Analysis Of Development of Traction Inverters and Control Strategies and Optimization of PWM And SVPWM

Chenyu Peng *

School of Electrical and New Energy, Three Gorges University, Yichang, 443002, China

* Corresponding Author Email: 202110090813@ctgu.edu.cn

Abstract. This article delves into the pivotal role of traction inverters in electrified transportation, highlighting their evolution, control strategies, and the challenges faced in optimizing their performance. Initially, it outlines the core principles of traction inverters, which convert direct current into alternating current to drive motors and discusses the historical progression from mechanical transmissions to advanced power electronics. The paper then explores two prevalent control methods, Pulse Width Modulation (PWM) and Space Vector Pulse Width Modulation (SVPWM), detailing their mechanisms and benefits. Moreover, it presents recent advancements like Discrete Waveform Optimization (DWO)-PWM and 240-degree clamped SVPWM, which have significantly reduced energy loss and electromagnetic interference. The article concludes by addressing the ongoing challenges in improving efficiency and reliability and underscores the importance of traction inverters in the broader context of sustainable transportation. The research presented herein is poised to contribute to the development of more efficient and reliable electric vehicles, thereby supporting the transition towards cleaner energy sources.

Keywords: Traction Inverters; Electrified Transportation; PWM; SVPWM; Energy Efficiency.

1. Introduction

In the field of electrified transportation, the technological advancement of traction inverters is increasingly becoming a key driver of progress. These inverters not only improve energy conversion efficiency but also facilitate the widespread application of electrified transportation vehicles such as electric cars and high-speed trains by providing efficient power support for electric motors [1]. The latest research indicates that traction inverters utilizing Silicon Carbide (SiC) semiconductor materials can further enhance efficiency and reliability, which is particularly important for large-scale electrified transportation vehicles such as electric buses [2]. Moreover, the topology and control strategies of traction inverters are continually advancing to meet the power and efficiency demands of different transportation systems [3].

The article will begin by introducing the working principle and basic theory of the traction inverter, followed by an explanation of its development history and practical applications in production. Next, two commonly used control methods will be introduced, along with their working principles and respective advantages. Then this paper will introduce the improved control methods based on these two methods Finally, the challenges encountered in the development of traction inverters will be discussed, along with prospects for future technological advancements.

2. Basic theory

First and foremost, as a power electronic device, a traction inverter's fundamental function is to transform the direct current provided by the power source into alternating current in order to drive the traction motor. Its foundational theory involves numerous fields such as power electronics technology, control theory, and the principles of motor driving.

In the process of converting direct current to alternating current, the control of switching devices becomes pivotal. Usually, Pulse Width Modulation (PWM) technique is applied to realize precise control over the output voltage and frequency. By adjusting the breadth and frequency of the output pulse, the inverter can generate the required alternate current signal to accurately control the motor's torque, speed, and direction [4].

Additionally, the control system of a traction inverter plays a crucial role. The control system adjusts the output voltage and frequency in line with the traction system's requirements by closely monitoring the status of the motor and inverter in real-time. In some advanced traction systems, vector control technology is adopted to enhance the motor's performance and efficiency, leading to more accurate motor control and dynamic responses.

2.1. Development history

From the early 20th century to the 1960s, electric vehicles predominantly utilized direct current (DC) motors as their power source, and DC power systems typically employed DC motor controllers for motor operation. During this period, traction systems mainly used mechanical transmissions, without the concept of traction inverters. The advent of DC speed controllers between the 1960s and 1980s marked a development facilitated by the evolution of electronic technology, as DC controllers began to be implemented in the traction systems of electric vehicles. DC speed controllers could adjust the voltage and current of DC motors to regulate their speed and torque, thus achieving precise control of the vehicle. For instance, Robert Davidson's Davidson Electric vehicle, designed and built in 1837, utilized early DC motors and a battery power system.

The rise of AC speed controllers (from the 1980s to the 1990s): As AC motor technology matured and power electronic devices developed, AC speed controllers gradually became mainstream in traction systems. AC speed controllers use inverters to convert DC power sources into AC power, driving AC motors with higher power density, higher efficiency, and a wider application range, including early DC speed controller products launched by companies like ABB and Siemens.

