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Research Article

Design of a Three Phase Z-Source Inverter for Photovoltaic Systems

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ABSTRACT

Due to the danger of extinction of fossil energy resources and their harmful effects on the environment, interest in renewable energy sources has increased today. Furthermore, the photovoltaic energy, which is among renewable energy sources, has started to gain importance day by day. Especially, grid-connected Photovoltaic (PV) power generation systems have begun to be installed and used widely. In the grid-connected power generation systems, variable environmental conditions cause the DC voltage obtained from the PV systems to vary continuously. In the applications where traditional inverters are used, additional DC/DC converters are required to obtain an output at the desired frequency and amplitude. On the other hand, Z-source inverters which are a new concept can perform this raising and lowering process without the need for any intermediate circuit elements, thanks to the impedance network in their structures. For this reason, in this paper, Z-source inverter is designed for the PV systems. Z-source inverter modeling with impedance network is realized by using a simple boost switching method, and the modulation index and duty cycle parameters are adjusted to increase the DC voltage applied to its input. It is observed from the simulation results that using of the Z-source inverter is proper and efficient in the PV power generation systems.

**CRITICAL: Photovoltaic Power Generation Systems, Inverters, Z-source Inverter, Simple Boost Pulse Width Modulation.*

Introduction

In recently, studies and applications on PV systems have become widespread with the increasing importance of the renewable energy sources. The most important reasons of that are that PV systems can convert the solar energy directly into the electrical energy, prevent the environmental pollution and have simple structure and easy to implement. PV systems can be applied in two different ways as connected to the grid and independent from the grid which are respectively on-grid and off-grid systems. It can be designed as fixed and mobile systems as the location of the solar panel.

Z-Source Inverter (ZSI) which is newly proposed is a simple single-stage power conversion concept [1]. It can stabilize or boost the AC output voltage, which is not possible with conventional inverters. Thanks to ZSI, the input DC voltage can be increase and also reduce. This feature, which cannot be achieved with conventional voltage and current source inverters, can be realized with an impedance network placed between the power source and the inverter. The use of traditional inverters in PV system applications not only increases the cost, but also leads to low efficiency and increased the number of components. However, this is not the case with ZSIs. The fact that ZSIs have the ability to raise and invert the voltage in only one step has revealed that they are more proper for using in the PV system applications.

The studies in the literature have been researched on the field of the ZSI. First of all is a design of a PV system with a single phase ZSI in [2]. Thanks to important advantages of the ZSI, a simple single-stage power conversion is realized. MPPT technique is utilized to reduce the shading problem of the solar light and the all system is designed by using MATLAB/Simulink simulation. By this method, power losses are decreased since less switching devices are used and the efficiency are increased. As a result, a less costly and more reliable system is obtained due to the lack of the bulky transformer. In [3], ZSI is presented for the single phase grid connected PV system. In this study, the circuit capacitors and inductors are calculated briefly. The performance of an example PV module is examined by using MATLAB/Simulink and the design parameters are validated by the simulations. Authors in [4] give a comparative study of different shoot through control schemes for ZSIs. The working of the ZSI is examined by using various control methods which are Simple Boost Control (SBC), Maximum Boost Control (MBC) and Constant Boost Control (CBC). The simulation of the ZSI is also realized by using these control methods in this paper. In [5], three phase ZSI is designed for the solar PV applications. Traditional inverters which are voltage source inverter(VSI) and current source inverter(CSI) and ZSIs are compared in terms of the performance, advantages, and drawbacks. It is observed that ZSI proposing a new PWM scheme is more advantageous than traditional inverters. Thus, the efficiency is increased and size and cost are reduced by the proposed three-phase ZSI for the solar PV systems. [6] explains a single phase cascaded semi-ZSI for the PV applications. This inverter uses a nonlinear Sinusoidal Pulse Width Modulation (SPWM) to produce sinusoidal voltage at the output as a micro inverter. The designed system solves the shading problem of the PV systems due to the independent maximum power point tracking. Furthermore, Total Harmonic Distortion and DC current components at the output during DC-AC conversion are reduced by this study. Topologies and controls of Z-source matrix converter are researched in [7]. These topologies are called as direct and indirect. While nine switching mosfets are used in the direct Z-source matrix converter, eighteen switching mosfets are utilized in the indirect Z-source matrix converter. It is observed that indirect Z-source matrix converter provides superiority over the traditional matrix converter and allows buck and boost operation by reducing the number of switches to get high efficiency. 3-Φ Z-source PWM controlled solar PV inverter is designed for the generation of three-phase electrical power in [8]. The proposed topology occurs from the single stage. Therefore, reliability of the system is high due to the less component. The low PV voltage is increased and maximum power tracking is realized by the designed MPPT charge controller. This proposed ZSI also decreases line harmonic distortions and cost as compared to conventional multilevel inverter. The analysis of Z-source based multilevel inverter is examined by using Matlab/Simulink in [9]. The performances of the ZSI are compared with the other traditional inverter topologies. As a result, the increasing in the voltage and current are filtered by the capacitors and inductors of the ZSI. Authors in [10] propose a single stage ZSI topology which eliminates some drawbacks of the conventional inverters like being the less or more output AC voltage than the input DC voltage and the shoot through faulty by providing two switches of the same leg to be gated in the circuit. Since ZSI also eliminates the dead time in the circuit, distortion is reduced and reliability of the system increases. In this study, the performance of ZSI is examined about reducing THD by using Matlab/Simulink for different load situations and modulation indexes. It is observed from the simulation results that ZSI shows higher performance than conventional VSI and ZSI. In the paper [11] explains a single stage ZSI topology based on the duty ratio and modulation index. The simulation of a single-phase induction motor is realized by the control of the single phase ZSI. This inverter provides lower line harmonics and shoot-through duty cycle. Therefore, it increases the reliability and efficiency and also extends the output AC voltage range of the inverter. [12] presents a ZSI concept which can also be used to DC-DC, AC-DC and AC-AC power conversions. A different impedance circuit is used to combine the source and power circuit. By a simple boost control method, Matlab/Simulink simulation and analysis of the ZSI are carried out in this study. The triggering pulses for six switches of the three phase ZSI are applied in the simulations. The simulation results show that the desired load sinusoidal voltage and current are obtained by the filtered ZSI compared to the traditional inverters. In [13], a topology of two level ZSI is explained. Two level ZSI receives the power supply from the PV. Sinusoidal Pulse Width Modulation (SPWM) is used to control the switches of the ZSI for the shoot through and non-shoot through operation modes. This inverter provides high efficiency, low cost, and low leakage current for the PV systems. Simulation and design of the single phase ZSI are given in [14, 15]. ZSI eliminates the limitations of the traditional VSI and CSI and presents a novel power conversion concept. By using SBC PWM technique, the simulation of ZSI is realized for various modulation indexes. As a result, it is observed that the sinusoidal load voltage and current can be obtained by the filtered ZSI compared to the conventional inverters.

