A Modified Quasi-Z-Source Inverter with Enhanced Performance Capability

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Abstract- This paper proposes a modified single phase quasi-Z-source inverter (qZSI) with enhanced performance capability. The total harmonic distortion (THD) values of output voltage and current are reduced differently using the unipolar pulse width modulation (PWM) technique. In addition, the voltage gain ability of the circuit is improved with the help of an additional boost switch connected in parallel with the impedance network and power MOSFETs. The employment of the unipolar PWM technique adapted for the qZSI is explained and the operating principle of the proposed circuit with the additional boost switch is described using mathematical expressions. Simulations are carried out to show the effectiveness of the circuit for a determined modulation index using Matlab/Simulink environment. Compared with the classical qZSI topologies, the presented circuit has lower THD and increased voltage gain.

Keywords Unipolar PWM, THD reduction, boost switch, voltage gain, qZSI.

1. Introduction

Nowadays power inverters play a significant role in many areas such as AC motor control, uninterruptible power supplies, variable speed drives and renewable energy sources. Based on the type of input source and operation principle, power inverters can be classified as voltage source inverter (VSI) and current source inverter (CSI) [1]. VSI operates simply in buck mode by switching an input voltage source. The power switches of the same leg cannot be on-state at the same time. Unlike in VSI, CSI operates only in boost mode by switching an input current source. Similarly in a CSI, the power switches of the same leg cannot be off-state at one time. Moreover, VSI and CSI have some further drawbacks such as two-stage power conversion, vulnerability to the effect of electromagnetic interference (EMI) and dead time interval between the turn-off of one power MOSFET and the turn-on of the other power MOSFET of the same leg to prevent the short circuit state [2].

In order to overcome the mentioned drawbacks, in [3] a unique Z-Source inverter (ZSI) topology was presented. The ZSI has a certain impedance network comprised of two identical capacitors and inductors placed between input source and power MOSFETs to get buck-boost capability. In ZSI topology, power MOSFETs of the same leg can be triggered at the same time which eliminates dead time interval. Thus, the circuit is kept clean of EMI effect and the stability is increased. Since the short-circuit operation in power MOSFETs in ZSI is allowed to have the buck-boost process, the need of power transformer or DC-DC converter is eliminated as demonstrated in [3]. Despite the ZSI has come out as a cost-efficient topology, the quasi-Z-Source inverter (qZSI) topology was introduced in [4] with a slight changes in the impedance network that keeps all the advantages of the ZSI and eliminates main drawbacks such as discontinuous constant DC current from the input source and higher component ratings. The qZSI topology can draw continuous constant DC current from the DC power source due to the inductor located at the input of the circuit and has much lower component ratings in the impedance network.

Compared to the ZSI topology, the qZSI has become more effective and widely preferred as a result of its advanced features considering renewable power generation systems. Additionally, this topology is well adapted for photovoltaic (PV) systems for the purpose of stable and regular output voltage since the PV power mainly depends on the solar radiation and outside temperature [4].

There are many presented pulse width modulation (PWM) techniques for ZSI/qZSI to develop the boosting ability, to minimize the component ratings and to maintain lower total harmonic distortion (THD). The sinusoidal pulse width modulation (SPWM) based techniques are simple boost modulation (SBM), maximum boost modulation (MBM) and maximum constant boost modulation (MCBM) respectively. SBM was the first presented modulation technique employed in the ZSI [3, 4]. The main drawbacks were the limited shoot-through duty ratio and higher voltages on power switches. In [5], MBM technique was presented to increase the voltage gain for any given modulation index. Although there is an increase in voltage gain, a low-frequency current ripples on the inductors of the ZSI network occurs which affects the inductance size. To deal with this issue, MCMB was proposed in [6] to keep a constant shoot-through duty ratio. Main challenge of the MCMB is the low usage rate of DC bus voltage as in SBM and MBM. In [7], a comprehensive and systematic review study for the future development of the high performance ZSI/qZSI circuits was presented. A new kind of voltage fed inverter [8] called switched-inductor qZSI (SL-qZSI) is based on the well-known qZSI topology is offered reduce the voltage stress on the circuit components. Two modified SL-qZSI topologies based on [8] are presented with higher boost inversion ability and lower voltage stress on the power MOSFETs [9]. In [10], the SL-qZSI topology is improved to increase the boosting effect. In [11], an extended SL-qZSI adapted for PV systems is proposed for better voltage boosting with improved power factor and reliability. Design and implementation of a new modulation technique for qZSI that can increase the voltage and current by using the additional converter is realized in [12]. In [13], basic topology improvements of the ZSI/qZSI are explained and a switched-inductor assisted ZSI (SL-ZSI) is implemented in order to enhance the circuit performance. The performance of a new ZSI-based single-stage power conversion is analyzed for a standalone PV system in [14]. Through analyzing many operating modes, the critical values of qZSI circuit parameters considering the load condition and switching frequency are analyzed and calculated in [15]. Two new enhanced-boost qZSI topologies [16] are presented with two-switched impedance networks with relative high boost voltage inversion. Many of the recent studies mainly focused on the voltage boost ability and reduced stress on the components with different circuit proposals.

