseltici kontrol tekniği belirli bir modülasyon indeksi için en fazla yükseltme faktörüne ve gerilim kazancına sahiptir. Bu nedenle, maksimum yükseltici kontrol tekniği aynı şartlar altında en büyük eşdeğer DC-hat gerilimi ve AC çıkış gerilimi sağlamaktadır. Bu kontrol tekniği en yüksek kazancın ihtiyaç duyulduğu inverter uygulamaları için kullanılabilir.

Anahtar Kelimeler: Z-Kaynak inverter, kontrol, kısa devre görev oranı, yükseltme faktörü, gerilim kazancı

1. Introduction

In recent years, renewable energy sources are gaining significant importance around the world because of the rising demand for electric energy, increased environmental concerns, and finite fossil fuel resources [1]. The most widely used renewable energy sources such as wind and solar power have a wide range of output voltage depending on the environmental factors. Therefore, an additional step-up transformer or DC-DC boost converter is frequently required for traditional inverter applications in power electronics [2,3].

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The top and bottom switches of the phase legs in a traditional inverter circuit cannot be driven at the same time which is called shoot-through operation. Due to the electromagnetic interference (EMI), the shoot-through state may occur during commutation which can destroy the DC power supply and the switches [4-6].

To overcome the drawbacks of the traditional inverter circuit, Z-Source inverter (ZSI) is introduced which is a new topology with buck-boost characteristics and single-stage conversion [7,8]. Unlike the traditional inverter, ZSI can be employed as a buck-boost converter circuit in different applications due to its particular impedance network [9].

As can be seen in Figure 1, the unique network of ZSI is composed of two inductors and capacitors forming an X shape that connects the DC power supply to the inverter bridge. In comparison to the traditional three-phase inverter which has six active states and two zero states, ZSI has nine switching states including the shoot-through state for S_1, S_2, S_3, S_4, S_5, and S_6 [10].

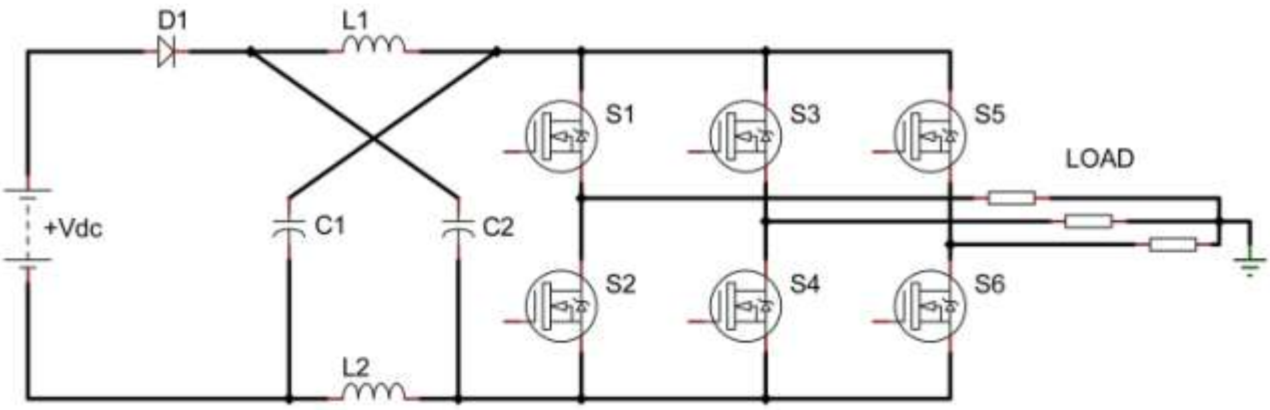

Figure 1. ZSI main circuit structure.

For the commutation of the switches in ZSI, there are several different control strategies based on PWM techniques. Simple boost control, maximum boost control, and maximum constant boost control are widely used carrier-based PWM techniques for ZSI [11-15].

In this study, the performance comparison of the three control techniques of ZSI is investigated. Under the same DC power supply and modulation index; the ZSI circuit parameters are calculated and compared for each control technique.