When examining the studies in the literature, it is observed that there are not many works on the ZSI gaining importance in the recent years. This structure provides significant advantages unlike the conventional inverters for the PV systems. Therefore, the ZSI is modeled and designed by using a simple boost switching method. According to the change of the modulation index and duty cycle parameters, the DC voltage applied to its input is increased. It is obtained from the simulation results that the ZSI is efficient and convenient for the PV power generation systems.

In the organization of the paper, the topology and analysis of the ZSI are firstly explained in Section 2. Then, Matlab/Simulink simulation of three phase ZSI is carried out in Section 3. The phase voltage, line voltage, and load current are analyzed for different modulation indexes and pulse width values. In order to reveal the difference of the ZSI from the VSI, the performances are compared with each other at the same operating conditions. In Section 4, the simulation results of the ZSI are given in detail. In the last Section, the conclusions are presented.

Z-Source Inverter

Topology

Three phase ZSI topology includes R-L output filter and loads as illustrated in Fig. 1.

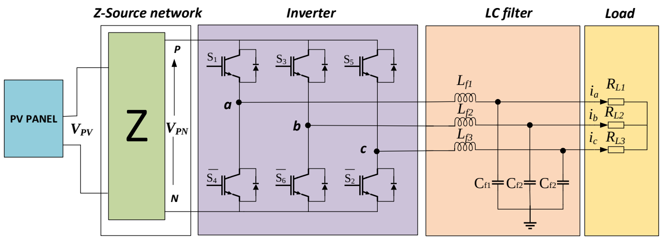

Figure 1. The topology of the three-phase ZSI

Analysis of the Z-Source Inverter Circuit

The equivalent circuit of the ZSI is shown in Fig. 2. In this structure, there is a single type of impedance circuit consisting of two capacitors and two inductors connected in an X-shape. This structure allows the main circuit to be transferred to the load, power supply or other converter. In this way, the circuit structure of traditional inverters using capacitors and inductors turns into a unique new circuit structure. In this circuit, when the inductances L_1 and L_2 and capacitances C_1 and C_2 are the same values, the Z source network becomes symmetrical.

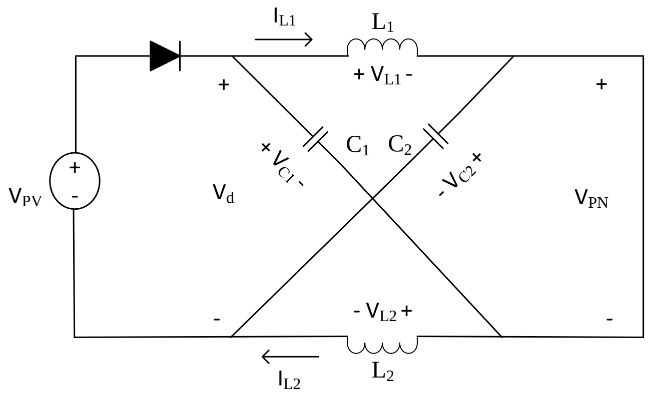

Figure 2. Equivalent circuit of the ZSI

As seen from the Fig. 2, the voltages can be written as follows

$$V_{C1} = V_{C2} = V_C \quad (1)$$

$$\upsilon_{L1} = \upsilon_{L2} = \upsilon_L \quad (2)$$

In the non-shoot-through situation (T_0), the Z-source circuit is shown by a constant current source in the Fig. 3.

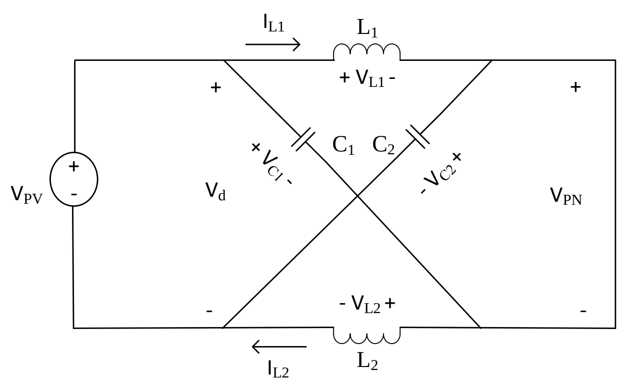

Figure 3. Equivalent circuit of the ZSI with non-shoot through state

According to the Fig. 3, the voltages in the circuit are given by

$$\upsilon_L = V_{PV} - V_C \quad (3)$$

$$\upsilon_d = V_{PV} \quad (4)$$

$$\upsilon_{PN} = V_C - \upsilon_L = 2V_C - V_{PV} \quad (5)$$

where υ_L, V_{PV}, V_{PN}, and υ_d are the inductor voltage, the input DC voltage, DC-link voltage, and diode voltage, respectively.