The novelty of the proposed circuit is focused on the two different parts of the qZSI. First, the question of how the circuit's output power quality can be improved is analyzed. Secondly, the question of how the circuit's output voltage can be boosted is examined. These two questions are analyzed differently from the circuit modifications explained in the reference studies. For this purpose, unipolar PWM strategy is employed differently to reduce the distortion in the fundamental voltage and current waveform and the voltage gain ability of the circuit is improved with the help of an additional boost switch at lower shoot-through duty ratio and higher modulation index compared to the classical qZSI.

The rest of this study is organized as follows. Section II explains the operating principles of the proposed qZSI circuit. Section III contains the simulation results. Section IV discusses the effect of the presented circuit along with the future research directions.

2. Proposed Single Phase Modified QZSI

As mentioned in the introduction, the ZSI circuit has been improved into the qZSI circuit as shown in Figs. 1–2 respectively [3, 4]. When the qZSI circuit analysis is done, it is noticed that all the ZSI equations in the continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are considered correct for qZSI. There are two basic differences between the two topologies as stated earlier. The qZSI has continuous constant DC current and lower components rating in the impedance network. At the same time, the qZSI is capable of operating a wide input voltage range which is highly essential for PV applications [4].

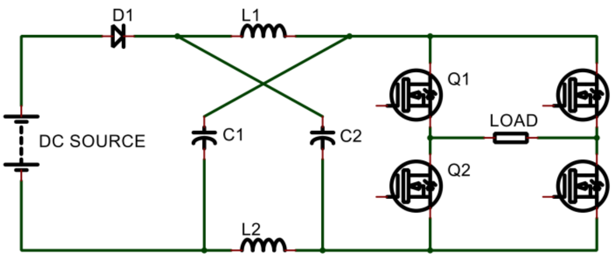

Fig. 1. Voltage fed Z-source inverter.

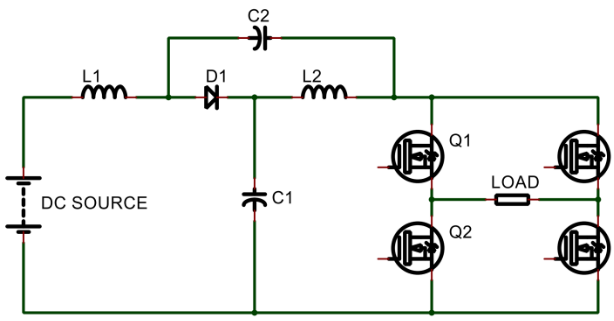

Fig. 2. Voltage fed quasi Z-source inverter.

2.1. Unipolar PWM Strategy Papers

In unipolar PWM technique, two 180° phase shifted reference waves are compared with a carrier triangular wave to generate the required triggering pulses for the power switches of the inverter bridge [17, 18]. Conventionally, unipolar PWM is employed to the power MOSFETs as indicated in Fig. 3. Two generated triggering pulses are sent to the top switches (Q_1 and Q_3) and the inverted triggering pulses are sent to the bottom switches (Q_2 and Q_4). Figure 4 displays us the waveforms of unipolar PWM technique in which the reference waves and the carrier wave are compared to generate two triggering pulses for Q_1 and Q_3 respectively.

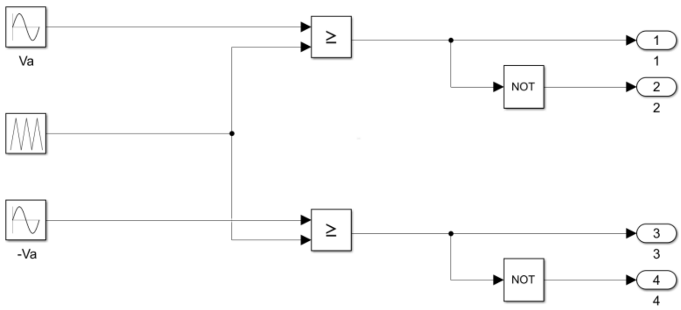

Fig. 3. Unipolar PWM technique block scheme.