2. ZSI Control Techniques

In ZSI during a switching cycle T, the shoot-through duty ratio D can be written as $T_0/(T_1+T_0)$ where T_0 is the shoot-through time and T_1 is the non-shoot-through time. The boost factor B of ZSI can be expressed as

$$B = \frac{1}{1-\left(2*\frac{T_0}{T}\right)} = \frac{1}{1-2D} \tag{1}$$

$$V_{PN} = B * V_{dc} \tag{2}$$

$$G = M * B \tag{3}$$

$$V_{ac} = M * B * \frac{V_{dc}}{2} \tag{4}$$

The DC-link voltage V_{PN}, voltage gain G, and output peak phase voltage V_{ac} of a three-phase ZSI can be written as below where V_{dc} is DC input voltage and M is the modulation index of the ZSI.

2.1. Simple Boost Control

Simple boost control (SBC) is the first introduced technique to drive the switches in ZSI. As shown in Figure 2, there are three reference signals, one carrier signal, and two straight envelope signals. When the amplitude of the carrier signal is greater than the envelope signals, ZSI is changed to a shoot-through state. Otherwise, the circuit behaves like a traditional carrier-based PWM inverter [16]. The available shoot-through duty ratio reduces when the modulation index is increased for this technique. The corresponding equations of SBC technique are as follows.

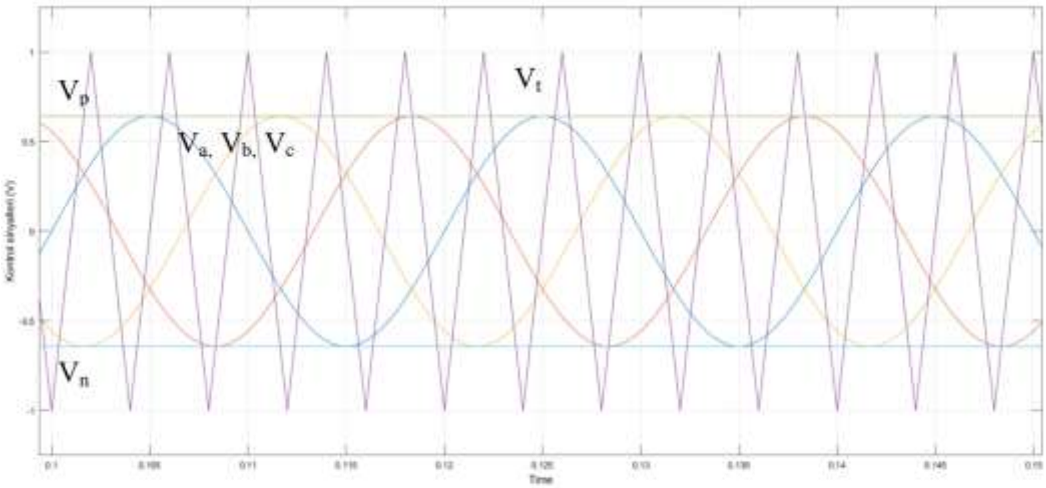

Figure 2. SBC technique waveforms.

$$D = 1 - M \tag{5}$$

$$B = \frac{1}{2M - 1} \tag{6}$$

$$G = \frac{B + 1}{2} \tag{7}$$

2.2. Maximum Boost Control

The six active states are not affected by the maximum boost control (MBC), and all zero states become shoot-through state. As given in Figure 3, when the amplitude of the carrier signal is either greater than or smaller than the maximum value of the reference signals, ZSI is changed to a shoot-through state [17]. The corresponding equations of MBC technique are as follows.