In the shoot-through situation (T_1), the Z-source circuit is shown by a short-circuit in the Fig. 4.

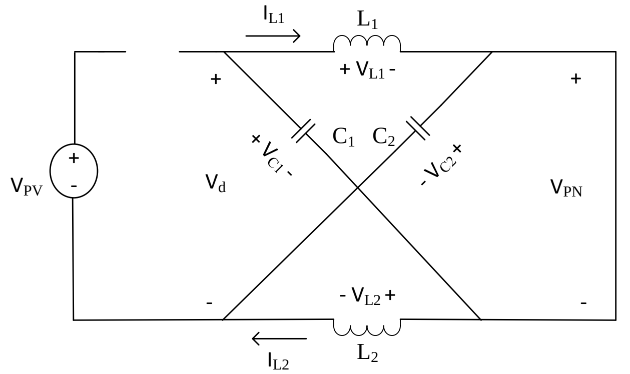

Figure 4. Equivalent circuit of the ZSI when the inverter is in the shoot through state

As seen from the Fig. 4, the voltages are calculated by using Kirchhoff's voltage law as follows

$$\upsilon_L = V_C \quad (6)$$

$$\upsilon_d = 2V_C \quad (7)$$

$$\upsilon_{PN} = 0 \quad (8)$$

The average voltage of the inductors over one switching period ($T=T_0+T_1$) should be zero in steady-state Equation (3-8).

$$V_C = \frac{T_1}{T_1 - T_0} V_{PV} \quad (9)$$

The average and peak values of the DC voltage on the inverter circuit can be given as follows respectively.

$$\upsilon_{PN} = \frac{T_1}{T_1 - T_0} V_{PV} = V_C \quad (10)$$

$$\hat{\upsilon}_{PN} = V_C - \upsilon_L = 2V_C - V_{PV} = \frac{T}{T_1 - T_0} V_{PV} = BV_{PV} \quad (11)$$

where B is the boost factor.

The Simulation of Three Phase ZSI

The modeling of three phase ZSI is realized by using Matlab/Simulink under sample working conditions as shown in Fig. 5.

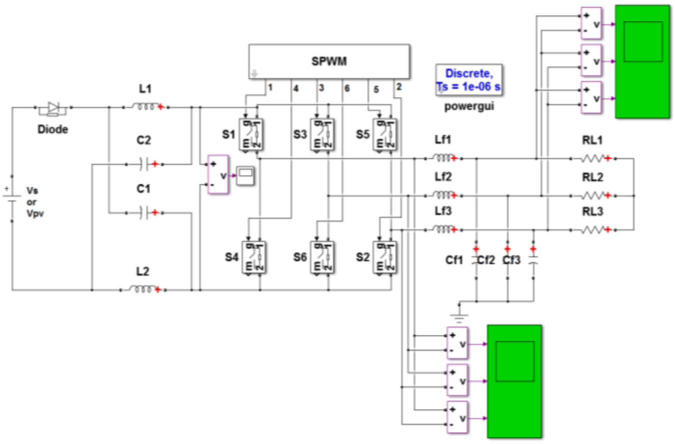

Figure 5. Matlab/Simulink model of the three-phase ZSI

In the model, the ZSI circuit consists of six main switches. The series connected diode in the three-phase ZSI model is utilized to prevent the reverse current. Transition signals for the switches are produced by the simple amplification pulse amplitude modulation technique as given in Fig. 6.

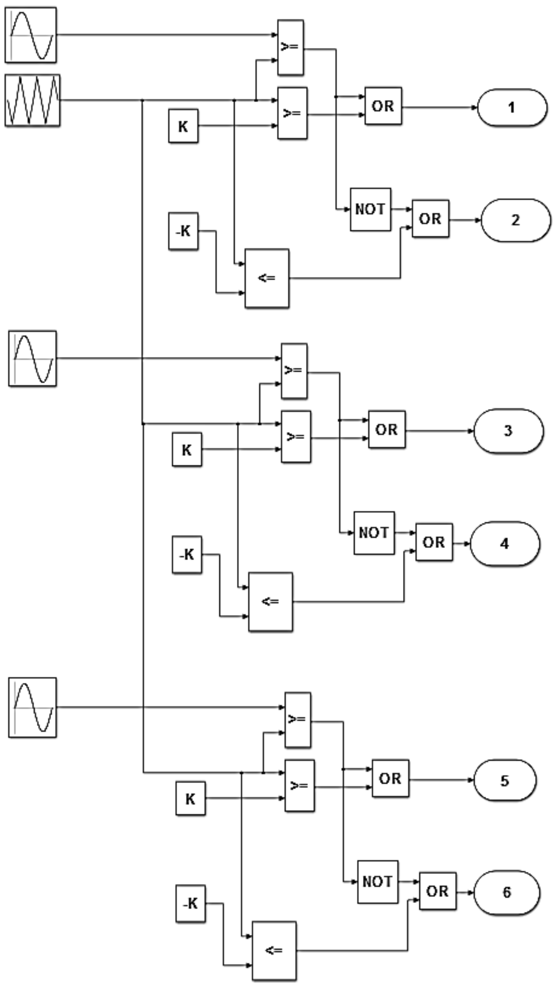

Figure 6. Simulation model of the SPWM switching signals for the three-phase ZSI

The transition signals applied to the switches of the ZSI are given in Fig. 7. In the simulation, the modulation index (*M*) used to generate the switching signals is 0.642 and the switching frequency is set to f_s=10 kHz.

