

Progress And Application of Single-Phase Multi-Level Rectifiers

Qingyao Deng *

School of New Energy, North China Electric Power University, Beijing, 100096, China

* Corresponding Author Email: 120211100603@ncepu.edu.cn

Abstract. The stable operation of the power system is inseparable from the efficient operation of power electronic devices. Single-phase multi-level rectifiers are widely used in power electronic systems. Improving the stability and efficiency of single-phase multi-level rectifiers is a key research area. Based on the existing literature and research results, this article first analyzes the principle of single-phase three-level rectifiers, while then discusses the three aspects of level layers, new materials, and harmonic suppression, and analyzes the principles and characteristics of various solutions, and compare the advantages and disadvantages of various solutions, and finally discuss the application of single-phase multi-level rectifiers and optimization in various fields from three aspects: electric locomotives, wind power generation and water storage. In addition, this article also discusses the future development trend of single-phase multi-level rectifiers and the problems faced by single-phase multi-level rectifiers in current research, aiming to provide valuable reference for further research and optimization of single-phase multi-level rectifiers.

Keywords: Power system; Single-phase multi-level rectifiers; Electric locomotives; Wind power; Water storage.

1. Introduction

Electric power development is one of the important areas of global development. The continuous improvement and optimization of the power system promotes human development and progress. Among them, power electronics technology plays an important role in various industries. The research and development and innovation of electronic devices further promote the development of power electronics technology. At present, a large amount of literature shows that the research on electronic devices has been perfected, and the continuous optimization of various inverters, rectifiers, and transformers has made the power system operate more stable and efficient. By optimizing the multi-stage single-phase boost rectifier to suppress the current ripple and improve the output performance [1]. By using cascaded H-bridge converters to synthesize multi-levels, the switching frequency and switching losses of the active rectifier are greatly reduced [2]. The proposal is for a novel single-phase five-level converter that uses two active switches to improve rectification efficiency. This rectifier can create distinct five-level voltages by using fewer active switches [3]. To fully utilize the benefits of multi-level converters, a novel four-level rectifier design is suggested [4]. To better manage the DC bus voltage, a single-phase multi-level rectifier made of four series/parallel H-bridges is suggested [5]. However, there are still problems and challenges, among which the optimization and development of single-phase multi-level rectifiers has become one of the hot spots. How to make single-phase multi-level rectifiers operate stably and reduce interference is an important challenge at present.

For single-phase multi-level rectifiers, this article summarizes single-phase multi-level rectifiers. It begins by outlining the working principles of single-phase three-level rectifiers while analyzing their topology. Second, the single-phase three-level rectifier's optimization plan was presented. It was thoroughly examined from three angles: employing novel SiC materials, reducing harmonics, and raising the number of level layers. The benefits and drawbacks of the different strategies were also contrasted. Finally, the application scenarios of single-phase multi-level inverters are analyzed. From the three scenarios of electric locomotives, wind power generation and water storage, the principles are explained and some optimizations in each field are carried out.

2. Working principle analysis

The most popular single-phase multi-level converter is the single-phase three-level converter. The single-phase three-level rectifier circuit, shown in figure 1, consists of eight electrical switching devices with IGBT and diodes coupled in parallel to form a single-phase full-bridge structure. It is divided into two upper and lower groups, and there are two groups of two diodes connected in the middle. The DC side consists of two support capacitors C_1 and C_2 connected in series, and R_L is the equivalent load resistance which is shown in figure 1 [6].

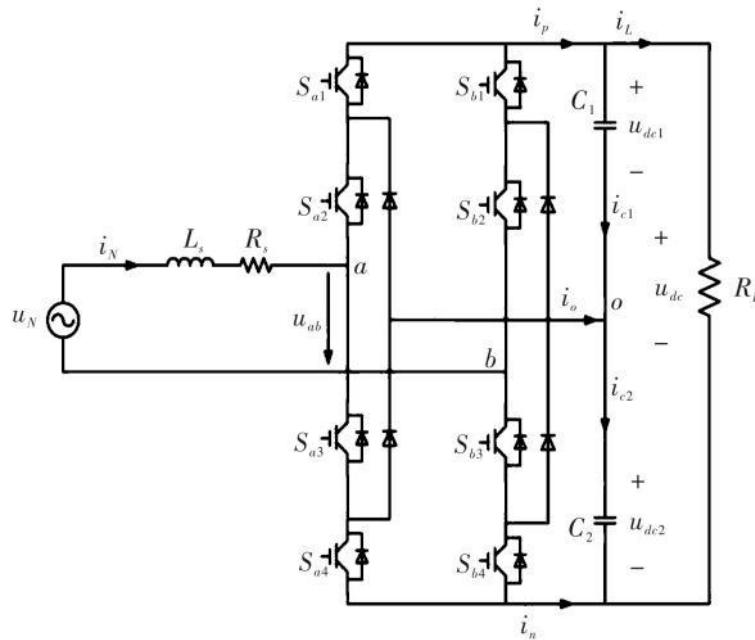


Fig. 1 Single-phase three-level rectifier topology diagram [6]