The development of modern traction inverters (from the 1990s to the present): Over the past few decades, the performance and functions of traction inverters have been significantly improved due to continuous advancements in power electronics technology, semiconductor device technology, and control algorithms. Modern traction inverters feature higher power density, higher efficiency, more reliable performance, and richer functionalities.

Application of new technology (since the 21st century): In recent years, with the development of new power semiconductor devices such as Silicon Carbide (SiC) and Gallium Nitride (GaN), as well as the application of intelligent control algorithms, traction inverters have seen further enhancements in performance and efficiency. The emergence of new energy vehicles has also promoted the evolution of traction inverter technology, as various modernized traction inverters have been widely applied in electric vehicles on the market. For instance, the Chevrolet Volt, Toyota Prius, Nissan Leaf, and Audi e-Tron use traction inverters with a 2-level topology structure featuring double-sided cooling Insulated-Gate Bipolar Transistor (IGBT) modules [4]. The Tesla Model S and Model 3, respectively, employ two-level inverters with Silicon Carbide Metal-Oxide-Semiconductor Field-Effect Transistors (SiC MOSFET) and IGBT modules. Moreover, more and more companies are opting to develop and apply new types of traction inverters [5]. The development history of traction inverter is shown in figure 1.

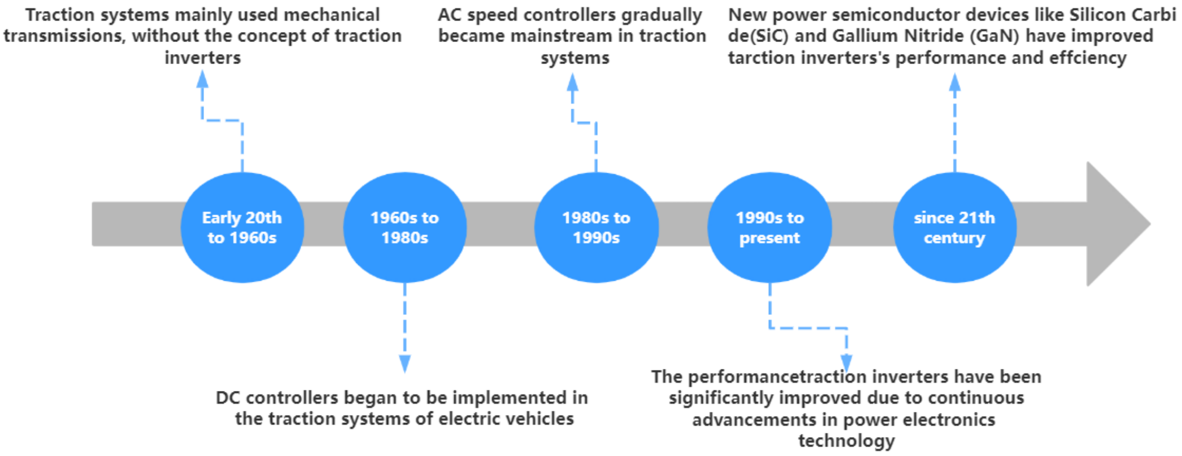

Fig. 1 Development history of traction inverter (Photo/Picture credit: Original)

2.2. Basic structure - circuit diagram

Among the various structures of traction inverters, the three-phase bridge-type voltage inverter circuit is the most widely applied [6]. This structure utilizes Insulated Gate Bipolar Transistors (IGBTs) as switching devices. The circuit diagram is shown as Figure 1. Common conduction methods include 120-degree and 180-degree conduction. Here, the 180-degree conduction method is chosen. Each phase consists of an upper and lower IGBT with three-phase bridge arms in total. The IGBT of the same phase conducts for 180 degrees within a cycle, thus, the upper and lower IGBT of the same phase cannot be on simultaneously. Whenever commutation occurs within the circuit, the upper and lower bridge arms of the same phase alternate, hence, this circuit is also known as the longitudinal commutation circuit [6]. Three-phase bridge voltage inverter circuit is shown in figure 2.