$$D = \frac{2\pi - 3\sqrt{3}M}{2\pi} \tag{8}$$

$$B = \frac{\pi}{3\sqrt{3}M - \pi} \tag{9}$$

$$G = \frac{\pi(B + 1)}{3\sqrt{3}} \tag{10}$$

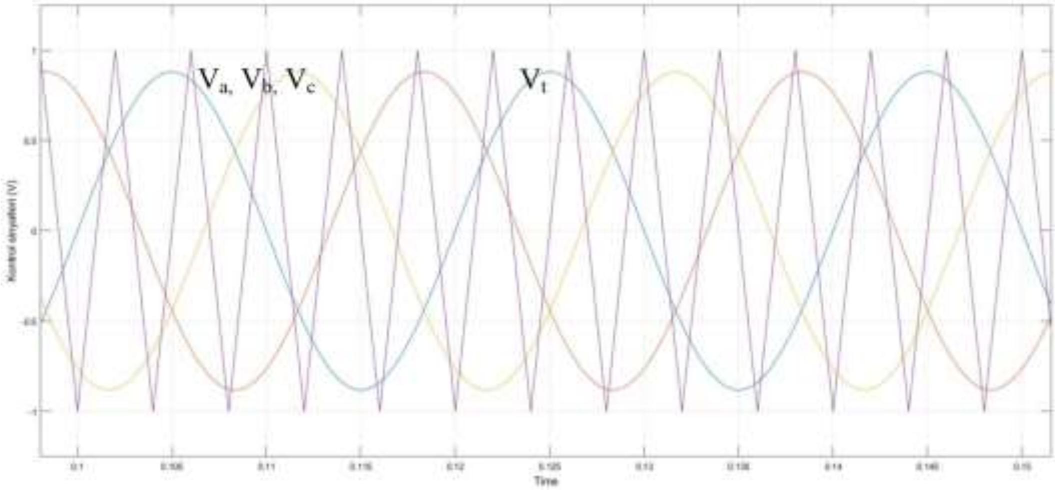

Figure 3. MBC technique waveforms.

2.3. Maximum Constant Boost Control

The main difference of the maximum constant boost control (MCBC) from the previous two techniques is the obtaining of the high voltage gain while maintaining a constant shoot-through duty ratio. As demonstrated in Figure 4, the ZSI is switched to a shoot-through state when the amplitude of the carrier signal exceeds the upper or bottom shoot-through envelope curves. The upper and bottom envelope signals are three times the output frequency of the fundamental and are periodical [18]. The corresponding equations of MCBC technique are as follows.

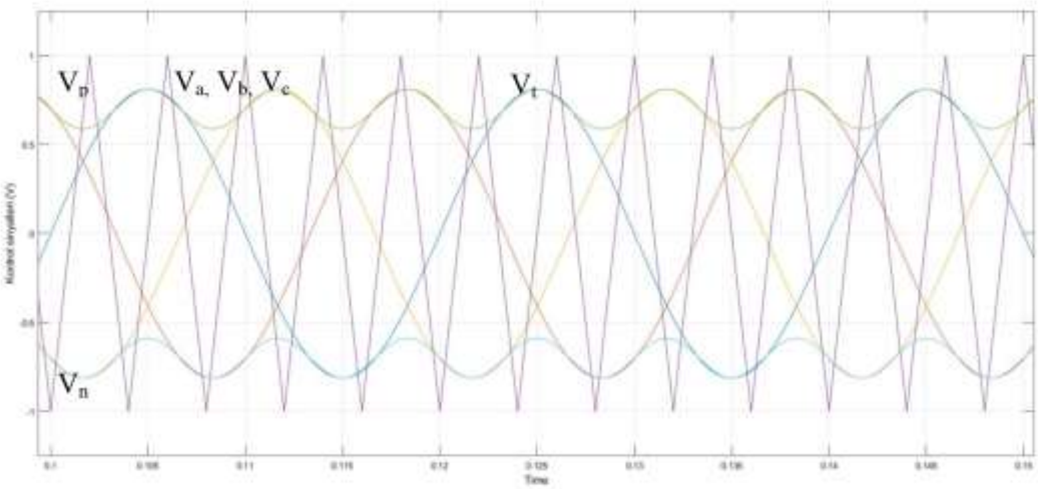

Figure 4. MCBC technique waveforms.

