

Recent Advancements and Application Of Z-Source Inverters

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Abstract. With the imminent energy crisis, mankind's demand for clean energy is increasing. Electricity, as the foundation of today's social development, its industry is developing at a high speed, and there is an urgent need for more efficient, stable and flexible power conversion solutions in the field of power electronics. However, traditional power electronics topologies encounter limitations, especially when confronted with wide-ranging input voltage fluctuations, posing challenges for meeting practical requirements. The Z-source inverter addresses issues inherent in conventional power electronic topologies. The Z-source inverter, a novel power electronic converter, has garnered significant attention in the power electronics domain due to its promising developmental prospects. The paper initially presents advancements in Z-source inverter topology, followed by a summary of pertinent technologies, including modulation techniques and closed-loop control strategies. Furthermore, it delves into a comprehensive examination of Z-source inverters, offering valuable references and insights to further enhance their performance and reliability. Finally, the challenges faced by Z-source inverters are discussed and possible directions of development are proposed.

Keywords: Z-source inverter, topology, modulation, control strategy, challenges.

1. Introduction

As society advances, the escalating consumption of natural resources underscores the impending energy crisis and the growing demand for clean energy. Amidst this context, electrical energy assumes a pivotal role in today's society and technology, propelling the development of power systems and conversion technologies. However, traditional power electronics topologies encounter limitations, especially when confronted with wide-ranging input voltage fluctuations, posing challenges for meeting practical requirements. Furthermore, power quality concerns like harmonics and reactive currents prevalent in power systems need effective solutions. Addressing these challenges, the emergence of Z-source inverters has gained prominence in the field of power electronics [1]. Proposed by Prof. Fangzheng Peng in 2002, the Z-source inverter concept features a distinctive impedance network that allows passage through its bridge arm, enabling voltage boost conversion functionality. This not only enhances inverter reliability but also mitigates output waveform distortion [1,2]. Consequently, Z-source inverters hold promise for various applications with diverse DC chain voltages [3,4].

Recent years have witnessed extensive research on Z-source inverters, encompassing design of converter main circuit parameters, topology enhancements, PWM modulation strategies, Z-source rectification, Z-source inversion, and integration of Z-source network with matrix converters. While Z-source inverters have found application across diverse domains (such as motor speed regulation, photovoltaic power generation, electric vehicles, etc.), this study concentrates on their usage within photovoltaic grid-connected power generation, wind power generation, and electric vehicle drive systems [2,4,5,6]. In grid-connected PV systems, the Z-source inverter, leveraging its distinctive boost capability and multiple control strategies, achieves efficient and stable power conversion, meeting grid stipulations and enhancing energy utilization [5]. Likewise, within wind power systems, the Z-source inverter's lift-voltage conversion and direct modulation characteristics offer a reliable approach for controlling direct-drive permanent magnet wind turbines connected to the grid, thereby enhancing system adaptability and stability. [6]. In electric vehicle drive systems, the Z-source inverter's utilization facilitates boost functionality via pass-through states, optimizing system performance and substantially enhancing electric vehicle power output [7]. Z-source inverters find extensive application in AC speed control systems, fuel cell power systems, distributed generation

setups, and microgrids. Notably in photovoltaic systems, Z-source inverters integrate effectively with the power grid, as grid-connection control techniques are continually refined [4,5]. However, despite the manifold advantages of Z-source inverters, they grapple with power quality challenges such as harmonics, reactive currents, and the pursuit of more refined control strategies [4]. Yet, the distinctive benefits of Z-source inverters coexist with certain challenges, including high capacitor voltage stress and significant start-up inrush currents. In response, researchers have introduced two improved Z-source inverters—Quasi-Z-source inverter and novel Z-source inverter—precisely designed to tackle issues of capacitor voltage stress and start-up inrush current. [8].

In essence, Z-source inverters, as an emerging power electronics topology, encompass a wide spectrum of applications. Through continuous refinement and surmounting challenges, Z-source inverters will continue to exert a pivotal influence in the realm of power systems and conversion. This paper's objective is to introduce, analyze, and compare prototype and enhanced Z-source inverters. Furthermore, it delves into a comprehensive examination of Z-source inverters, offering valuable references and insights to further enhance their performance and reliability.

2. Advantages of Z-source inverters

The Z-source inverter, a promising power electronic converter, offers numerous advantages in power systems and conversion. This paper highlights its five key strengths: enhanced reliability and stability, adaptability to wide input voltage ranges, heightened power conversion efficiency, versatile application across multiple domains, and improved power quality [1, 2].

High reliability and stability: The Z-source inverter utilizes a unique impedance network design, allowing bridge arm passage and voltage boosting. Unlike traditional inverters, it notably enhances waveform quality, circumventing dead zone-induced waveform distortion [1, 2, 8]. This elevates system stability and reliability, effectively catering to diverse input voltage fluctuations [9, 10].

Wide range input voltage adaptability: Traditional inverters struggle with varying input voltage, unlike the Z-source inverter which, due to its unique impedance network, excels in stability across voltage ranges, rendering versatile power conversion for systems [11, 12].

Efficiency of electrical energy conversion increased: The Z-source inverter's design minimizes energy loss in power conversion. Its unique impedance topology and direct lift-voltage conversion function significantly curtail energy consumption [8, 13, 14]. This heightened efficiency lessens environmental impact and bolsters energy utilization efficiency, crucial for addressing energy scarcity and environmental concerns.

