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# Performance Evaluation of Z-Source Inverter Under Different Conditions

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## Abstract

A suggested PI-controlled closed-loop Z-source inverter (ZSI) constructed in MATLAB/Simulink is presented in this research and evaluated under various conditions. The ZSI topology is suitable for renewable energy systems because it provides single-stage buck-boost operation through shoot-through, unlike traditional inverters such as VSI and CSI, which require additional converter stages. This paper investigated the impact of switching frequency, modulation factor, and load resistance on output voltage and total harmonic distortion (THD). Simulation results show that the output voltage remains constant at 209 V while THD decreases from 0.47% to 0.17% when switching frequency increases from 2 kHz to 10 kHz. Furthermore, the output voltage reaches 209.6 V, and THD remains low at 0.23% at 20 kHz. Simulation also shows that increasing the modulation index from 0.7 to 0.9 improves the waveform. It was also observed that the output voltage increases across loads from 10 Ω to 100 Ω. The controller maintains a low THD of 0.15% to 0.23%. These results confirm that the proposed PI-controlled closed-loop ZSI provides stable operation and good power quality for renewable-energy applications and distributed-generation systems.

***Keywords***- Z-source inverter, Boost Converter, Pulse Width Modulation (PWM), Load Regulation, Total Harmonic Distortion (THD).

## I. INTRODUCTION

Electrical power generation, particularly solar PV energy, uses the sun's light directly to produce electricity [1]. Solar energy can generate heat, electricity, and lighting [2]. Photovoltaic energy costs are predicted to fall further as supply and demand rise [3]. Because there are no moving parts in the system, it has a reasonably long lifespan due to solar power. However, because most common appliances in homes and businesses use alternating current (AC), a mix of both active and passive parts, such as inverters, is required because solar cells generate direct current (DC) [4].

It is composed of a few active and passive components [5][6]. Conventional inverters (VSI/CSI) have the following issues such as the traditional inverter operates in either boost in (CSI) mode or buck in (VSI) mode [7] [8]. To make the inverter function as a buck-boost inverter, an extra circuit is inserted before it, which results in a larger number of parts and more intricate circuitry [9].

Design of gate drivers of traditional inverters should be carried out with high accuracy in order to reduce the chances of erroneous activation of the switches caused by electromagnetic interference (EMI) [10]. Incorrect design might result in inductor open-circuiting in current-source inverters (CSI) or a shoot-through situation in voltage-source inverters (VSI). It is also associated with the possibility of shutdown caused by the high voltage and stress from voltage and current. Moreover, overlap time of CSI and dead time of VSI cause waveform distortion; also, traditional inverters have distinctive power circuitry [11][12][13][14].

To give the VSI buck and boost capabilities, a DC-DC converter is typically placed in front of it. Nevertheless, this inverter is expensive and inefficient due to the DC-DC converter, and the two-stage topologies additionally complicate the control approach [15]. Recently, distributed generation (DG) systems have employed a Z-source inverter that has both voltage-buck and boost capacities within one stage [16]. By increasing the DC voltage, the ZSI can generate an output that exceeds the DC bus voltage. The intended output is that it exceeds the DC bus voltage. Additionally, as dead time is presently not required, although any phase leg may have a short circuit, it can significantly lower output distortion and increase dependability [17]. Z-source inverters have therefore been produced in a variety of ways. Z-source inverters were introduced by authors to reduce capacitor voltage suppression, and writers have enhanced the Z-source's capacity for voltage boost inversion [18]**.** In this paper, a control topology is utilized to minimize component stress and ensure system stability across varying load conditions. Through the analysis of the performance indices, specifically the connection between the resistive load, output voltage control, and THD, this research shows how the new system offers better reliability and quality of electricity than the existing design of the Z-source inverter.