$$D = \frac{2-\sqrt{3}M}{2} \tag{11}$$

$$B = \frac{1}{\sqrt{3}M-1} \tag{12}$$

$$G = \frac{B+1}{\sqrt{3}} \tag{13}$$

3. Results and Discussion

The performance of the ZSI control techniques has been compared for a determined modulation index. Under the modulation index M=0.8; the shoot-through duty ratio, the boost factor, and the voltage gain are calculated using the related equations. DC-link and AC output voltage waveforms are illustrated using Matlab/Simulink to verify the theoretical analysis.

The ZSI circuit parameters of the simulation model are: DC input voltage is V_{dc}=150V, the ZSI network inductor and capacitor are L_1=L_2=500uH, C_1=C_2=1000uF, the fundamental frequency is f_1=50Hz, the switching frequency is f_s=10kHz, the filter inductor and capacitor are L_f=1mH, C_f=10uF, and the resistive load R_L=10Ω.

Using the corresponding equations of SBC with M=0.8, the shoot-through duty ratio, the boost factor, and the voltage gain are calculated as given below:

$$D = 1 - M = 0.2 \tag{14}$$

$$B = \frac{1}{2M - 1} = 1.66 \tag{15}$$

$$G = \frac{B + 1}{2} = 1.33 \tag{16}$$

In Figure 5 the DC-link and AC output voltage waveforms are shown. It can be noted that V_{PN} and V_{ac} are equal to 249V and 100V respectively.

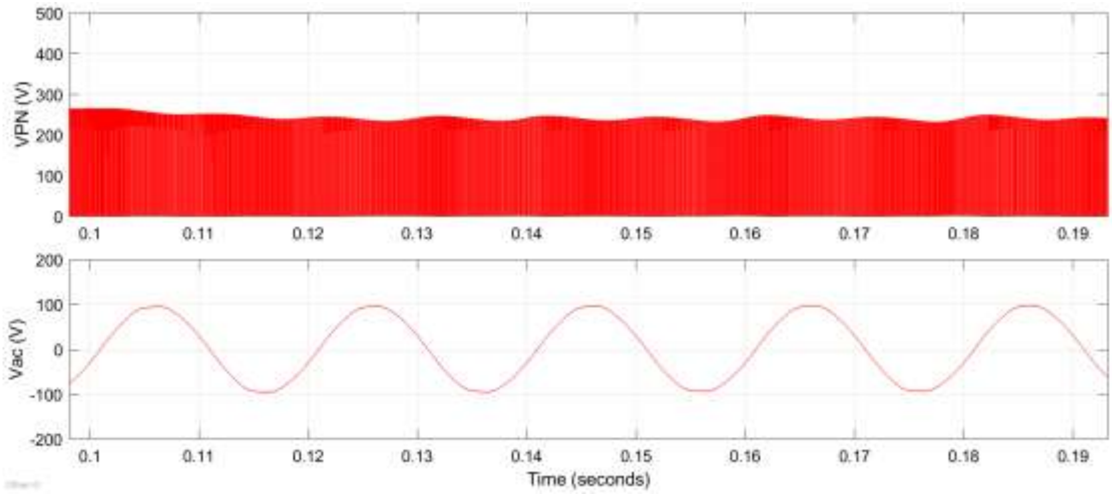

Figure 5. V_{PN} and V_{ac} for SBC.

For MBC with M=0.8, the shoot-through duty ratio, the boost factor, and the voltage gain are calculated as given below:

$$D = \frac{2\pi - 3\sqrt{3}M}{2\pi} = 0.34 \tag{17}$$

$$B = \frac{\pi}{3\sqrt{3}M - \pi} = 3.09 \tag{18}$$

$$G = \frac{\pi(B+1)}{3\sqrt{3}} = 2.47 \tag{19}$$

In Figure 6 the DC-link and AC output voltage waveforms are shown. It can be noted that V_{PN} and V_{ac} are equal to 463V and 185V respectively.