Wide range of applications in multiple fields: Z-source inverters find diverse applications. In AC speed control systems, they enable precise motor control, enhancing efficiency and stability [4]. In fuel cell power systems, they stabilize output voltage for consistent operation. For distributed generation and microgrids, they manage energy balance, enhancing reliability and autonomy [7,11]. These broad applications establish Z-source inverters as a power electronics research focus with practical engineering significance.

Effective solutions to power quality problems: Power quality issues like harmonics and reactive currents are prevalent in power systems. Z-source inverters, through refined design and control strategies, effectively mitigate these power quality challenges, enhancing power system stability and reliability [2, 8].

3. Comparison between Different Z-Source Inverters

3.1. Conventional Z-Source Inverter

The traditional Z-source inverter, a novel power electronic converter, incorporates a distinct impedance network that enables bridge arm passage, thus achieving lift-voltage conversion. However, practical deployment exposes certain shortcomings. Issues include zero capacitor voltage at startup causing elevated input currents that could harm the inverter, discontinuous output currents, and

capacitor voltage surpassing input voltage [1,8]. These constraints curtail the conventional Z-source inverter's boost capability and stability, compelling scholars to suggest diverse enhanced topologies for performance enhancement.

Fig. 1 illustrates the Z-source inverter topology. Unlike traditional inverters, it introduces a 9th zero-vector state, where upper and lower power switches simultaneously conduct within a bridge arm. This state, unconventional in traditional inverters, enables the boost function. U_{dc} denotes the dc input voltage, while L_1 , L_2 , C_1 , and C_2 , assumed equal (L and C), lead to a symmetrical Z-source network. Capacitor voltages U_{C1} , U_{C2} , and inductor voltages U_{L1} , U_{L2} satisfy symmetry principles: $U_C = U_{C1} = U_{C2}$, $U_L = U_{L1} = U_{L2}$. This symmetry underpins stable and optimized Z-source inverter performance [1].

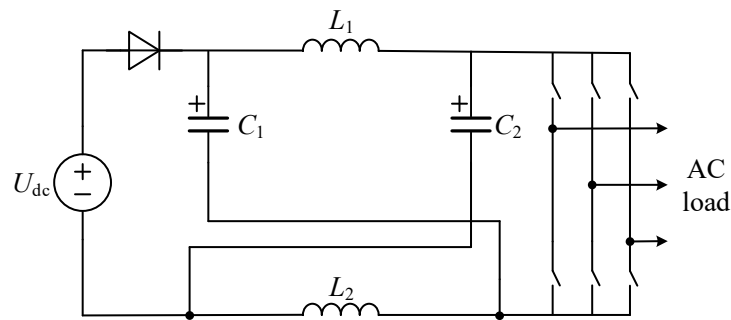


Fig. 1 Topology of Z-source inverter [1]

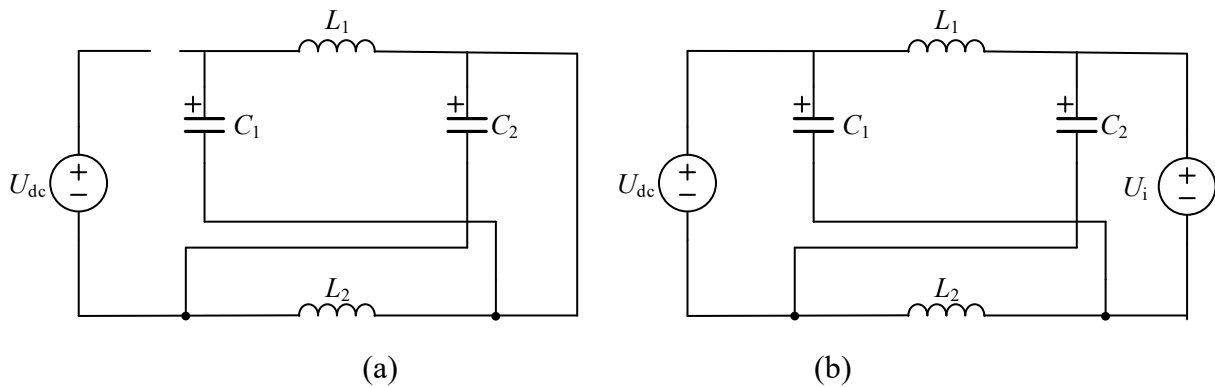


Fig. 2 Steady state performance analysis of Z-source inverter. (a) Straight-through zero-state. (b) Non-straight-through zero-state [1].

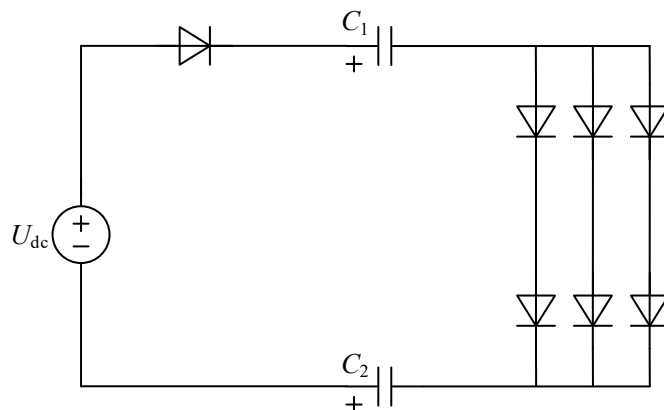


Fig. 3 Start equivalent circuit of Z-source inverter [1]

Fig. 2 illustrates the equivalent circuit of a Z-source inverter [1, 2]. Assuming the inverter's bridge arm is on during time T_0 within a switching cycle T , while the voltage applied to both ends of the inverter bridge at this time is U_i . The analysis of Figure 2(a) leads to the following conclusions $U_i=0, U_L=U_C$. During the startup of the Z-source inverter, a current path as shown in Fig. 3 will be

formed due to the zero initial voltage of the capacitor and influenced by the interaction of the IGBTs and the anti-parallel diode in the inverter's the bridge arm [1, 2].