## II. OPERATING PRINCIPLE OF Z-SOURCE INVERTER

When DC voltage is applied to the load in a traditional VSI, there are six active switching states that are characterized by only one conducting switch either in the upper or lower position among the three-phase legs, in addition to two zero states that are characterized by shorting the load terminals through all the upper or lower switches. Load terminals in one, two, or three-phase legs can be shorted between the top and bottom switches in a Z-source inverter; this results in another zero state. A special buck–boosting function of the inverter is provided through shoot-through zero states; however, it stays inactive when the DC voltage is high enough to create an AC voltage. In any other case, DC input voltage is increased using shoot-through states. When the inverter bridge operates within a symmetrical Z-source structure in one of the eight non-shoot-through states for $T_1$ and a shoot-through state for $T_0$ within one switching period T [1][19][20][21].

$$T = T_0 + T_1 \tag{1}$$

The duty ratio of shoot-through is: -

$$D = \frac{T_0}{T} \tag{2}$$

$$B = \frac{1}{1 - 2\frac{T_O}{T}} \tag{3}$$

In equation (4), the DC-link voltage is:

$$V_{dc-link} = B\, V_{dc} \tag{4}$$

The buck-boost gain is: -

$$G = MB \tag{5}$$

Where the modulation index is denoted by M

The inverter's output AC peak phase voltage is:

$$V_{out} = M\, B\, \frac{V_{dc}}{2} \tag{6}$$

The capacitor voltage $V_C$ is: -

$$V_C = \frac{1 - \frac{T_O}{T}}{1 - 2\,\frac{T_O}{T}}\; V_{dc} \tag{7}$$

The voltage gain relationship for different PWM is: -

$$\frac{V_s}{GV_{dc}} = \frac{B\, V_{dc}}{G\, V_{dc}} = \frac{B}{G} = \frac{1}{M} \tag{8}$$

For Simple Boost PWM

$$\frac{V_s}{GV_{dc}} = \frac{B\,V_{dc}}{G\,V_{dc}} = 2 - \frac{1}{G} \tag{9}$$

For Maximum Boost PWM

$$\frac{V_s}{GV_{dc}} = \frac{B\,V_{dc}}{G\,V_{dc}} = \frac{3\sqrt{3}}{\pi} - \frac{1}{G} \tag{10}$$

For Maximum constant Boost PWM

$$\frac{V_s}{GV_{dc}} = \frac{B\,V_{dc}}{G\,V_{dc}} = \sqrt{3} - \frac{1}{G} \tag{11}$$

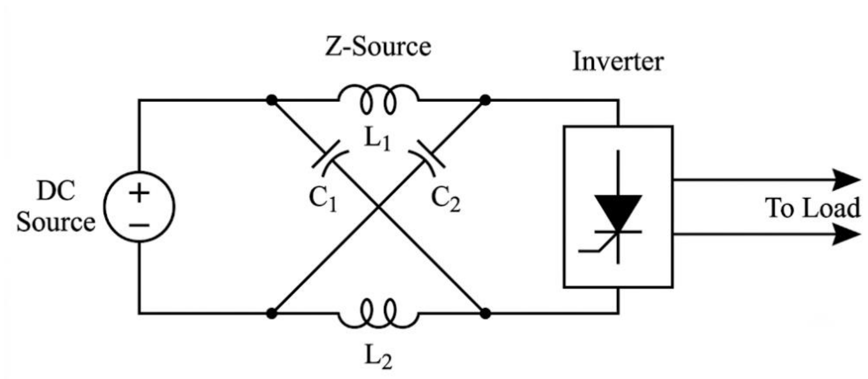
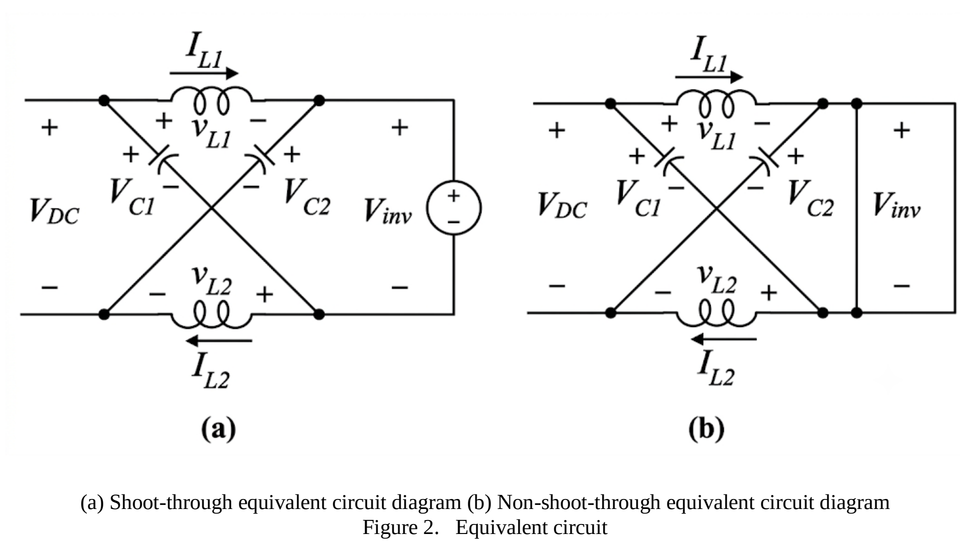