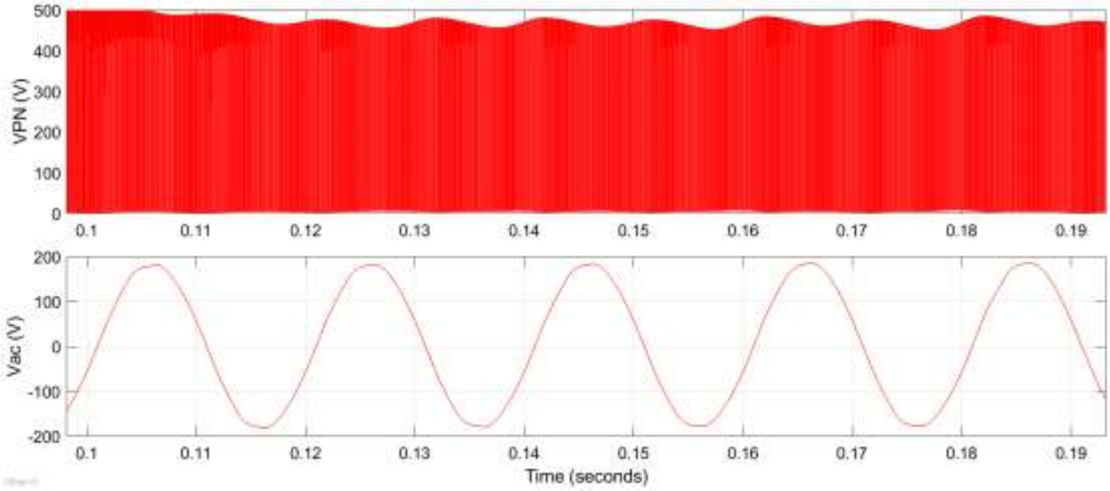

Figure 6. V_{PN} and V_{ac} for MBC.

Using the corresponding equations of MCBC with M=0.8, the shoot-through duty ratio, the boost factor, and the voltage gain are calculated as given below:

$$D = \frac{2-\sqrt{3}M}{2} = 0.3 \tag{20}$$

$$B = \frac{1}{\sqrt{3}M-1} = 2.59 \tag{21}$$

$$G = \frac{B+1}{\sqrt{3}} = 2.07 \tag{22}$$

In Figure 7 the DC-link and AC output voltage waveforms are shown. It can be noted that V_{PN} and V_{ac} are equal to 388V and 155V respectively.

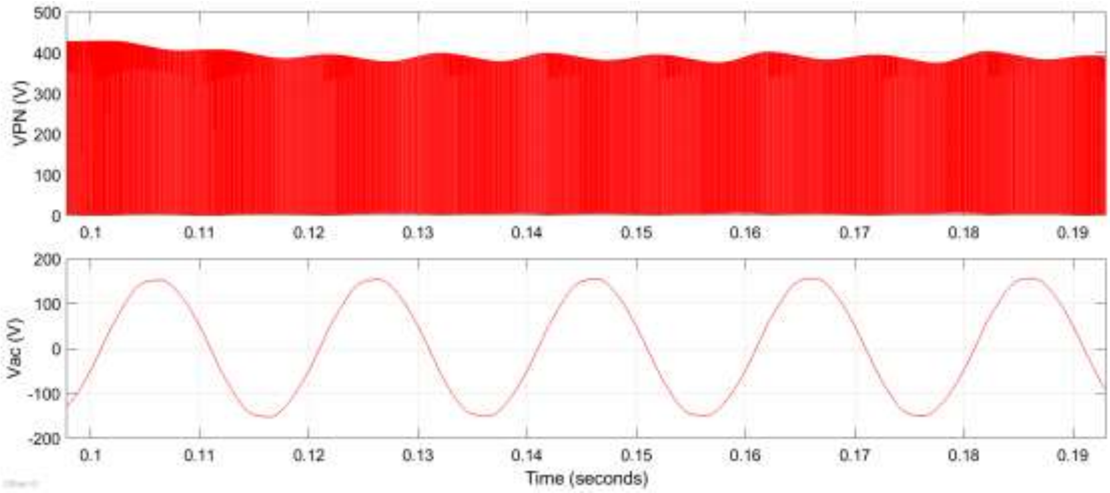

Figure 7. V_{PN} and V_{ac} for MCBC.