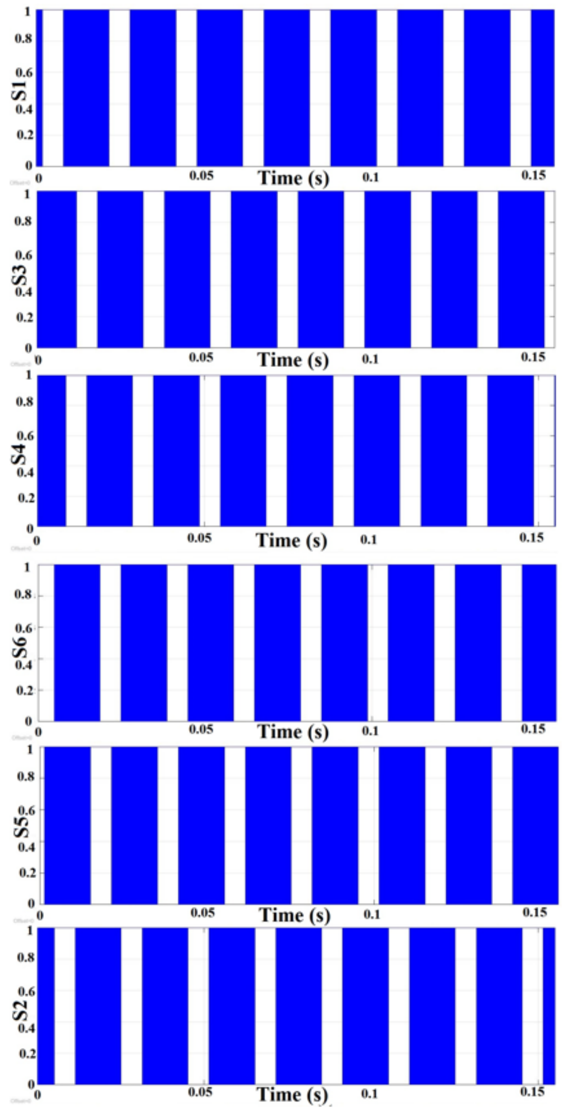

Figure 7. Simulink results of the three-phase simple boost control method of the switching signals

The parameters of the ZSI used in the simulation are shown in Table 1.

Table 1. The system parameters used in the ZSI.

Parameters	Value
Modulation Index	0.642
Duty Cycle *(T_0/T)*	0.358
Photovoltaic DC Input Voltage(V_{pv})	150 V
Fundamental Frequency	50 Hz
Switching Frequency *(f_s)*	10 kHz
Load Resistance(R_{L1}=R_{L2}=R_{L3})	3.8 ohm
Z-source network inductance *(L_1=L_2)*	160 µH
Z-source network capacitor *(C_1=C_2)*	1000 µF
Output filter inductance *(L_{f1}= L_{f2}= L_{f3})*	15 mH
Output filter capacitor *(C_{f1}= C_{f2}= C_{f3})*	470 µF

The Simulation Results of Three Phase ZSI

In this section, Matlab/Simulink simulation results of three phase ZSI are given in detail. Firstly, the phase-to-phase output voltage of the ZSI is shown in Fig. 8.

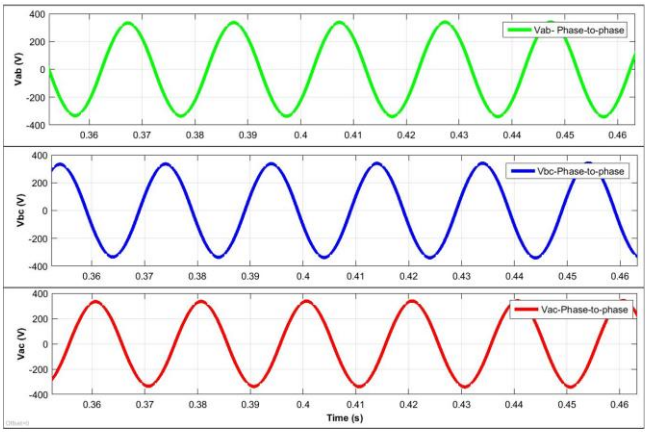

Figure 8. Phase-to-phase output voltage waveforms of the modeled ZSI

The phase-neutral voltages of the inverter output are also illustrated in Fig. 9.

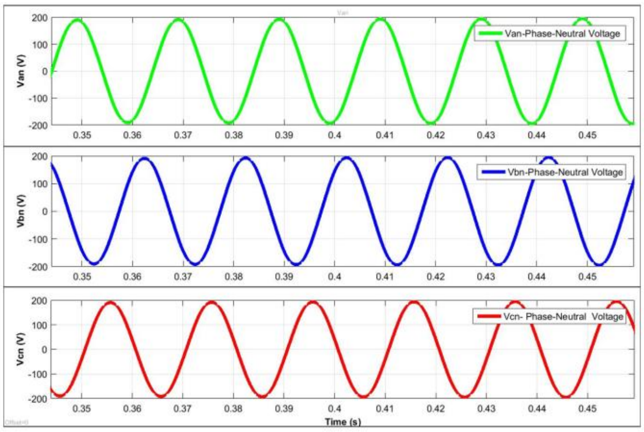

Figure 9. Phase-neutral output voltage waveforms of the modeled ZSI

The phase voltage and harmonic spectrum belonging to the unfiltered and filtered outputs of the model realized for the modulation index which is $M=0.642$ and $D_0=0.348$ are respectively shown in Fig. 10 and Fig. 11, respectively.