Figure 1. ZSI topology




(a) Shoot-through equivalent circuit diagram (b) Non-shoot-through equivalent circuit diagram
Figure 2. Equivalent circuit

## III. Z-SOURCE INVERTER PWM TECHNIQUES

In order to obtain the voltage boosting effect in ZSI, a shoot-through state is intentionally introduced along with active switching states. To attain the goal, only slight modifications of the conventional three-phase sinusoidal pulse-width modulation (SPWM) technique are needed. Three basic PWM techniques can be used for this purpose. They include the simple boost control, maximum boost control and maximum constant boost control.

The simplest approach is the simple boost control technique. In this case, two constant-envelope waves placed above and below three-phase sinusoidal waves are added. The shoot-through state is created whenever the triangular carrier crosses the upper envelope or goes below the lower envelope. Despite its simplicity, the achievable voltage gain is limited by considerable voltage stress of semiconductor devices. Moreover, due to the conduction of all switches during the shoot-through state, there are quite high switching losses.

Maximum boost control is an extension of the conventional carrier-based PWM control. This method creates the shoot-through state from all zero switching states, leaving six active states. The shoot-through occurs when the triangular carrier exceeds the maximum reference wave or drops below the minimum reference wave. As a result, the voltage boost range increases and the voltage stress of switches becomes smaller. However, the shoot-through duty cycle varies from one switching cycle to another, increasing the inductor current ripple. Thus, bigger inductors are needed at lower output frequencies, which increases the converter size and cost.

To eliminate such drawbacks, the maximum constant boost control technique employs not constant but two sinusoidal envelope waves at three times the fundamental modulation frequency. The shoot-through state is created in case when the carrier goes above the upper threshold or below the lower threshold. The constant shoot-through duty cycle provides significantly smaller inductor current ripple in comparison with maximum boost control and high voltage gain.

Finally, recently new space vector pulse-width modulation (SVPWM) approaches have been developed for quasi-Z-source inverters. In such case, the modulation index and shoot-through duty cycle are controlled independently, providing high voltage boosting, small switching losses, low voltage stress of semiconductors and reduced electromagnetic interference. Therefore, SVPWM techniques show better efficiency than conventional SPWM ones. [22][23][24].

## IV. MATLAB/Simulink Model

A (ZSI) closed-loop system to assess its performance was simulated and modeled under various operating situations by using Matlab/Simulink. The simulation model includes a DC voltage source, an impedance network made up of two inductors (L1 and L2) and two capacitors (C1 and C2), a three-phase inverter bridge, an LC output filter, and a resistive load.
The Z-Source network increases inverter performance and voltage gain by allowing for both step-down and step-up operations via direct connection. We measured and examined the total harmonic distortion (THD) and output voltage.
A PI controller was utilized to control the output voltage. The PI controller created a control signal by processing the error signal received from comparing the output voltage measured to a baseline value. A PWM generator then generated gate pulses for the inverter switches based on the control signal.
Some simulation tests were conducted to determine how modulation factor, switching frequency and load resistance affect the inverter's performance, using a discrete sampling time of 1 microsecond in the simulations.