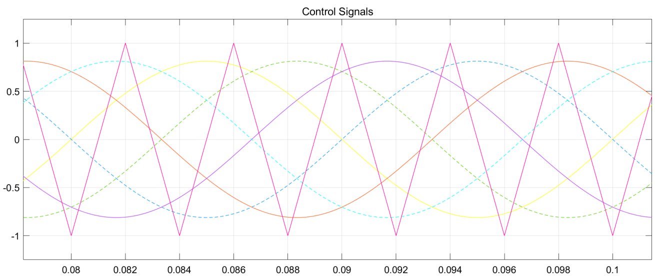

Fig. 4. Unipolar PWM technique block scheme.

2.2. Additional Boost Switch Effect

Secondly, the question of how the circuit's output voltage gain can be increased is investigated. One of the biggest challenges the current ZSI/qZSI topologies face is the increase the voltage gain of the overall circuit. Therefore an additional boost switch Q_5 is connected in parallel with the impedance network and power MOSFETs of the qZSI circuit as depicted in Fig. 5.

The main idea behind this modification is to provide high boost voltage conversion ability. In the proposed circuit the power switches in the inverter bridge and the included boost switch Q_5 are short-circuited at the same time during the shoot-through state. But during the non-shoot-through state, the switches in the inverter bridge are triggered in the same way as the traditional carrier based PWM inverter while the included boost switch Q_5 is in off-state. In other words, the boost switch is operated only for a short time interval to assist the boost capability. In order to drive the included boost switch, two generated triggering pulses of the same phase leg are connected using AND gate and the output of the AND gate is sent to the additional boost switch Q_5. Thus, the output voltage level is increased significantly.

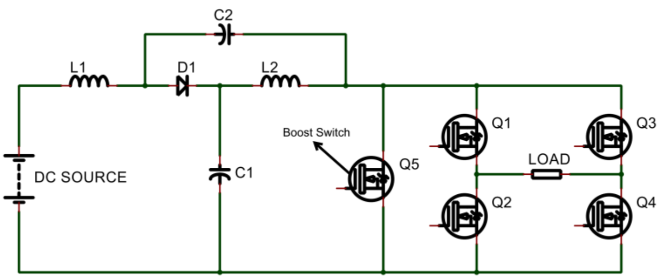

Fig. 5. Modified qZSI circuit with additional boost switch.

2.3. Circuit Analysis

In this study, the generated triggering pulses are employed in a different way from the unipolar PWM block scheme given in Fig. 4. Unlike the operation of the block scheme, the first triggering pulse is forwarded to the Q_1 and Q_4 switches, whereas the second triggering pulse is forwarded to the Q_3 and Q_2 switches. The synchronous driving of the diagonal MOSFETs using unipolar PWM technique is carried out for the purpose of creating the required shoot-through pulses. Two generated triggering pulses and the resulting shoot-through pulses are demonstrated in Fig. 6. Conventional single phase inverters have four non-shoot-through states (two active states and two zero states) in the operation process. Along with these states, the qZSI has an additional shoot-through state, in which the power MOSFETs of one phase leg or two phase legs are short-circuited. As it is known from [4], there are two operation modes of the qZSI: shoot-through state and non-shoot-through state. In shoot-through state, DC energy coming from the input source is transferred into the inductors via capacitors. In non-shoot-through state, the stored energy on the inductors is transferred to the load, thus boost process is provided. PWM pulses are generated to provide the sinusoidal output and the shoot-through pulses are generated in the same phase leg to boost the voltage gain. It is clear that the shoot-through duty ratio D can be controlled by changing the control waveforms as seen in Fig. 4. It can be inferred from Fig. 4 and Fig. 6. that the generated shoot-through pulses in other words duty ratio varies periodically each ($\pi/3$) in a cycle. Therefore the average D over one switching cycle T should be calculated using Eq. (1) during ($\pi/6$, $\pi/2$). Using Eq. (1), the boost factor B can be acquired in Eq. (2). The voltage gain G which is the product of the modulation index M and the B is obtained in Eq. (3) and the output peak phase voltage V_{AC} is expressed from the input DC voltage V_{DC} in Eq. (4).