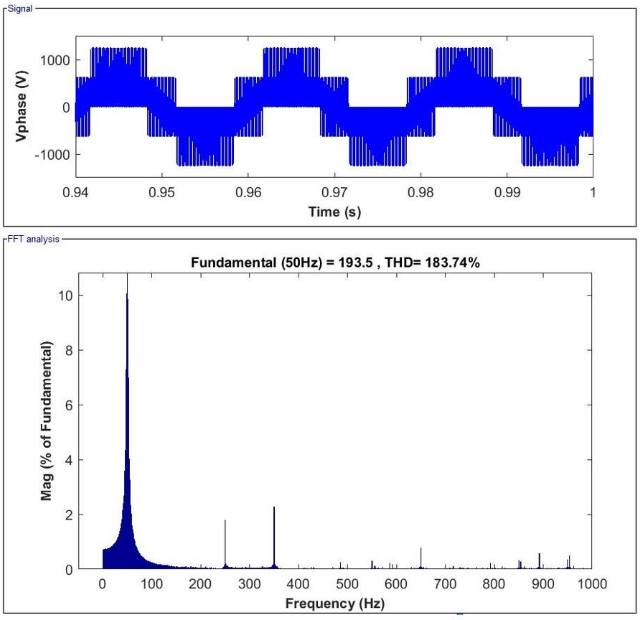

Figure 10. Phase voltage and harmonic spectrum of unfiltered output (M=0.642 and $T_0/T=0.358$)

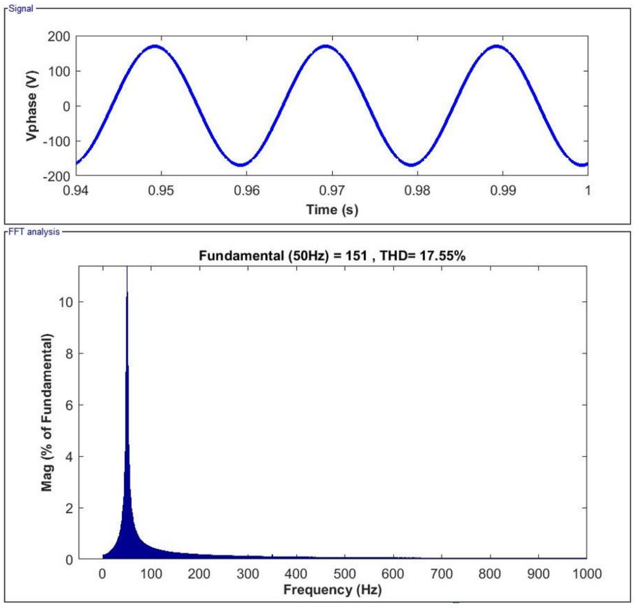

Figure 11. Phase voltage and harmonic spectrum of filtered output (M=0.642 and $T_0/T=0.358$)

The line voltage and harmonic spectrum belonging to the unfiltered and filtered outputs of the model realized for the modulation index which is $M=0.642$ and $D_0=0.348$ are respectively shown in Fig. 12 and Fig. 13, respectively.

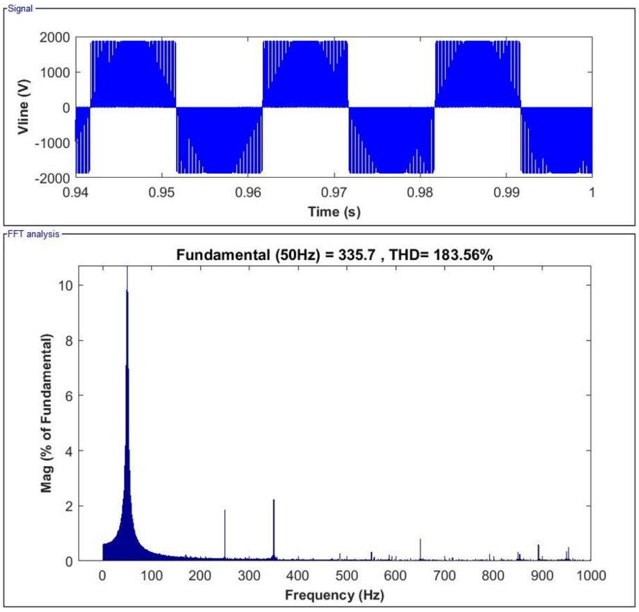

Figure 12. Line voltage and harmonic spectrum of unfiltered output (M=0.642 and T_0/T=0.358)

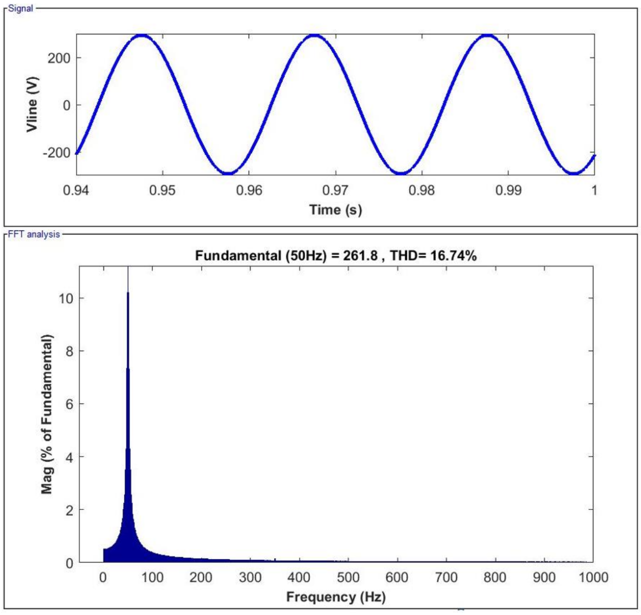

Figure 13. Line voltage and harmonic spectrum of filtered output (M=0.642 and T_0/T=0.358)

After that, the phase voltage and harmonic spectrum belonging to the filtered and unfiltered outputs of the model realized for the modulation index which is $M=0.9$ and $T_0/T=0.1$ are respectively shown in Fig. 14 and Fig. 15, respectively.