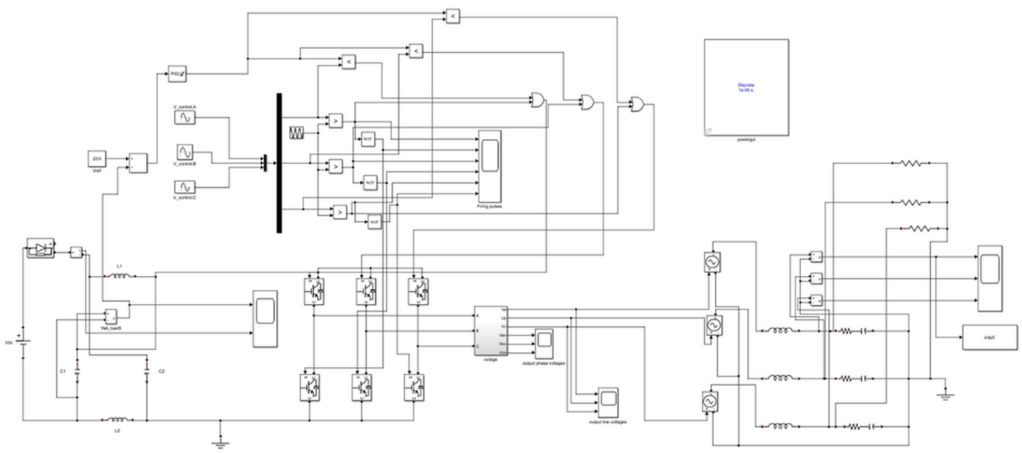


Figure3. Simulink model for ZSI

## V. RESULTS AND DISCUSSION

The efficiency of the suggested inverter is evaluated based on three different modes of operation: the variation of the switching frequency, the modulation index, and the load resistance. The focus is put on the voltage output regulation and THD, as these parameters define system stability, as shown in Table 1.

TABLE 1. SIMULATION PARAMETERS

| **Parameter** | **Value** |
|---|---|
| Input DC Voltage | 80 V |
| DC-link Voltage | 235 V |
| Load Resistance | 10-100 Ω |
| Switching Frequency | 20 ,10 ,5 ,2 kHz |
| PI Controller Gains | 25, 1 |

***a. Switching Frequency Variation***

In this study, the ZSI performance was analyzed and assessed using MATLAB/Simulink software at different switching frequencies (5-20 kHz), with Vdc = 80 V and Vdc link = 235 V. The simulation results showed an inverse relationship between THD and switching frequency, where the value of THD was found to be equal to 0.47% at a switching frequency of 2 kHz, while it decreased to 0.17% at a changing frequency of 10 kHz. Then it changed slightly to 0.23% at 20 kHz, which remains within acceptable limits. This is attributed to the improved waveform quality caused by the increased frequency, which significantly enhanced the waveform due to the filter's efficiency (LC). Simultaneously, the output voltage remained constant across the tested frequencies, confirming the PI controller's effectiveness in regulating the output voltage across frequency changes, as shown in table2.

TABLE 2. EFFECT OF SWITCHING FREQUENCY ON ZSI PERFORMANCE

| Switching Frequency (kHz) | Output Voltage (V) | THD (%) |
|---|---|---|
| **2** | 209.7 | 0.47% |
| **5** | 209.5 | 0.19% |
| **10** | 209.1 | 0.17% |
| **20** | 209.6 | 0.23 % |

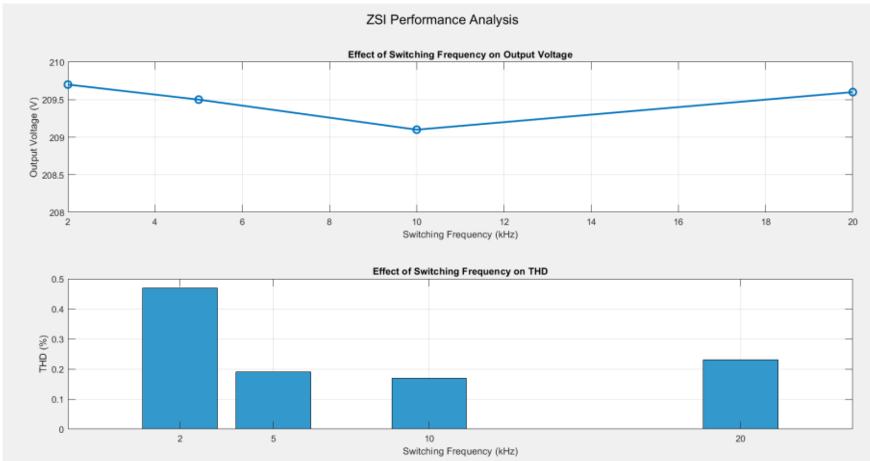



Figure 4. Effect of switching frequency

### *b. Modulation Index Variation*

The relationship between the modulation factor and system performance is displayed in Table 3. When the modulation factor increased from 0.7 to 0.9, an improvement in signal quality was observed, as the harmonic distortion (THD) decreased from 0.41% to 0.23%. The table also shows a change in the output voltage, which was recorded as 173.8 V at M=0.7 and reached 209.6 V at M=0.9, reflecting the system's ability to control the voltage level through the modulation factor.