3.2. Quasi-Z-Source Inverters

To address certain limitations of conventional Z-source inverters, researchers have introduced the concept of quasi-Z-source inverters. In the topology shown in Fig. 4, an asymmetric design is adopted by rearranging the position of the inductor L_2 so that it is connected in series with the dc power supply. This design guarantees uninterrupted input current in the quasi-Z-source inverter, reducing the need for additional filters, thus reducing system size and cost. In the fifth figure, the cathode node position of capacitor C_1 is adjusted based on the structure shown in Fig. 5 [15]. This modification aligns the capacitor voltage with the supply voltage, mitigating inrush current and diminishing capacitor-end voltage stress. Despite partial improvements by the quasi-Z-source inverter, it does not fully maximize the Z-source inverter's boosting capability [15].

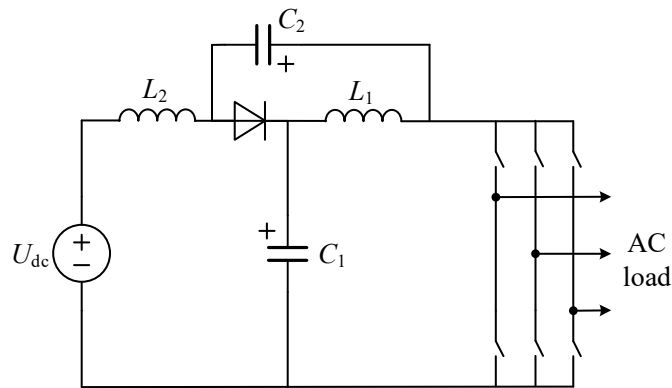


Fig. 4 Input current continuous quasi-Z-source inverter [4]

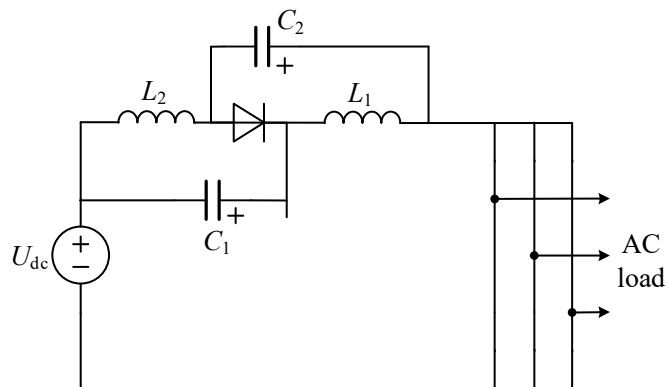


Fig. 5 Capacitor voltage stress reduction quasi-Z-source inverter [4]

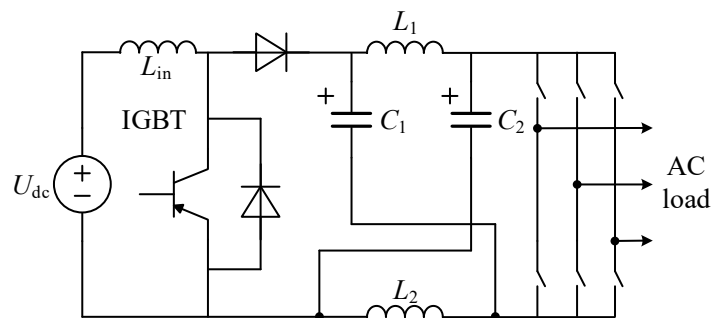


Fig. 6 Pre-boost Z-source inverter [4]

3.3. Improved Z-Source Inverter with Increased Boost Capability

To enhance the Z-source inverter's boosting capability, researchers have proposed augmented topologies, including the addition of an active switch and an inductor to the traditional design (Figure 6). This integration, together with the diode from the original circuit, constitutes a front-stage Boost circuit. This arrangement is serially connected with the Z-source network to augment its boosting capacity. This configuration offers the benefit of uninterrupted input current and does not form a starting inrush loop, effectively eliminating the effect of inrush current [15,16].

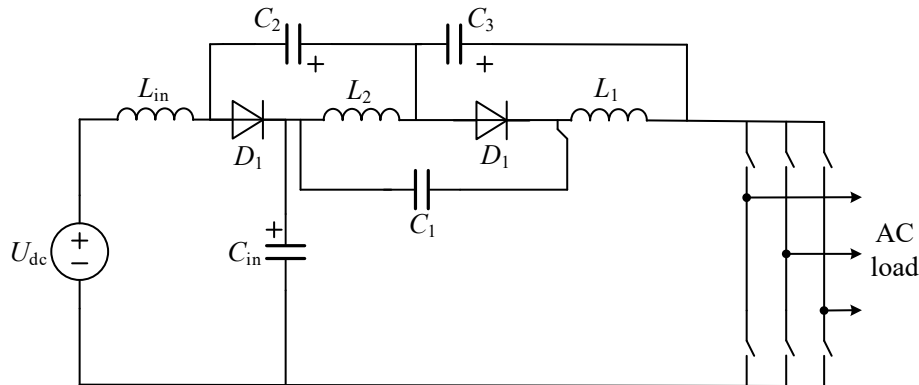


Fig. 7 Capacitor-assisted stretch type Z-source inverter [4]