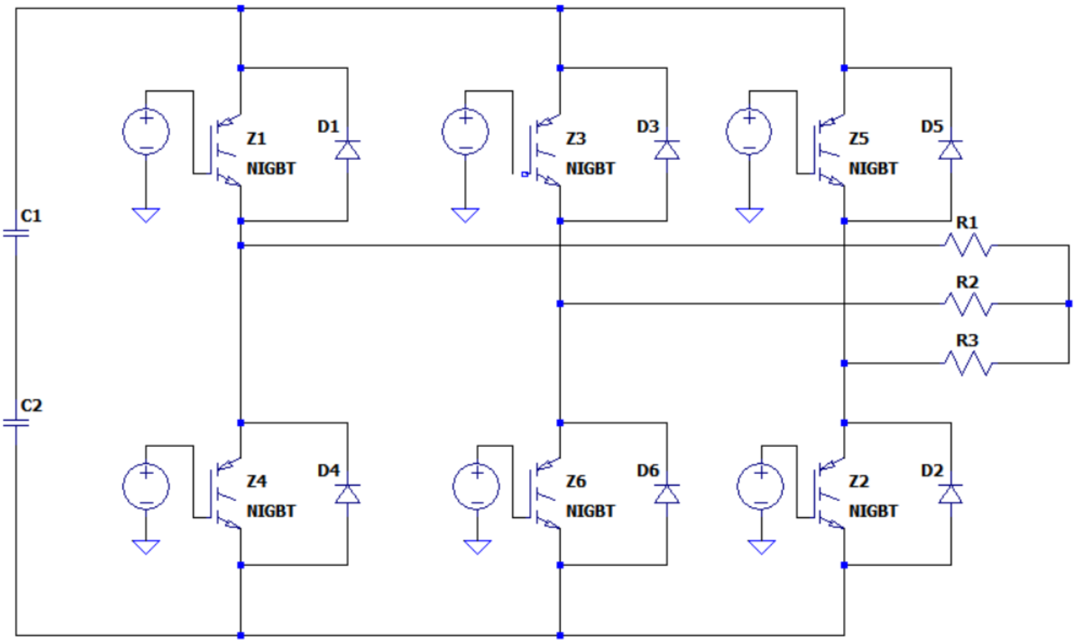

Fig. 2 Three-phase bridge voltage inverter circuit (Photo/Picture credit: Original)

Each IGBT (from Z1 to Z6), the phase difference is 60°, and each device is disconnected after 180° conduction. The specific conduction status is shown in Table 1.

Table1. The conduction state of each IGBT in different phase states

IGBT phase state		Z1	Z2	Z3	Z4	Z5	Z6
1	0°-60°	open	turn-off	turn-off	turn-off	open	open
2	60°-120°	open	open	turn-off	turn-off	turn-off	open
3	120°-180°	open	open	open	turn-off	turn-off	turn-off
4	180°-240°	turn-off	open	open	open	turn-off	turn-off
5	240°-300°	turn-off	turn-off	open	open	open	turn-off
6	300°-360°	turn-off	turn-off	turn-off	open	open	open

In a complete turn-on cycle, the inverter converts the input DC signal into an AC square wave signal, but because the gate signal that controls the IGBT turn-on is an ordinary square wave signal, the input AC signal will have many harmonic components, in order to reduce the harmonic components, it is necessary to make the output signal close to the sine wave. At this time, PWM technology is needed to control each IGBT to on-off and off.

3. Control Strategy

3.1. Traditional PWM control strategy

Pulse width modulation (PWM) is to precisely control the output voltage, frequency, waveform and power of the inverter by controlling the on-off time of the power electronic switch, while protecting the inverter and load, so as to ensure the safe and stable operation of the inverter [7]. The following will briefly introduce the PWM technology in the traditional IGBT traction inverter application. Traditional IGBT traction inverter low frequency PWM modulation method is shown in figure 3.