TABLE 3. EFFECT OF MODULATION INDEX ON ZSI PERFORMANCE

| Modulation Index (M) | Output Voltage (V) | THD (%) |
|---|---|---|
| **0.7** | 173.8 | 0.41% |
| **0.8** | 189.8 | 0.40% |
| **0.9** | 209.6 | 0.23 % |

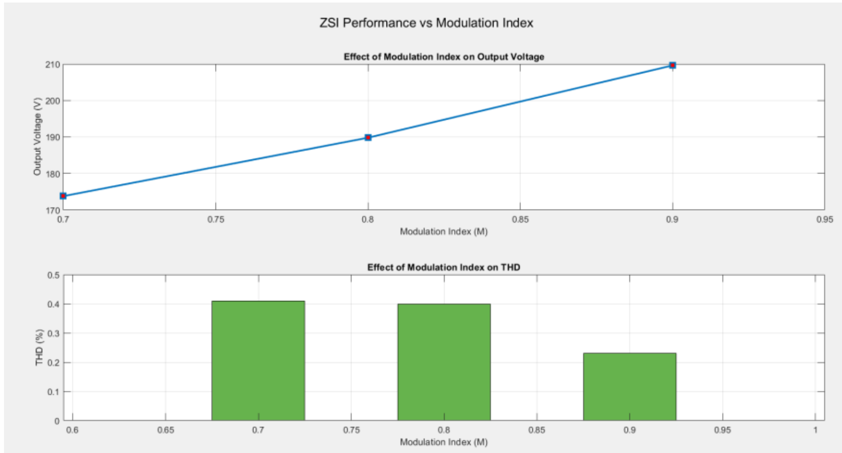



Figure 5. Influence of varying modulation index

### *c. Load Variation*

The performance of the Z-source inverter under different loads is analyzed in Table 4 using a wide range of resistance from 10 to 100 ohms to determine its dynamic stability. It is clear from the table that the designed Z-source inverter sustains a stable voltage, rising from 91.84 volts to 209.6 volts. The THD values show little change in their values in the range of 0.15% to 0.23%, demonstrating the efficiency of the controller in minimizing the impact of varying loads on the system.

TABLE 4. LOAD REGULATION

| **R load (*Ω*)** | **Output Voltage (V)** | **THD (%)** |
|---|---|---|
| **10** | 91.84 | 0.15% |
| **50** | 167.2 | 0.19% |
| **100** | 209.6 | 0.23 % |