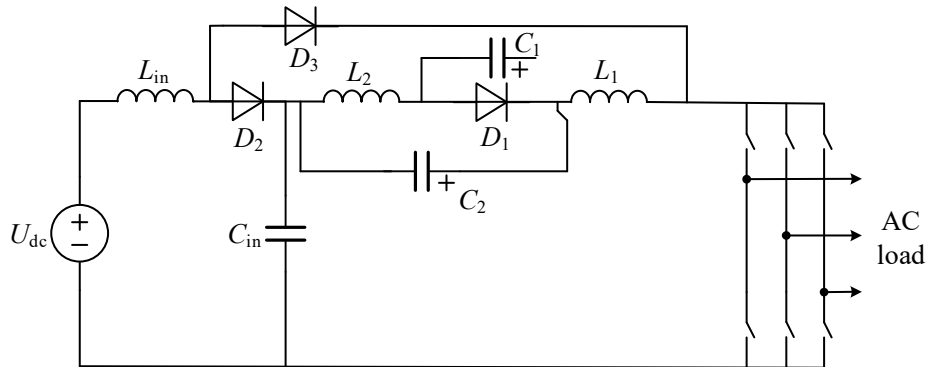


Fig. 8 Diode-assisted stretch type Z-source inverter [4]

Another improved topology, shown in Fig. 7, can increase the boosting capability by adding inductors and connecting them in series with the input power supply, forming a Boost circuit with the input power supply and then connecting them in series with the Z-source network [15,17]. This topology also has the advantage of continuous input current. In addition, this topology is scalable and the boosting capability can be further improved by adding series networks [4, 15].

An enhanced topology, depicted in Figure 8, replaces a diode with a capacitor in the conventional Z-source inverter enhances its boosting capacity. This topology offers the benefit of continuous input current [15].

3.4. Improved Z-Source Inverter with Increased Boost Capability

All three discussed topologies exhibit continuous input current, enhancing Z-source inverter performance. Nevertheless, these topologies exhibit modest voltage boosting effectiveness. To further enhance the Z-source inverter's boosting capability, we introduce the switched inductor technique. Specifically, in the topology, we replace the conventional Z-source inductors with switched inductor branches, as shown in Fig. 9. This innovative improvement not only adds three diodes and an inductor in each inductor branch, but also differs from the conventional topology. Although this may entail some cost increase, it pays off in terms of significantly improved boost capability [15-17].

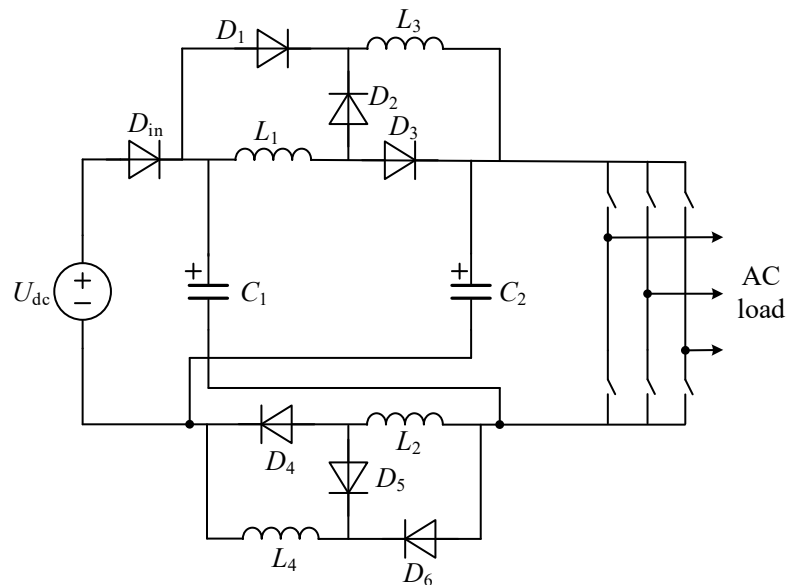


Fig. 9 Switched inductor type Z-source inverter [4]

Table 1. Comparison between different Z-source inverter

Types	Characteristics
Conventional Z-source inverter	Upper and lower bridge arms pass through to boost the input DC voltage The inverter will not be damaged by the straight-through condition caused by electromagnetic interference, etc. Higher size and cost of Z-source network capacitors Z-source inverter with limited boost capability The presence of a start-up shock circuit in the converter can easily damage the inverter.
Current-continuous quasi-Z-source inverter	Asymmetric structure Simplified filter circuit Reduce system size and cost
Capacitor Voltage Stress Reduction Quasi-Z Source Inverter	The capacitor voltage is the same as the power supply, thus greatly reducing the voltage stress on both sides of the capacitor.
Front Boost Z-Source Inverter	no start-up shock circuit no need to add additional control sections
Capacitor-assisted stretch Z-source inverter	This topology is scalable, and it can further increase boost capability by adding a series network without increasing the number of switching devices.
Diode-assisted stretch type Z-source inverter	It has stronger boosting capability compared with the traditional z-source inverter. Has the advantage of continuous input current.
Switched Inductor Z-Source Inverter	Higher cost and higher boost capability compared to other improved z-source inverters.

3.5. Several Other Improved Z-Source Inverter

Furthermore, novel topologies enhance boost capacity and alleviate capacitor voltage stress, there are some several other improved Z-source inverters. Some of these topologies achieve circuit current continuity and reduce the start-up shock by changing the original circuit component distribution, while others achieve circuit simplification at the expense of reducing the boost capability, thus reducing the cost. Each of these topologies has its own characteristics and can be advantageous in different application scenarios, which is summarized in Table 1 [4,15].