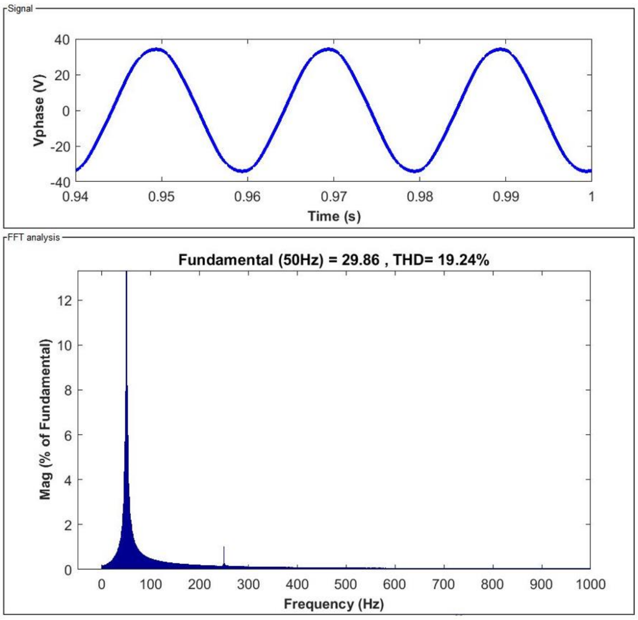

Figure 14. Phase voltage and harmonic spectrum of filtered output (M=0.9 and T_0/T=0.1)

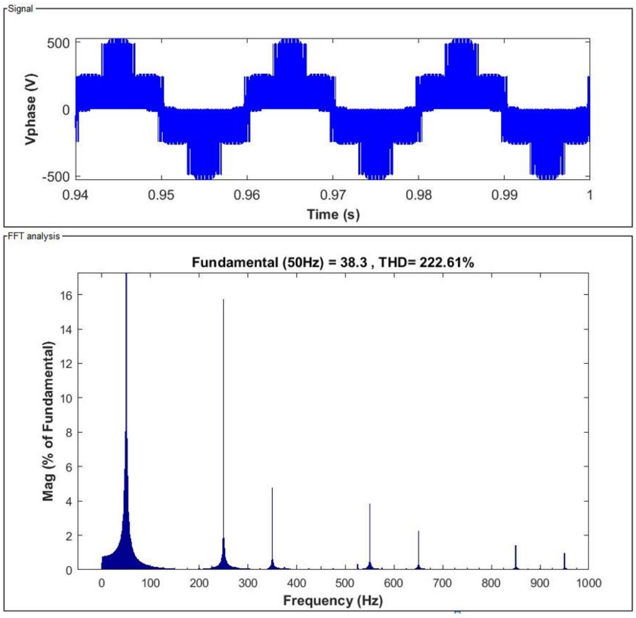

Figure 15. Phase voltage and harmonic spectrum of unfiltered output (M=0.9 and T_0/T=0.1)

The phase current and harmonic spectrum belonging to the filtered output of the model realized for the modulation index which is $M=0.9$ and $T_0/T=0.1$ are shown in Fig. 16.

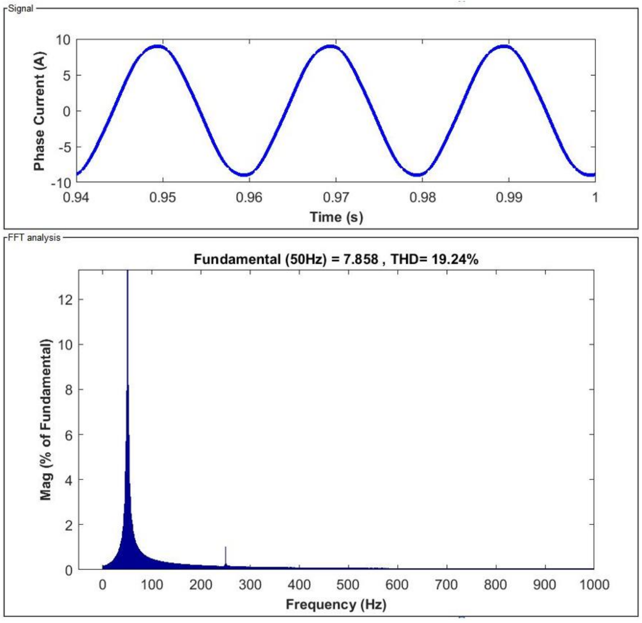

Figure 16. Phase current and harmonic spectrum of filtered output (M=0.9 and T_0/T=0.1)

The line voltage and harmonic spectrum belonging to the unfiltered and filtered outputs of the model realized for the modulation index which is *M=0.9* and *T_0/T=0.1* are respectively shown in Fig. 17 and Fig. 18, respectively.