$$D = \int_{\pi/6}^{\pi/2} \frac{2 - \{M\sin\varphi - M\sin(\varphi + \frac{4\pi}{3})\}}{2} d\varphi = \frac{2 - \sqrt{3}M}{2} \quad (1)$$

$$B = \frac{1}{1 - 2D} = \frac{1}{\sqrt{3}M - 1} \quad (2)$$

$$G = M * B = \frac{M}{\sqrt{3}M - 1} \quad (3)$$

$$V_{AC} = M * B * \frac{V_{DC}}{2} = G * \frac{V_{DC}}{2} \quad (4)$$

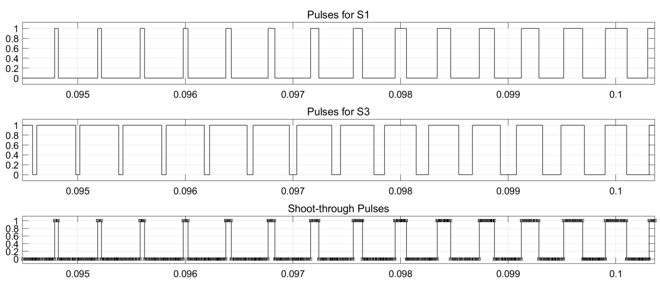

Fig. 6. Generated pulses and the shoot-through pulses.

3. Results and Discussion

Simulations are conducted to show the effectiveness of the proposed single phase modified qZSI for different modulation indexes using Matlab/Simulink. For the simulations, the parameters have been determined in the qZSI according to [3].

The input DC voltage V_{DC} is 100 V, switching frequency f_S is 10 kHz, the modulation index M is set to 0.642, the inductors (L_1=L_2) and capacitors (C_1=C_2) of the impedance network are 160 uH and 1000 µF respectively. The inductance and capacitance values of the output filter (L_F and C_F) are 1 mH and 100 µF respectively. The inductive load of the qZSI consists of 10 Ω and 1 mH. For the proposed circuit the theoretical calculations are given below:

$$D = \frac{2-\sqrt{3}M}{2} = 0,448 \tag{5}$$

$$B = \frac{1}{1-2D} = \frac{1}{\sqrt{3}M-1} = 9.65 \tag{6}$$

$$G = M * B = 6.15 \tag{7}$$

$$V_{AC} = M * B * \frac{V_{DC}}{2} \approx 300V \tag{8}$$

The first aim of the simulations is to observe the boosting effect of the boost switch Q_5 of the qZSI under the given input voltages and modulation indexes. For these parameters, the simulations are conducted with and without using boost switch Q_5 to see the improvement in the output voltage. The generated pulse signals shown in Fig. 6 are applied to the power MOSFETs of the qZSI circuit to get sinusoidal output. In Figs. 7–9 are shown the simulation results of the output voltages with corresponding load after the LC filter which is consistent with the theoretical values.

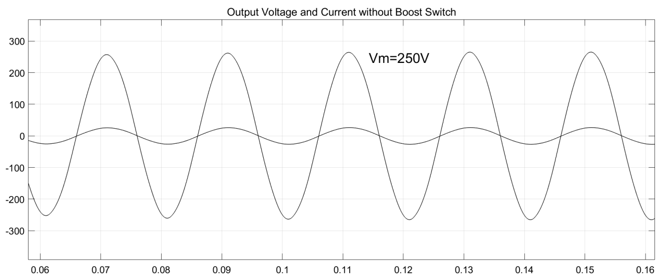

Fig. 7. Peak phase voltage-current without boost switch Q_5.

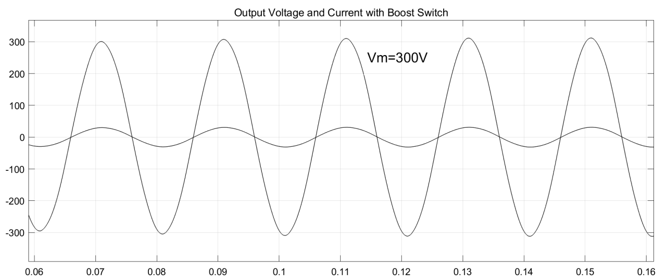

Fig. 8. Peak phase voltage-current with boost switch Q_5.