3.6. Advantages of Z-source inverter in applications

Boost function, stable output voltage applies to both photovoltaic and wind power generation systems, because of the influence of the environment, their output voltage has a large fluctuation and unstable, and the electric car also exists because of different working conditions such as starting, accelerating and so on, the voltage exists a large fluctuation. Reduced battery array requirements. Straight-through modulation to ensure system output power and improve system energy utilization. It's direct modulation eliminates dead time seen in conventional inverters, which improves the response speed and dynamic performance of the system. The grid-connected control strategy of the inverter maintains in-phase current with grid voltage, achieving a high power factor and minimizing grid pollution.

4. Control Strategy for Z-Source Inverter's DC Link Voltage

4.1. Control Strategy for DC Link Voltage

In power electronics, inverter control is crucial. While traditional inverters mainly focus on AC-side control with established methods, the unique characteristics of Z-source inverters require special attention to DC chain voltage control for practical needs. Adaptation of traditional inverter control strategies is feasible for Z-source inverters [8]. For common inverters under PWM modulation, a zero vector can adjust DC chain voltage. Unique Z-source inverter characteristics necessitate precise DC voltage control due to volatile new energy sources [18]. Fluctuations in DC voltage can impact inverter output performance. Traditional open-loop systems suffer output degradation or damage from input voltage variation [9,18]. Closed-loop control ensures stable performance, intrinsic to Z-source inverters' operation, eliminating extra DC-side control circuits. A set DC chain voltage value and controller enable stable Z-source inverter operation, adjusting on-time for stable DC voltage [8,18].

DC chain voltage control divides into direct and indirect methods. Direct control entails peak detection and real-time input to the controller, with high accuracy but complexity [9,18]. Indirect control relies on capacitor voltage monitoring for stability, easier to measure, reducing complexity, and improving dynamic response [9]. DC chain voltage acquisition from DC voltage or capacitor voltage is challenging due to the square waveform, often needing complex second-order filters. Capacitive voltage feedback strategies are common. Literature suggests PID-controlled capacitor voltage stabilization while AC-side using open-loop control [19]. However, output power quality might be compromised.

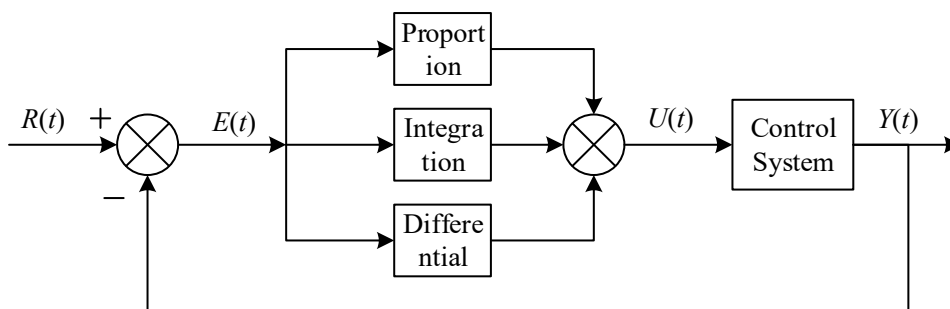


Fig. 10 Structure of conventional PID control algorithm [8]

4.2. PID control strategy for DC Chain Voltage Control

In practical engineering, the PID control algorithm remains prevalent. Its model-independent application and mere three parameters facilitate simpler tuning compared to more intricate modern control methods. Moreover, its algorithmic simplicity demands less microprocessor computation, consequently reducing industrial production costs [19]. Fig. 10 illustrates the structure of a conventional PID controller, comprising three fundamental components: proportional, integral, and

differential. The proportional element addresses current error, the integral term mitigates steady-state error, and the differential factor suppresses system overshoots and oscillations. The PID controller's output is a weighted sum of these elements, each optimizable through parameter adjustment to meet system control requisites [9,19].

In positional PID control, controller output directly influences system position, making output errors critical for stability. In contrast, incremental PID control mitigates such errors' impact on the system [5,8,9], rendering it programmably favored for practical applications.

Figure 11 portrays the DC chain voltage control structure of the Z-source inverter based on PID. Voltage acquisition circuit gathers Z-source network capacitor voltage, computing DC chain voltage peak. PID controller processes this peak difference versus set peak. Its output, the pass-through duty cycle, feeds the Space Vector Pulse Width Modulation (SVPWM) controller, regulating inverter bridge [5,9,19]. This process maintains desired DC chain voltage, ensuring system stability.