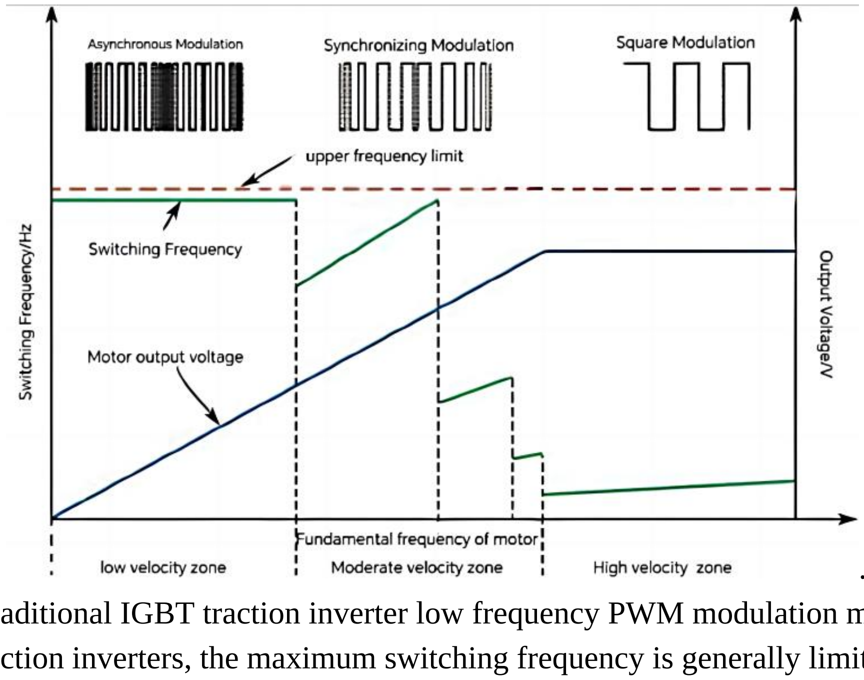

Fig. 3 Traditional IGBT traction inverter low frequency PWM modulation method [7]

For IGBT traction inverters, the maximum switching frequency is generally limited to 500Hz due to the substantial switching losses of IGBTs and their limited heat dissipation capacity. Therefore, for this type of traction inverter, a multimode composite PWM modulation method is usually adopted, which employs asynchronous modulation in low-speed areas, segmented synchronous modulation in mid-speed areas, and square wave modulation in high-speed areas [7]. The magnitude of the output is determined by the modulation ratio, which represents the utilization rate of the number of direct current bus sections, and the duty cycle of the IGBT switch in turn determines the modulation ratio [8]. Overall, the PWM control method is simple to implement, highly flexible, responds quickly in real-time, and has relatively low costs, making it widely used in the control field. However, PWM still has many drawbacks such as high harmonic distortion, as the pulse signals generated by PWM control introduce a large number of higher-order harmonics, causing the system's output voltage to contain a significant harmonic component and affecting wave quality. There is also a higher level of electromagnetic interference; the frequent pulse signals produced by PWM control may cause electromagnetic interference, impacting system stability and reliability, and even interfering with surrounding electronic equipment. Furthermore, the control precision is low; compared to SVPWM control, PWM control has lower control accuracy. With PWM control, it is not possible to precisely control the size and phase of the output voltage, which can result in significant errors. Also, the efficiency is lower; under PWM control, frequent switching of switching devices increases the loss of these devices, reducing system efficiency [9].

3.2. Space Vector Pulse Width Modulation (SVPWM)

The SVPWM Space vector graph is shown in figure 4.

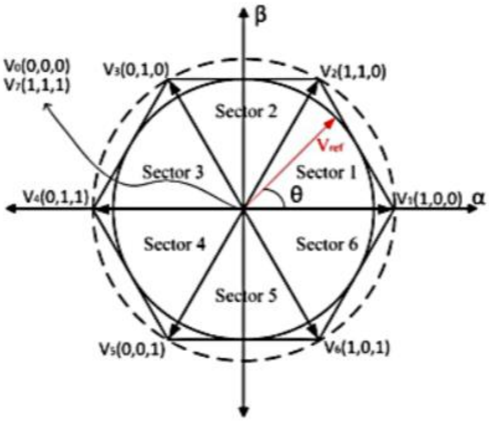

Fig. 4 SVPWM Space vector graph [8]