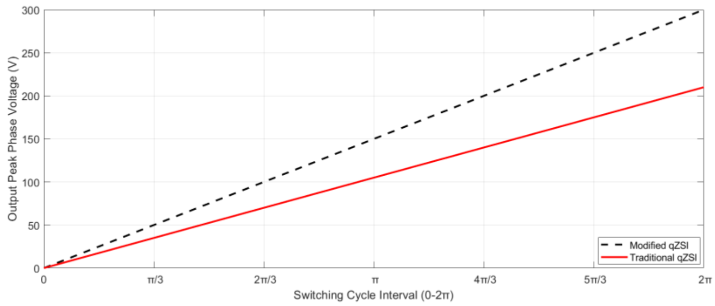

Fig. 9. Comparison of the peak phase voltages at V_{DC}=100V.

Table 1. Simulation results under two different input voltages and modulation indexes.

Operation condition	V_{DC} (V)	V_M (V)	I_M (A)
M=0.642, without boost switch	100	≈250	≈25
M=0.642, with boost switch	100	≈300	≈30

According to the simulation results, the output voltage and current values of the modified qZSI is boosted for the given parameters as listed in Table 1 which is consistent with the theoretical values. While the output peak phase voltage without boost switch is about 250 V according to Fig. 7, it becomes almost 300 V with boost switch as seen in Fig. 8. As illustrated in Fig. 9, due to the additional switch a boosting ability of about 20 % was achieved for the selected input voltage and modulation index.

The second aim of the simulations is to demonstrate THD reduction in the fundamental voltage and current waveform of the qZSI using the unipolar PWM. In general, harmonics are defined as the distortions in currents or voltages with frequencies mostly ranging from the 3rd order to the 20th order that are integer multiples of the main frequency. The analysis of harmonics in the fundamental voltage and current waveform is the operation of calculating the magnitudes and phases of the higher order harmonics. [19, 22].

THD performance is calculated using fast Fourier transform (FFT) analysis in Matlab/Simulink which is a decomposition of a signal in sine waves. The analysis and modelling of the harmonics can be performed using the Fourier analysis tool in details. The presence of harmonics should be dealed either with active or passive filters. In this paper, a passive filter consisting of an inductor and capacitor is used for filtering. For each modulation technique, the same filter circuit is used with the equal inductors and capacitors of 1 mH and 100 µF respectively as studied in [3]. Under the same conditions, the unipolar PWM technique employed differently from the usual way is compared to the traditional PWM based modulation techniques SBM, MBM and MCBM regarding the effects of harmonics on power quality. THD calculation results including the harmonics from 3rd order to 10th order for each modulation technique are depicted in Figures 10–13 respectively.

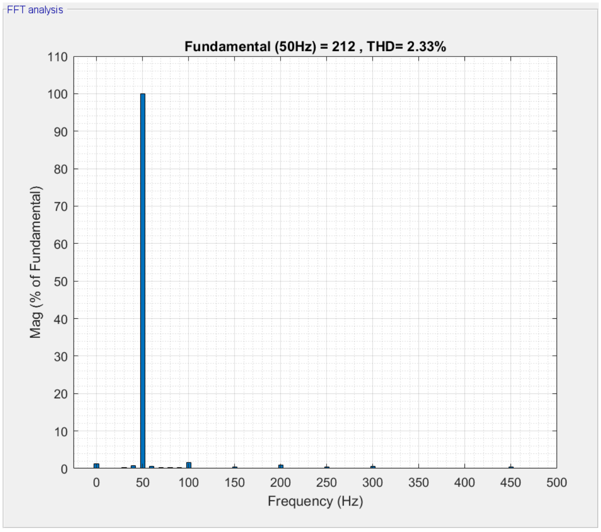

Fig. 10. FFT analysis for the employed unipolar PWM.

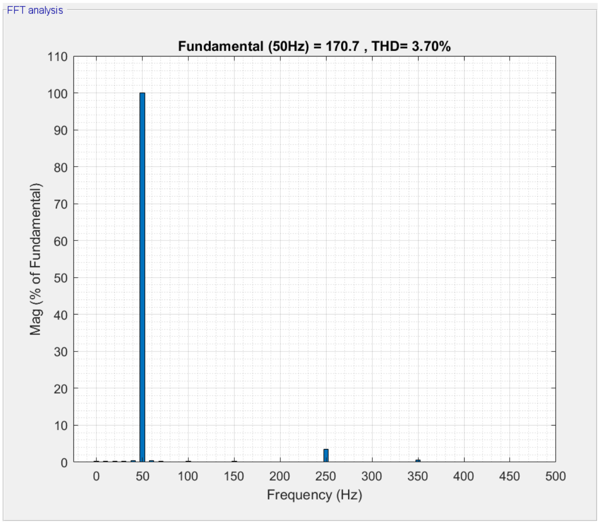

Fig. 11. FFT analysis using SBM technique.