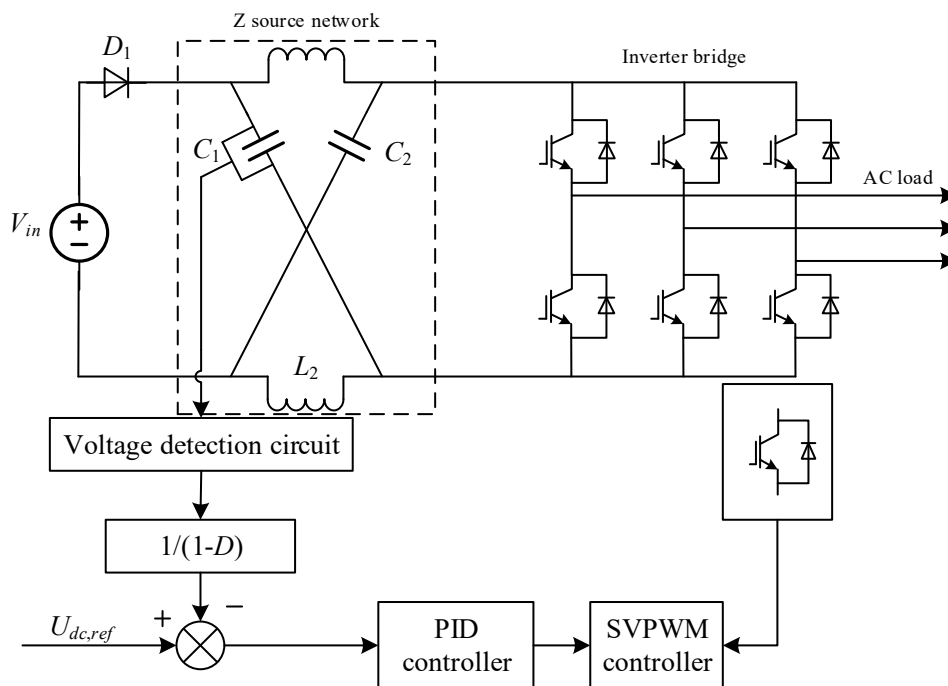


Fig. 11 PID-based control structure for Z-source inverter's DC link voltage [8]

However, PID-based control systems face stability issues due to parameter sensitivity and struggle with balancing overshoot and rapid response [8,19-21]. Ideal differentiator implementation is practically limited. Integrators eliminate steady-state errors but risk integral saturation, potentially leading to oscillations and prolonged regulation [19,21].

To address these PID control challenges, the linear self-immunity control technique introduces a linearly expanding state observer to extract feedback signal differentials. The real-time estimation of total system perturbation by this observer enables perturbation compensation via control law, avoiding integral feedback drawbacks and enhancing perturbation immunity [9,19,21]. The control law's simple linear PD combination maintains PID benefits. This advancement is anticipated to further enhance Z-source inverter control performance.

4.3. DC Voltage Control Strategy Based on Linear Self-Impedance Control

The surge in Active Disturbance Control (ADRC) techniques arises from the pressing need for alternative control algorithms beyond traditional PID. While control theory has advanced notably since the industrial revolution and aerospace development in the 1950s fostered modern control theory, PID control still dominates engineering practice, often exceeding 95% application rate [8,9]. However, many engineering systems with PID closed-loop control exhibit incongruent control outputs that lead to mechanical wear and energy wastage.

Han Jingqing introduced an error reduction-based approach known as self-immune control. This method amalgamates internal and external disturbances into total disturbance and offers real-time compensation. Self-immune control rectifies PID shortcomings, notably enhancing system dynamic response speed and reducing overshoot [9,21]. The self-immune controller integrates Tracking Differentiator (TD), Extended State Observer (ESO), and Nonlinear State Error Feedback (NLSEF) control law [9,19], as shown in Figure 12 for a second-order system.

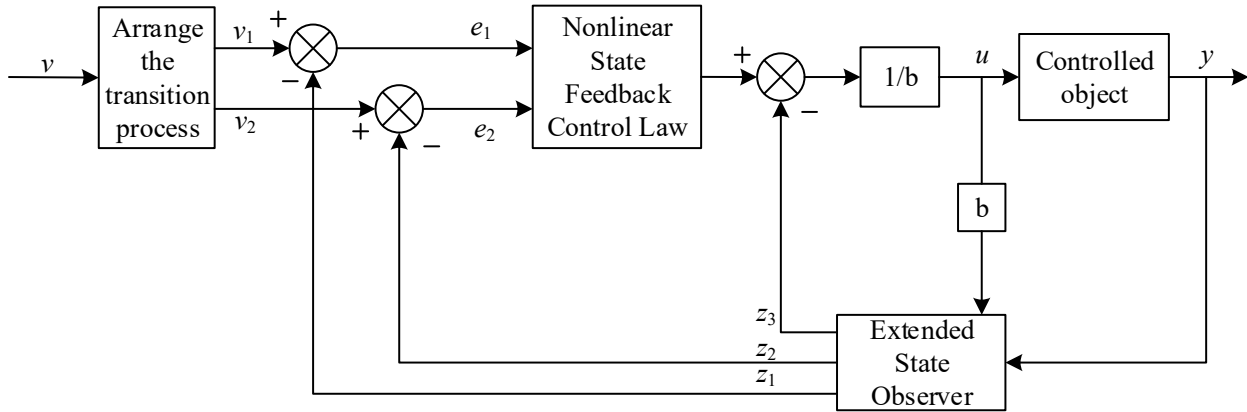


Fig. 12 Nonlinear self-immune controller [8]

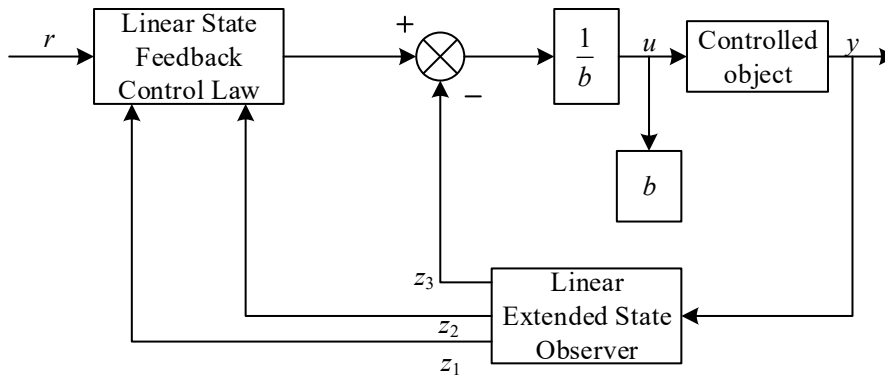


Fig. 13 Block diagram of linear self-immunity control [8]