Space Vector Pulse Width Modulation (SVPWM) control is a novel PWM control technique that utilizes space vectors as its base vectors. By calculating the duration each space vector acts in the phase coordinate system, they can be combined to form a sector. Then, the operational times of all vectors within a sector are combined to generate a PWM output waveform [10]. SVPWM technology is characterized by: (1) the use of fewer switching devices, allowing efficient use of power tubes; (2) output inverter voltage waveforms being closer to sine waves; (3) an intrinsic logical relationship between phase voltage vectors; (4) easy coupling of space vectors with phase voltage vectors; (5) relying on only one voltage vector within each sector, maximizing the use of switching device resources.

SVPWM has begun to be widely applied in traction inverters. It creates multiple voltage space vectors using the switching states of a three-phase inverter and generates the required three-phase AC output by appropriately controlling the magnitude and phase of these vectors [4]. This method excels in producing accurate sine wave outputs at a higher voltage utilization rate and effectively reduces the total harmonic distortion (THD) and switching losses compared to traditional PWM methods. Specifically, SVPWM uses the concept of space vectors, synthesizing the desired three-dimensional voltage by selecting and combining eight possible states (six active vectors and two null vectors) based on the inverter bridge arms. In practice, these different voltage vectors are applied in a certain sequence and timing to emulate continuous sine wave voltage [11]. SVPWM also helps to balance the DC link voltage of the inverter and significantly reduces the harmonic content of the output current and voltage. In the traction inverters of electric vehicles, SVPWM's unique duty cycle control not only enhances the system's dynamic response but also plays a crucial role in achieving stringent motor control. An optimal SVPWM strategy can find the most advantageous switching events for motor control, especially where traction systems require dynamic response and high efficiency [12].

Moreover, overmodulation techniques in SVPWM can further increase the inverter's output voltage; in the overmodulation area of SVPWM, the switching vectors are not confined within the hexagon's inscribed circle but can extend outwards, achieving higher output voltage and power. This is particularly beneficial when dealing with special carrier frequencies and large motor drives [11]. As the performance requirements for traction inverters increase, the SVPWM technology continues to evolve. Choudhury has proposed a three-level Neutral Point Clamped (NPC) traction inverter drive for tram applications, where the use of SVPWM technology can effectively improve the system's heat dissipation and power density, allowing the tram traction system to operate under harsher conditions [13]. It also reduces the weight and volume of the whole vehicle system, providing a significant technical pathway for high-performance electric vehicles.

4. Optimization of control strategy

In the realm of traction inverters, traditional PWM techniques often encounter challenges such as poor efficiency, thermal issues, and electromagnetic interference (EMI). To overcome these hurdles, the Discrete Waveform Optimization PWM (DWO-PWM) technology has emerged. Based on a series of algorithm optimizations, the DWO-PWM technique has the capability to skip some carrier waves in specific scenarios, thereby reducing the switching actions of the inverter [4]. Compared to traditional PWM, DWO-PWM effectively reduces electromagnetic interference (EMI) by decreasing the switching frequency, and the improved IGBT switching strategy helps to lower switching losses. Literature reports indicate that using DWO-PWM can increase the inverter's thermal efficiency and reduce switching losses by approximately 15%, thereby not only enhancing the inverter's energy efficiency but also indirectly improving the driving range of electric vehicles [4].

In terms of SVPWM (Space Vector Pulse Width Modulation) technology, Wu et al. proposed an innovative 240-degree Clamped Space Vector PWM technique in 2020. This technique is crucial for the operation of traction inverters in electric vehicles under dynamic DC link conditions [11]. The introduction of this technology aims to address the additional switching losses caused by the introduction of zero states in traditional SVPWM. The 240-degree Clamped Space Vector PWM technique reduces dependency on zero states by optimizing the switching sequence, effectively reducing switching losses. By extending the working angle of effective states to 240 degrees (rather than the traditional 180 degrees), this technique reduces the number of switching times of the inverter within the PWM cycle, thus lowering energy consumption. Additionally, the 240-degree clamping technique reduces the common-mode voltage of the inverter output, reducing the voltage stress between the motor and the inverter and alleviating IGBT thermal losses [11]. The application of this technology not only reduces switching losses but also helps improve the inverter's thermal management, enhancing system reliability and efficiency. Reducing switching losses is crucial for improving overall energy efficiency, prolonging battery life, and increasing vehicle driving range in electric vehicles, while also reducing the cooling requirements of heat sinks. Operating the inverter at lower temperatures further extends the lifespan of power electronic components. Research indicates that the improved SVPWM technology can reduce common-mode voltage by 20%-30%, reducing the risk of overheating of electronic components and significantly reducing maintenance costs [11].