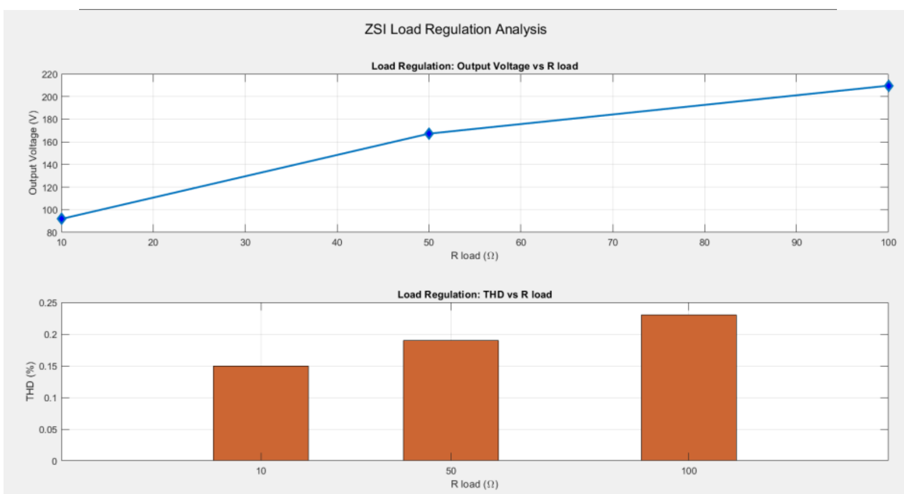



Figure 6. Influence of varying load conditions

***d. Varying Z-Network Component Values***

The performance of the system has been tested using different passive network component values (L and C) to understand the robustness and sensitivity of the proposed ZSI Converter. It is observed that an improvement in the performance of output voltage regulation and THD is achieved by increasing the Z-grid component value from case 1 to case 2. On the other hand, performance deterioration is observed in case 3 with L being equal to 2mH and C being 1000 µF, where THD drops to 0.15% and output voltage becomes 184.5V. This variation in performance indicates that if the range of values for passive components increases above their optimum value, it will negatively affect the performance of both the filter and the switching dynamics of the ZSI converter.

TABLE 5: IMPACT OF Z-NETWORK COMPONENT VARIATIONS ON ZSI PERFORMANCE

| Case | Inductance L (mH) | Capacitance C (µF) | Output Voltage (V) | THD (%) |
|---|---|---|---|---|
| **Case 1** | 0.5 | 250 | 212.3 | 0.22% |
| **Case 2** | 1.0 | 500 | 209.6 | 0.23 % |
| **Case 3** | 2.0 | 1000 | 184.5 | 0.15 % |

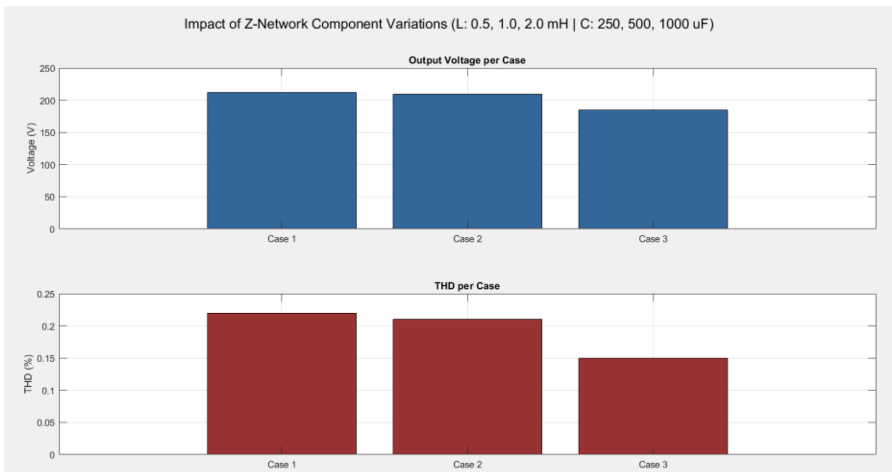
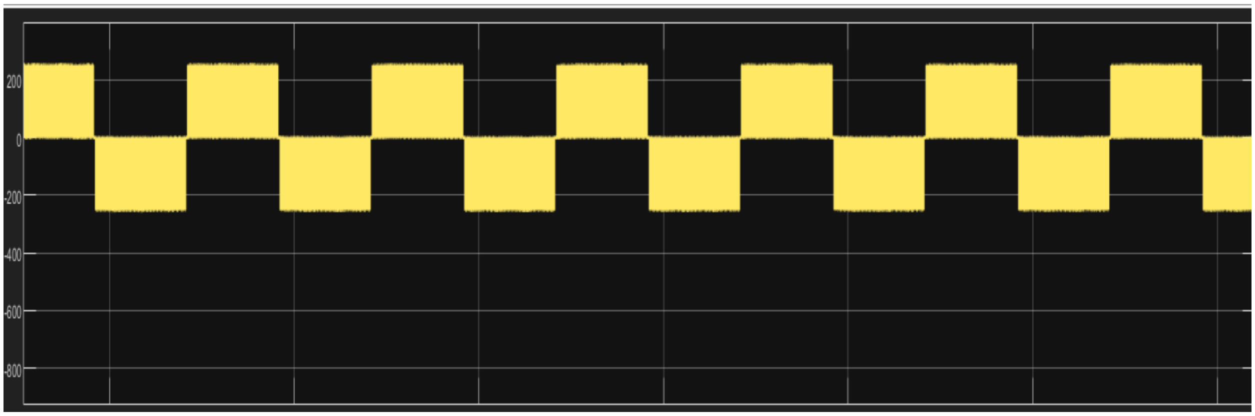