The newly developed control strategy exhibits robust steady-state and transient responses while being independent of intricate mathematical models, contributing to energy savings. These features underline its significance. Nevertheless, the "user-friendliness" of widely adopted control strategies stands as a pivotal factor in assessing their real-world feasibility. Over recent decades, more efficient control algorithms than PID have emerged; however, they have struggled to surpass PID due to their demanding application conditions and complexity. Consequently, user-friendliness is a pivotal trait for a technology to gain wide traction in engineering applications. Given the Z-source inverter's nonlinear traits, tailored control methods suitable for nonlinear systems are essential. In this context, self-oscillatory control particularly suits DC voltage control in Z-source inverters, fully harnessing their distinct advantages. For self-oscillatory control, optimal outcomes are achieved by selecting nonlinear extended state observers and feedback control laws. Nonetheless, the complexity of parameter tuning limits its applicability in practical engineering scenarios. Conversely, Linear Auto-Disturbance Rejection Control (LADRC) achieves outcomes akin to traditional auto-disturbance control while significantly streamlining parameter adjustment complexities, rendering it more suitable for engineering applications [8,9]. Despite advances, PID controllers still find widespread use in engineering due to their simplicity and versatility across scenarios. Yet, conventional self-oscillating controllers entail complex parameter tuning, curbing their broader engineering implementation. Linearizing the extended state observer and control law in these controllers greatly simplifies parameter adjustment, rendering linear self-oscillating control more applicable in engineering practice [8]. This method has found application across various engineering domains. The

feedback control law part of the linear self-immunity controller is described in detail below. The block diagram of the linear self-immunity control is shown in Fig. 13.

Capacitive voltage in the Z-source network is acquired using voltage detection circuitry, enabling calculation of the peak DC chain voltage. This peak value along with its corresponding reference value is used as an input to the linear self-oscillating controller. After the computation of the linear self-oscillating controller, the required pass-through duty cycle for supplying the space vector modulation (SVPWM) controller will be obtained [8,18,22]. Its design scheme provides a key support to ensure the stability and high efficiency of Z-source inverters in practical applications. The dc-chain voltage control structure based on linear self-immunity control is shown in Fig. 14. The block diagram of the linear self-immunity controller structure is shown in Fig. 15.

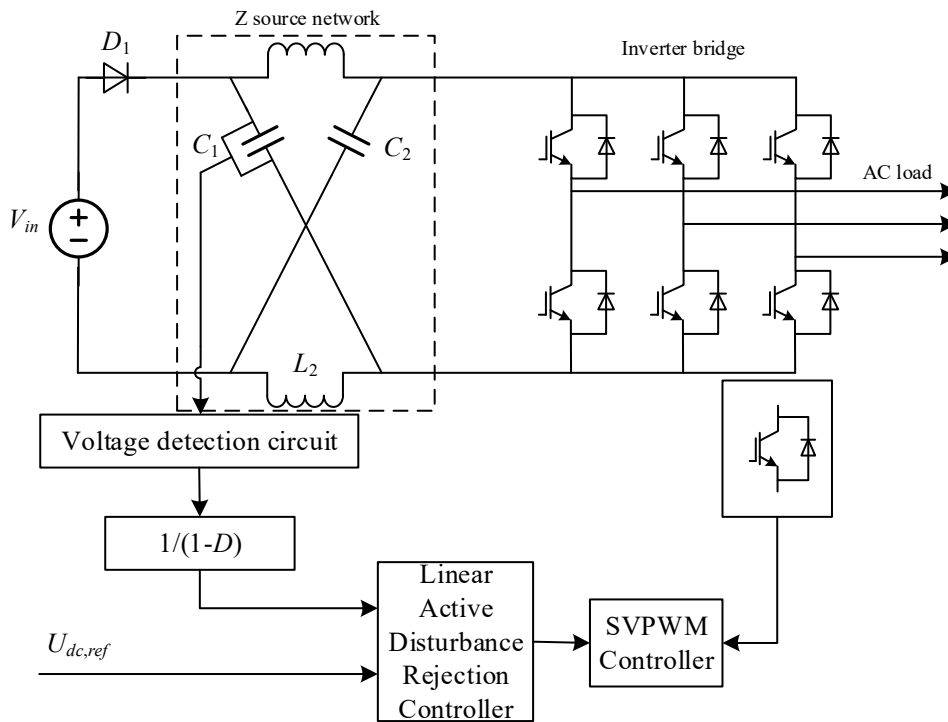


Fig. 14 Structure of DC chain voltage control based on linear self-immunity control [8]