In addition to hardware-level optimizations, software control strategies for inverters are also continuously improving to reflect advancements in PWM technology. For example, PSC-PWM technology optimizes the control accuracy of inverters and the dynamic response of electric motors by adjusting the phase of synchronous carrier PWM [14]. Inverters adopting advanced modulation techniques not only improve the flatness of output voltage waveforms but also reduce system energy consumption, alleviating the burden on electric vehicle batteries. Furthermore, technological improvements enhance the performance of inverters in multiple parameters, including power factor, efficiency, and output voltage range. For instance, some studies have found that improved PWM technology can bring the power factor of inverters close to the ideal value of 1 and increase efficiency to over 98%. Moreover, the expanded output voltage range means that electric motors can maintain stable performance under a wider range of operating conditions [15].

5. Challenges and Prospects

As a core component of electric traction systems, the development and optimization of traction inverters are directly linked to the performance and efficiency of electric vehicles and rail transport tools. Currently, the traction inverter field is facing a variety of technical challenges, including increasing energy efficiency, reducing losses, miniaturizing design, enhancing system reliability and durability, and strengthening electromagnetic compatibility, among others. Increasing efficiency and power density are the primary objectives in the development of traction inverter technology. High-efficiency and high-power-density inverters can improve the entire vehicle's energy consumption, lighten the load, and thereby optimize the overall performance of the traction system. However, this also poses challenges for thermal management—how to effectively dissipate the heat generated during power conversion is a key research focus. In material science, the use of wide-bandgap semiconductor materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) has been proven to significantly improve the efficiency and reduce the size of inverters, but their high cost and packaging technology remain barriers to widespread application [12]. In terms of control strategies for traction inverters, modern research is increasingly integrating artificial intelligence technologies, such as model-based predictive control and machine learning algorithms, to further optimize the dynamic response and adaptability of inverters. These methods are intended to achieve real-time monitoring of operational states and adaptive adjustment to cope with complex driving conditions and load changes [16].

Facing the multifaceted technical demands and challenges at the current stage, the future development of traction inverters is also filled with hope. With the rapid progress of electronic technology and material science, combined with advanced manufacturing processes, the inverters of the future will tend towards greater integration and intelligence. This means more robust systems, superior control precision, and longer life expectancy. Against the backdrop of cleaner and renewable energy promotion, the efficient and reliable operation of traction inverters is endowed with special practical significance and long-term value.

6. Conclusion

The application of power electronics technology in the field of electrified transportation is increasingly important, and as a key component of electric vehicles, the performance and efficiency of traction inverters are crucial to the operation of the entire system. This article provides an overview of the basic theory, historical development, and the latest technological applications and optimized control strategies for traction inverters. Firstly, the fundamental principles of traction inverters encompass multiple fields including power electronics technology, control theory, and motor driving principles. The main function of inverters is to convert direct current into alternating current to drive motors. With pulse width modulation (PWM) technology, inverters can precisely control the output voltage and frequency, thereby regulating the torque, speed, and direction of the motor. Secondly, the historical development of traction inverters has evolved from direct current to alternating current, and from traditional to modern control methods. With the rapid advancement of electronic technology and materials science, the performance of modern traction inverters has continuously improved, becoming increasingly sophisticated and gradually emerging as one of the core components of electric vehicles. The advent of new power semiconductor devices, such as silicon carbide (SiC) and gallium nitride (GaN), along with the application of intelligent control algorithms, has further enhanced the performance and efficiency of traction inverters. Lastly, the optimized control strategies for traction inverters include both traditional PWM and improved SVPWM techniques. The application of Discrete Waveform Optimization PWM (DWO-PWM) and 240-degree clamped SVPWM has resulted in significant improvements in reducing energy loss, increasing thermal efficiency, and minimizing electromagnetic interference. Additionally, the continuous improvement of software control strategies also provides strong support for the enhancement of inverter performance.