Figure 7. Effect of Z-network component

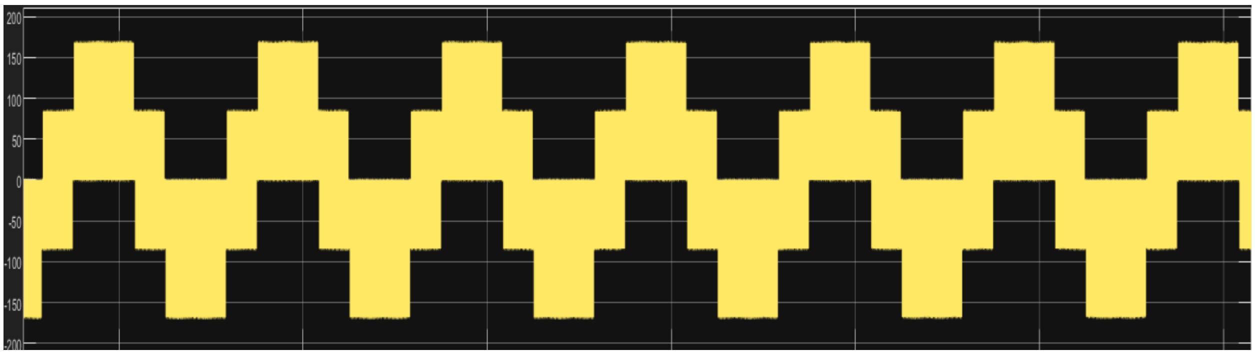
TABLE 6: OPEN LOOP VERSES CLOSED LOOP

| Performance Parameter | Open Loop | Closed Loop (PI) | Improvement |
|---|---|---|---|
| **Input Voltage (V)** | 80 | 80 | — |
| **DC-Link Voltage (V)** | 197 | 235 | +19.3% |
| **Output Voltage (V)** | 203.8 | 209.6 | +1.5% |
| **THD (%)** | 9.08 | 0.23 | 97.7% Reduction |

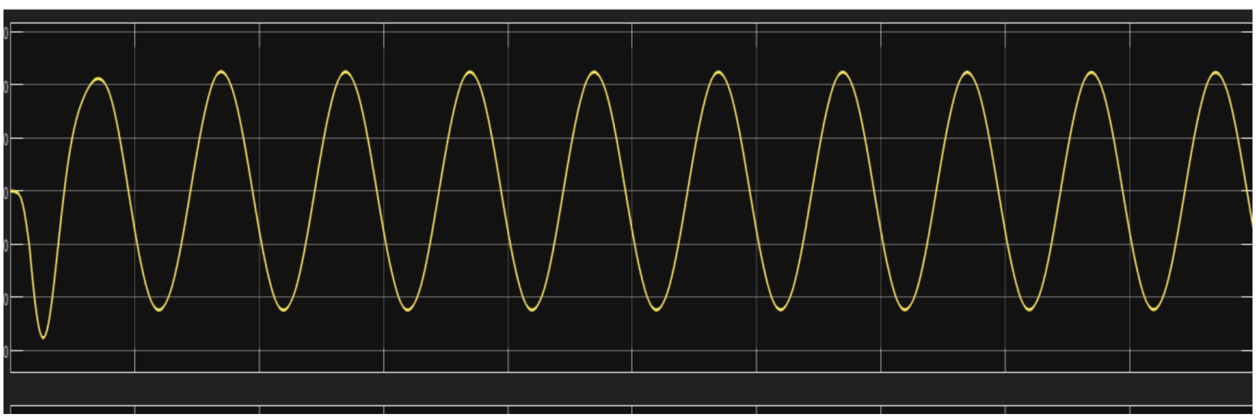
Compared with the open-loop configuration, the proposed PI-controlled closed-loop Z-source inverter demonstrates a better result in terms of voltage regulation and power quality. The DC-link voltage has risen from 197 V to 235 V, while the output voltage improved from 203.8 V to 209.6 V. As well, the total harmonic distortion (THD) significantly decreased from 9.08% to 0.23%, corresponding to approximately 97.7% harmonic reduction. These results confirm that the proposed PI controller effectively enhances voltage regulation, improves waveform quality, and increases the overall stability of the Z-source inverter.