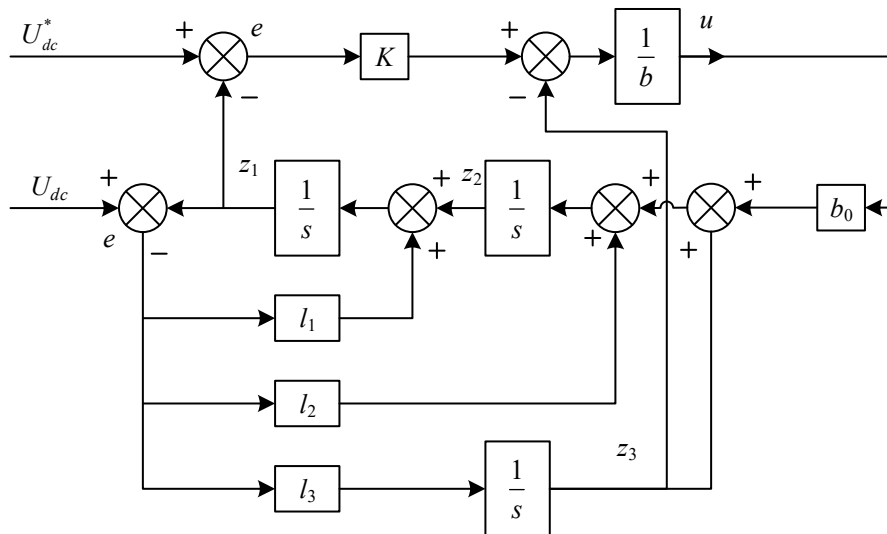


Fig. 15 Block diagram of linear self-immunity controller structure [8]

The first and foremost step of the linear auto-impedance control (LADRC) based DC chain voltage control system for Z-source inverters involves the utilization of a linear expanded state observer (LESO) to observe the overall perturbations of the Z-source inverter system. Subsequently, the system

aims to mitigate disturbances using linear error feedback control (LESF). Eventually, the control volume straight through duty cycle is obtained [8,23]. This control method provides a more effective guarantee for the stability and response performance of the DC chain voltage in Z-source inverter systems.

Utilizing linear self-immunity control signals, the Space Vector Pulse Width Modulation (SVPWM) controller dynamically adjusts the pass-through duty cycle, enabling accurate regulation of capacitor voltage [8,18]. The use of this control strategy enables the voltage across the capacitor in the Z-source network to be maintained at a stable level.

5. Challenges, Solutions, and Future Prospects

5.1. Common Problems and Corresponding Solutions

In the widespread application of Z-source inverters, addressing common issues is crucial. Harmonic problems arise due to potential output voltage harmonics impacting power system quality. Effective mitigation involves filter design optimization to control harmonic content within acceptable limits [2,4]. Stability concerns are another focal point. To ensure system stability, controller parameter adjustments optimize the strategy, preventing instability and faults through system modeling and simulation [8,15]. Advanced control strategies like adaptive control or model predictive control enhance dynamic performance and precision. These methods adjust parameters based on operational states, yielding rapid and stable system responses [8]. Additionally, selecting an appropriate multilevel topology for specific applications is pivotal. Optimal topology choice aligns with requirements and performance benchmarks, harnessing Z-source inverter advantages and catering to diverse scenarios. Despite Z-source inverters' benefits, issues of harmonics, stability, control strategies, and topology persist. Harmonic issues are resolved using filters, stability via strategy optimization, and topology choice for enhanced potential. Further research and optimization of Z-source inverter technology and application strategies are vital for better results.

5.2. Future Prospects

Looking ahead, the emergent Z-source inverter holds significant promise in ongoing research and applications within power electronics. Future directions encompass optimizing Z-source inverters to boost efficiency, reliability, and versatility [2,8,15].

Efficiency enhancement is paramount. Investigating operation and circuit attributes can refine control strategies and topologies to reduce harmonics and power loss, enhancing efficiency and stability. This entails exploring advanced control algorithms and topology optimizations grounded in modern power electronics theories [8,15].

Multi-energy integration is a key pursuit. In microgrids, hybrid energy systems, and electric vehicle-power system integration, Z-source inverters align diverse energy sources, fostering sustainable clean energy development and reducing reliance on conventional sources.

Novel materials research is essential. Exploring new material properties enhances advanced capacitive and inductive component design, amplifying Z-source inverter performance and reliability, necessitating collaboration with materials science experts.

Integrating intelligent control strategies is pivotal. Infusing artificial intelligence into Z-source inverter control enhances automation and intelligence, augmenting system response and adaptability, thus expanding horizons for power electronics applications.

Continued Z-source inverter refinement is vital. Beyond discussed aspects, efforts encompass topology enhancement, output voltage stability, cost reduction, and control algorithm improvement. Exploring Z-source inverter potential spurs technological advancement, innovation, and clean energy conversion, aligning with sustainability goals.

6. Conclusions

This paper presents recent advancements in Z-source inverters and their applications in power electronics. Through an analysis of topologies, modulation, and control. The unique impedance network design imparts high reliability and stability, adapting to varying input voltages. Straight-through modulation achieves lift-voltage conversion, enhancing efficiency and reducing losses. Z-source inverters find applications in PV grids, wind power, and EVs, contributing to clean energy growth. Comparing enhanced Z-source topologies—quasi-Z-source, improved inverter with active switches/inductors, and diode-to-capacitor replacement—highlights benefits. Optimal topology selection aligns with requirements for enhanced boosting, stability, and efficiency. For control, indirect Z-source inverter DC voltage control exhibits advantages. Linear self-oscillating control stands out, addressing PID limitations. A linear self-immunity controller includes an observer and feedback, with detailed parameter tuning. Simulations verify its superiority over PID, especially in handling power supply fluctuations and load changes. Addressing Z-source inverter challenges, such as harmonics, stability, control, and multilevel topology, this paper offers remedies. Harmonic filters, control optimization, and topology selection effectively overcome these issues, unlocking Z-source inverter potential across applications.

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