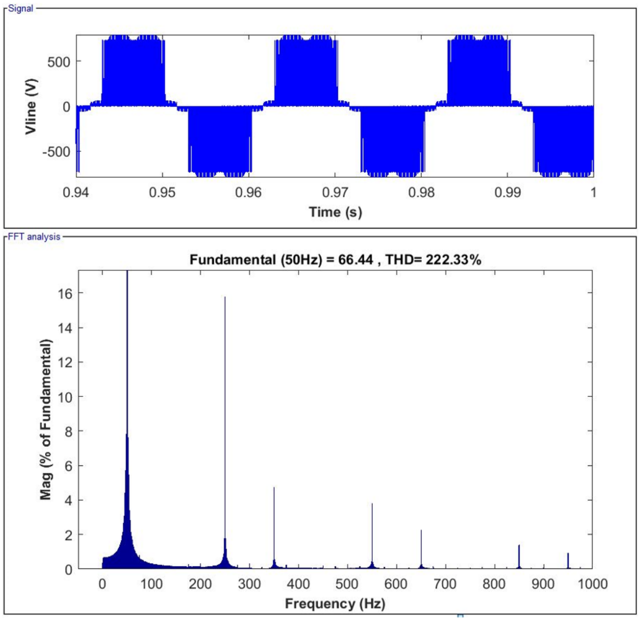

Figure 17. Line voltage and harmonic spectrum of unfiltered output (M=0.9 and T_0/T=0.1)

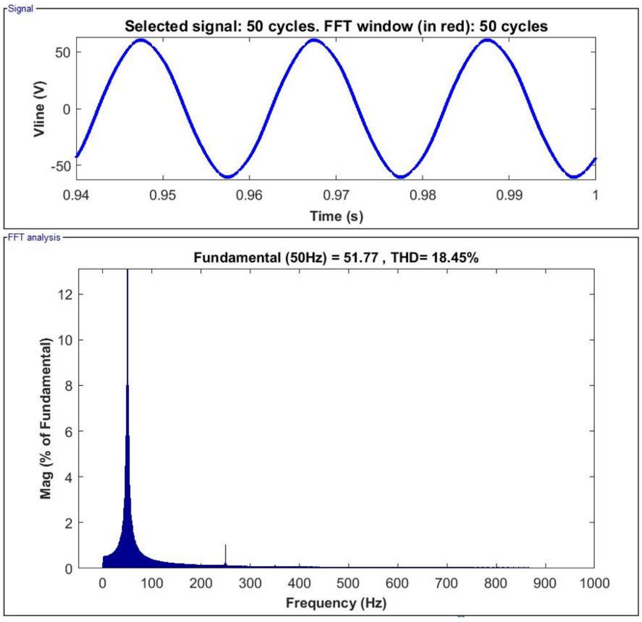

Figure 18. Line voltage and harmonic spectrum of filtered output (M=0.9 and T_0/T=0.1)

The effective values of the filtered phase voltage, line voltage and phase current for different pulse width values (*T_0/T*) and the total harmonic distortion percentages at these voltage values are given in Table 2, provided that the impedance network parameters in the circuit and the switching frequency and modulation index remain the same.

Table 2. Phase voltage, line voltage, phase current, and total harmonic distortion values of the filtered output for the fixed M and variable T_0/T values.

Pulse Width	V_{Phase}/THD	V_{Line}/THD	I_{Phase}/THD
0.1	22.7 19.66%	39.32 18.87%	5.974 19.66%
0.2	53.53 18.63%	90.99 17.83%	13.82 18.63%
0.3	93.38 17.94%	161.7 17.13%	24.57 17.94%
0.4	139.7 17.28%	242 16.46%	36.76 17.28%
0.45	163.1 16.96%	282.5 16.14%	42.92 19.96%
0.46	167.7 16.90%	290.5 16.08%	44.13 16.90%
0.47	172.3 16.83%	298.4 16.01%	45.34 16.83%
0.49	182.2 16.68%	315.7 15.86%	47.96 16.68%
0.499	190.7 16.59%	330.4 15.77%	50.2 16.59%
0.6	131.2 4.65%	226.7 4.07%	34.53 4.65%
0.7	65.59 4.00%	113.7 3.12%	17.26 4.00%
0.8	46.41 4.00%	80.34 2.74%	12.21 4.00%
0.9	31.17 3.98%	53.9 2.86%	8.2 3.98%

When the output values in the Table 2 are examined, it is observed that the output phase and line voltages of the ZSI increase for the pulse width which is in the range of 0.1-0.499. On the other hand, it is obtained that the output phase and line voltages of the ZSI decrease in the range which the pulse width is 0.5-0.9. These results show that the ZSI works as an amplifier for the pulse width values less than 0.5 and as a reducer for the pulse width values greater than 0.5.

The effective values of the output phase voltage, line voltage, phase current, and harmonic spectrum values belonging to different modulation indexes for the pulse width range which is less than 0.5 in the boost mode operation of the ZSI are given in Table 3.

Table 3. Phase voltage, line voltage and total harmonic distortion values of the filtered output for different modulation index values when the pulse width value is in the boost mode.

Pulse Width	M	V_{Phase}/THD	V_{Line}/THD	I_{Phase}/THD
0.1	1	24.99 19.08%	43.29 18.29%	6.577 19.08%
	0.9	24.39 19.24%	42.24 18.45%	6.418 19.24%
	0.642	22.7 19.66%	39.32 18.87%	5.974 19.66%
	0.55	22.02 19.84%	38.15 19.04%	5.796 19.84%
	0.4	20.77 20.15%	35.97 19.36%	5.465 20.15%
0.45	1	160.8 16.25%	278.5 15.43%	42.32 16.25%
	0.9	162.4 16.42%	281.3 15.60%	42.73 16.42%
	0.642	163.1 16.96%	282.5 16.14%	42.92 16.96%
	0.55	157.7 17.08%	273.1 16.26%	41.49 17.08%
	0.4	126.4 17.16%	219 16.35%	33.27 17.16%

As the values in Table 3 are handled, it is seen that the output voltage is highest when the pulse width is close to 0.5 and the modulation index is greater than 0.5. As a result, according to different modulation indexes and pulse widths, the simulation results show that ZSIs make it possible to obtain the desired voltage level by simply changing the inverter gain without the need to change the DC voltage value applied to its inputs.