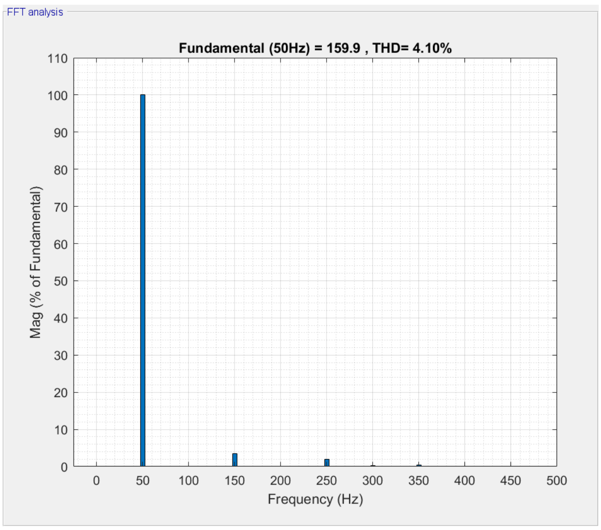

Fig. 12. FFT analysis using MBM technique.

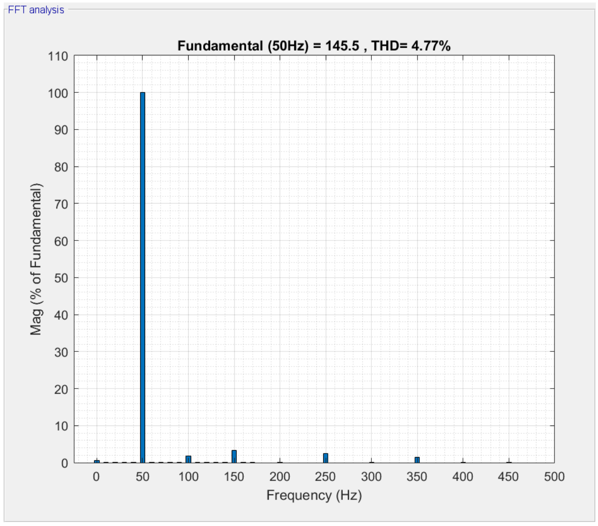

Fig. 13. FFT analysis using MCBM technique.

Performances of the FFT analysis for the simulated modulation techniques are given in Table 2. Employing the unipolar PWM technique differently than the usual way, not only the required shoot-through pulses are generated but also harmonic distortions at the output are minimized. It is clear that using differently employed unipolar PWM technique, current THD value under the same output filter circuit is about 2.33 % as shown in Fig. 10 which is in the permissible THD of the IEEE STD 519-1992 Harmonic Limits.

Since there are two 180° phase shifted sine reference waves and three voltage levels in the output in this technique, more sinusoidal waveform is provided. However, when the classical PWM based modulation techniques SBM, MBM and MCBM are analysed; current THD values are calculated 3.70 %, 4.10 %, and 4.77 % as seen in Figs. 11-13 respectively. These results proved that employed unipolar PWM technique has a great impact on the THD reduction in the fundamental voltage and current waveform.

Table 2. Performances of the FFT analysis for the simulated modulation techniques.

Modulation techniques at M=0.642	V_{DC} (V)	THD with passive filter
SBM	100	3.70%
MBM	100	4.10%
MCBM	100	4.77%
Unipolar PWM	100	2.33%

According to the mathematical analysis and simulation results, using Matlab/Simulink environment, the main specificities of the proposed solution from the traditional circuits are observed in the voltage boosting and THD minimizing that are very important aspects considering the PV power generation systems. The only drawback to the implementaiton of the proposed qZSI circuit could be the small cost of the additional boost switch Q_5 which can be neglected as the voltage gain of the circuit is increased significantly.

4. Conclusion

A modified single phase qZSI with enhanced boost capability has been presented in this study. Compared to the traditional qZSI, the proposed qZSI is very effective for achieving higher boost on output voltage and current by adding a simple boost switch which operates only in shoot-through state during the switching cycles. This slight modification in the qZSI configuration assisted to improving of the circuit performance. In addition to this, unipolar PWM technique is utilized in a different way from the traditional implementation to generate shoot-through pulses and to reduce voltage and current distortions. The working principle of the employed unipolar PWM technique is analyzed in details. Simulations were conducted to validate the proposed theory using Matlab/Simulink. Future research should be concentrated on the different circuit modifications and modulation techniques to improve the overall performance.

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