In Figure 8 is plotted the boost factor versus the modulation index for each control technique. As can be seen clearly, MBC technique has the greatest boost factor at a given modulation index than the other two control techniques. Depending on the decrease of the modulation index, the boost factor differences of the ZSI control techniques increase significantly.

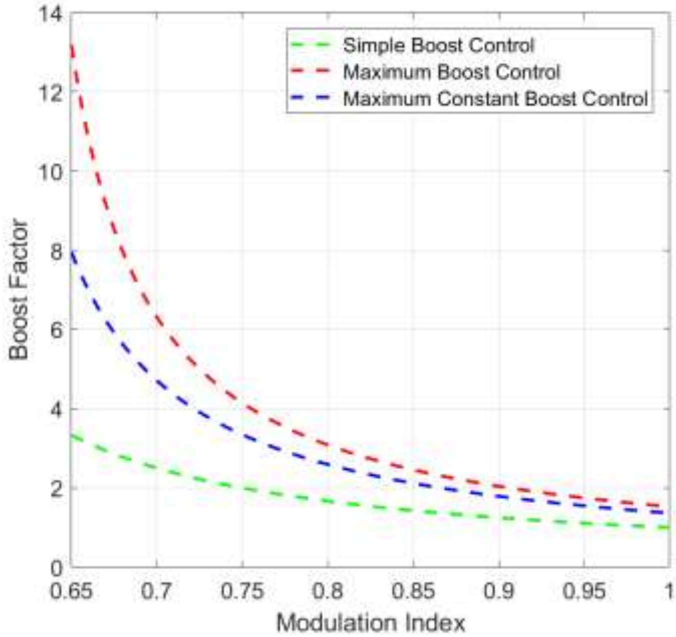

Figure 8. Boost factor comparison of different control techniques.

SBC technique has a limited shoot-through duty ratio and voltage gain. A small modulation index must be utilized to generate an output voltage with a higher gain. Therefore this technique cannot be used to get higher gain with a small shoot-through duty ratio.

MBC technique has the greatest boost factor and voltage gain compared to the other control techniques. Therefore to get a maximum voltage gain, this technique can be employed in ZSIs. The only drawback of this technique is the periodic variation of the shoot-through state and accordingly the increase in inductance size to overcome the low-frequency ripples.

MCBC technique has a much higher boost factor and voltage gain than the simple boost control but slightly lower than the maximum boost control. The main difference of this technique is to get a higher voltage gain with a constant shoot-through state due to the upper and lower envelope signals.

Table 1. Comparison of the ZSI control techniques.

Control Techniques (M=0.8 V_{DC}=150V)	**D**	**B**	**G**	$\mathbf{V_{PN}}$	$\mathbf{V_{ac}}$
SBC	0.2	1.66	1.33	249V	100V
MBC	0.34	3.09	2.47	463V	185V
MCBC	0.3	2.59	2.07	388V	155V

4. Conclusions

In this paper, the performance comparison of the ZSI control techniques is examined under the same conditions. For the same modulation index; the shoot-through duty ratio, the boost factor, and the voltage gain are calculated using the related equations. DC-link and AC output voltage waveforms are shown to verify the theoretical analysis. Compared to the other control techniques, MBC technique can be employed for ZSI applications where the highest voltage gain with a smaller shoot-through duty ratio is required.

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Authors' Contributions

MSE and RA conceived of the presented idea. MSE performed the computations and carried out of the simulations according to the circuit parameters. MSE wrote the manuscript with support from RA. MSE and RA discussed and contributed to the interpretation of the results. Both authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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