Output line voltage




Output phase voltage



Output voltage

Figure 8. Simulation waveforms

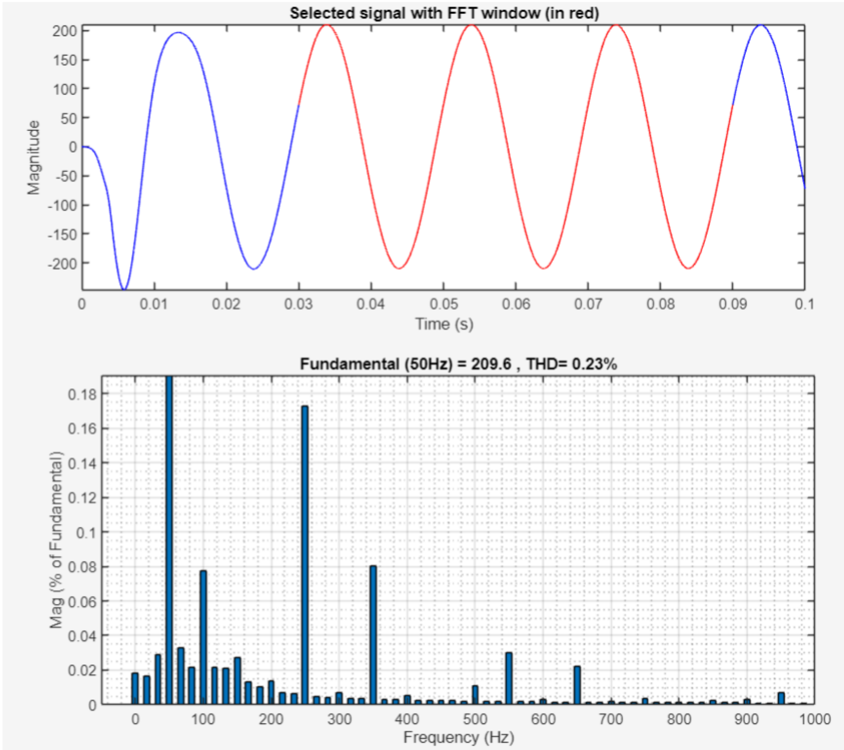



Figure 9. Fourier analysis for output voltage at 50 Hz

TABLE7. COMPARISON WITH RECENT LITERATURE [25]

| Feature | Proposed Work | Özkara and Karaarslan (2023) |
|---|---|---|
| **Inverter topology** | ZSI | qZSI |
| **Controller** | PI | CT-LSM PI |
| **Simulation** | MATLAB/Simulink | MATLAB/Simulink |
| **THD evaluation** | ✓ | ✓ |
| **Switching frequency analysis** | ✓ | ✗ |
| **Modulation index analysis** | ✓ | ✗ |
| **Load variation** | ✓ | ✓ |
| **Open-loop vs Closed-loop** | ✓ | ✗ |

The results show a reduction in total harmonic distortion (THD) and a stable output voltage. These results indicate that the proposed PI-controlled inverter achieves good voltage regulation and suitable power quality while relying on a simple control architecture. Furthermore, the comprehensive evaluation of this study demonstrates that evaluating the effects of modulation index, switching frequency, and using closed-loop (PI) control, compared to an open-loop control strategy, helps the designer select a suitable operating condition that maintains voltage stability, reduces total harmonic distortion (THD), and makes the inverter design more efficient and perform better under different operating conditions, thus making it suitable for practical applications. This is because renewable energy systems do not always operate under the same conditions.

## VI. CONCLUSION

This paper presents a Z-source inverter with closed-loop PI control. The model was implemented using MATLAB/Simulink, and the findings indicate that the output waveform quality remained stable across the 10-20 kHz range, where the best THD performance was achieved. The system maintained a low level of total harmonic distortion (THD) under varying loads. High switching frequencies and modulation indices improved harmonic performance.

PI-based closed-loop control showed a practical and efficient approach for Z-source inverter applications in renewable energy conversion and distributed power generation.

For future work, research should include experimental verification, transient response testing, efficiency analysis, and comparison with advanced controllers such as fuzzy logic, PID controllers, and model-based predictive techniques.

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