In conclusion, as a critical power conversion device in electric vehicles, the technological development and performance optimization of traction inverters are essential for advancing the field of electrified transportation. In the future, with ongoing technological progress and expanded applications, traction inverters are expected to achieve greater breakthroughs in energy efficiency, system reliability, and intelligent control, contributing even more to the development of clean energy transportation.

References

[1] Reimers J, Dorn-Gomba L, Mak C, et al. Automotive traction inverters: Current status and future trends. IEEE Transactions on Vehicular Technology, 2019, 68(4): 3337-3350.

[2] Yu S, Wang J, Zhang X, et al. The potential impact of using traction inverters with SiC MOSFETs for electric buses. IEEE Access, 2021, 9: 51561-51572.

[3] Poorfakhraei A, Narimani M, Emadi A. A review of multilevel inverter topologies in electric vehicles: Current status and future trends. IEEE Open Journal of Power Electronics, 2021, 2: 155-170.

[4] Poorfakhraei A, Narimani M, Emadi A. A review of modulation and control techniques for multilevel inverters in traction applications. IEEE Access, 2021, 9: 24187-24204.

[5] Sambhavi Y V, Ramachandran V. A technical review of modern traction inverter systems used in electric vehicle application. Energy Reports, 2023, 10: 3882-3907.

[6] Aibin Cao, Zhenhua LI, Ming YU, Liyuan PENG. Research on Inverter Simulation and Harmonic Suppression Based on PWM Control. Shanxi Electronics Technology, 2024, (01): 109-112.

[7] Liang Hu, Xiangyu Fu, Yongcan LV, Ling Feng, Dong HU. A kind of High frequency and low frequency Hybrid multi-mode PWM modulation Method for SiC Traction Inverter. Control and Information Technology, 2022

[8] Altintas G, Kocabas D A. Extended Overmodulation Operation of Space Vector PWM for Traction Motor Control at Low Switching Frequency. IEEE Access, 2022, 10: 120274-120284.

[9] De Klerk M L, Saha A K. A comprehensive review of advanced traction motor control techniques suitable for electric vehicle applications. IEEE Access, 2021, 9: 125080-125108.

[10] Taha W, Azer P, Callegaro A D, et al. Multiphase traction inverters: State-of-the-art review and future trends. IEEE Access, 2022, 10: 4580-4599.

[11] Wu D, Qamar H, Qamar H, et al. Comprehensive Analysis and Experimental Validation of 240-Clamped Space Vector PWM Technique Eliminating Zero States for EV Traction Inverters With Dynamic DC Link. IEEE Transactions on Power Electronics, 2020, 35(12): 13295-13307.

[12] Xiao L, Li J, Xiong Y, et al. Strategy and implementation of harmonic-reduced synchronized SVPWM for high-power traction machine drives. IEEE Transactions on Power Electronics, 2020, 35(11): 12457-12471.

[13] Choudhury A, Pillay P, Williamson S S. Performance comparison study of space-vector and modified-carrier-based PWM techniques for a three-level neutral-point-clamped traction inverter drive. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2016, 4(3): 1064-1076.

[14] Yin J, Dai N Y. On Carrier-to-Fundamental Phase Displacement in Phase-Shifted PWM for Modular Multilevel Converters. IEEE Transactions on Power Electronics, 2024.

[15] Chen Z, Yue S, Peng C, et al. Hydrogen-related recovery effect of AlGaN/GaN high-electron-mobility transistors irradiated by high-fluence protons[J]. IEEE Transactions on Nuclear Science, 2021, 68(2): 118-123.

[16] Zhang H. A Traction Inverter Design for Increasing the DC Link Voltage in Electric Vehicles. 2021 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE, 2021: 464-471.