The effective values of the output phase voltage, line voltage, phase current, and harmonic spectrum of the ZSI and VSI are comparied with each other for the same modulation indexes and different pulse width ranges in the Table 4.

Table 4. Comparison of the performance results of the ZSI and VSI for M=0.8 and R=5 ohm, L=8 mH.

f_s kHz	V_{Phase}/THD ZSI	V_{Phase}/THD VSI	V_{Line}/THD ZSI	V_{Line}/THD VSI	I_{Phase}/THD ZSI	I_{Phase}/THD VSI
Pulse Width=0.1						
5	43.48	24.16	75.25	41.87	7.769	4.318
	18.39%	3.30%	19.19%	1.84%	19.27%	4.86%
10	29.38	24.1	51.67	41.76	5.331	4.307
	18.14%	3.30%	19.20%	1.85%	19.28%	4.86%
15	25.56	24.2	44.26	41.91	4.567	4.324
	18.44%	3.30%	19.23%	1.85%	19.31%	4.86%
20	26.25	24.6	45.47	42.62	4.691	4.397
	18.20%	3.30%	18.99%	1.86%	19.08%	4.86%
Pulse Width=0.4						
5	329.7	33.56	571	58.15	58.92	5.997
	16.03%	3.30%	16.85%	1.86%	16.96%	4.86%
10	174.6	33.5	302.5	58.03	31.19	5.986
	16.03%	3.30%	16.85%	1.87%	16.97%	4.86%
15	122.9	33.59	212.9	58.18	21.96	6.003
	15.97%	3.30%	16.79%	1.88%	16.91%	4.86%
20	96.35	33.34	166.9	57.74	17.22	5.957
	16.01%	3.30%	16.82%	1.88%	16.94%	4.86%

According to the Table 4, the effective values of the phase voltage, line voltage and phase current vary significantly depending on the switching frequency and pulse width in the Z-Source Inverter. An increase is observed in the effective values of the phase and line voltages and phase current, especially at low switching frequency values for both step-down/boost operating states of the inverter. It is also seen that different switching frequencies and pulse width conditions do not have a great effect on these voltages and the phase current in the VSI inverter obtained by deactivating the impedance network in the modeled Z-Source inverter, and the VSI inverter continues to operate in step-down mode despite the change in the pulse width.

Conclusion

In this study, a three-phase ZSI, which is a new inverter application that eliminates the disadvantages of traditional inverters, is modeled in the simple boost switching mode by Matlab/Simulink and its suitability for the PV systems has been tried to be determined by monitoring the values of the output alternating voltage and load currnet at different operating parameters. In addition, comparison of the performances of the with VSI is realized at the same operating conditions and different frequencies to reveal the difference of the ZSI from traditional VSI. According to these comparisons, when the values in Table 2 obtained for the operating conditions of the constant M=0.642, fs=10 kHz and variable T0/T (pulse width) are examined, it is seen that the voltage value closest to the mains voltage is obtained when the pulse width is 0.499. Furthermore, it is observed that the effective value of the line voltage obtained from the inverter outputs under these operating conditions is 330.4 volts. Besides, Table 3 is examined for the constant fs=10 kHz and different pulse width values (M=0.1 and M=0.45) in boost mode and operating states in different modulation index values. It is observed that the voltage value closest to the mains voltage is obtained for the values of the pulse width and the modulation index which are 0.45 and 0.9, respectively and also, the effective value of the line voltage at the output of the inverter is 281.3 V under these operating conditions. Finally, some operating conditions which the modulation index of ZSI and VSI is fixed are compared for the different switching frequencies and pulse width values in the Table 4. According to the Table 4, the voltage value closest to the mains voltage is obtained for the values which are 5 kHz switching frequency, M=0.8, and DG=0.4. It is also observed that the effective value of the line voltage obtained from the inverter output under these operating conditions is 571 V. Accordingly, the ZSI which is designed and modeled for the fs=5 kHz, M=0.8 and DG=0.4 operating conditions, increases the DC supply voltage of 150 volts applied to its input to the mains voltage without the need for any DC-DC amplifier. As a result in this study, the quantitative data show that the use of the ZSI in the PV power generation systems is the right choice compared to the conventional inverters. In existing PV power generation systems, the duration of sunshine varies at different times of the day. Therefore, the DC voltage obtained is also not constant. In order to convert the DC voltage produced in PV power generation systems to an AC with constant amplitude and frequency using a conventional inverter, a DC-DC amplifier converter must be added between the conventional inverter used and the output of the PV arrays. As seen from the Table 4, where ZSIs are compared with the VSIs, the desired voltage from the system output can be obtained by the ZSI without the need for any amplifier in between, by choosing the duty cycle parameters and appropriate switching frequencies. The fact that the gain of ZSIs can be adjusted to a value between zero and infinity makes these inverters attractive for the PV power generation systems where the value of the input DC voltage produced at certain times of the day is constantly changing. By the help of a control system to be designed, the changes in the environmental conditions can be determined and PV systems can be utilized at the maximum level by changing the duty cycle parameters of the ZSI according to these changes. Thus, the performance and efficiency obtained from PV systems can be increased in nowadays when the need for energy has been increasing day by day.

Conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared

There is no conflict of interest with any person / institution in the article prepared

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