The main circuit shown in figure 1 is equivalent to the switch equivalent circuit shown in figure 2. Each IGBT has three equivalent switching states of 1, 0, and -1, so there are $3 \times 3 = 9$ switching combinations, and the single-phase three-level rectifier has 9 corresponding working states.

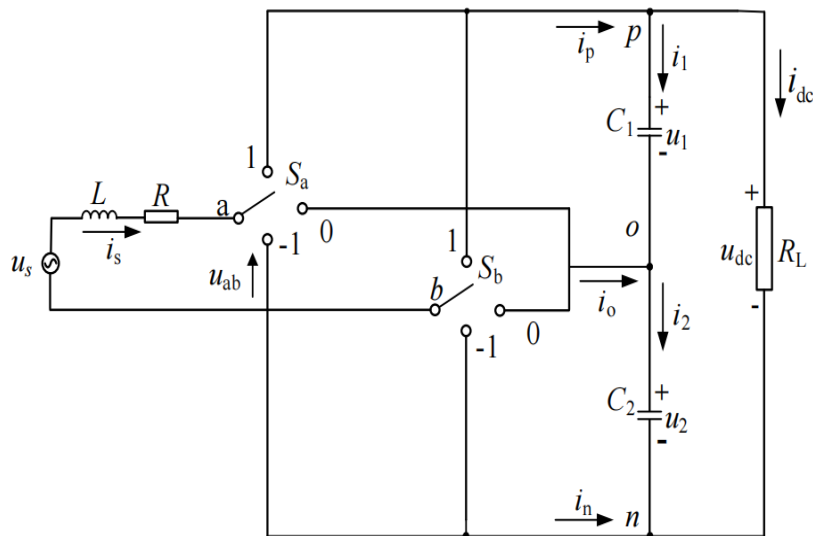


Fig. 2 Equivalent switching diagram (Photo/Picture credit: Original)

By summarizing the 9 switch combinations, the switch status table shown in table 1 can be obtained.

Table 1. Switch status table

S _{1a}	S _{2a}	S _{3a}	S _{4a}	S _{1b}	S _{2b}	S _{3b}	S _{4b}	S _a	S _b	u _{ao}	u _{bo}	u _{ab}	Mode
1	1	0	0	1	1	0	0	1	1	u ₁	u ₁	0	1
1	1	0	0	0	1	1	0	1	0	u ₁	0	u ₁	2
1	1	0	0	0	0	1	1	1	-1	u ₁	-u ₂	u ₁ +u ₂	3
0	1	1	0	1	1	0	0	0	1	0	u ₁	-u ₁	4
0	1	1	0	0	1	1	0	0	0	0	0	0	5
0	1	1	0	0	0	1	1	0	-1	0	-u ₂	u ₂	6
0	0	1	1	1	1	0	0	-1	1	-u ₂	u ₁	-u ₁ -u ₂	7
0	0	1	1	0	1	1	0	-1	0	-u ₂	0	-u ₂	8
0	0	1	1	0	0	1	1	-1	-1	-u ₂	-u ₂	0	9

The theoretical representation of the single-phase, three-level rectifier may be obtained using Kirchhoff's law and the operational condition depicted in the graphic above.

$$\begin{cases} \frac{di_s}{dt} = -\frac{R}{L}i_s - \frac{S_a(S_a + 1) - S_b(S_b + 1)}{2L}u_1 + \frac{S_a(S_a - 1) - S_b(S_b - 1)}{2L}u_2 + \frac{u_s}{L} & (1) \\ \frac{du_1}{dt} = \frac{S_a(S_a + 1) - S_b(S_b + 1)}{2C_1}i_s - \frac{u_1 + u_2}{R_L C_1} & (2) \\ \frac{du_2}{dt} = \frac{S_a(S_a - 1) - S_b(S_b - 1)}{2C_2}i_s - \frac{u_1 + u_2}{R_L C_2} & (3) \end{cases}$$

3. Optimization research

To better realize the rectification function and meet the needs of various power occasions, many new single-phase multi-level rectifiers have been proposed. In the following sections, we will discuss three aspects: improving the number of layers of level topology, improving device materials, and suppressing harmonics.

3.1. Number of level layers

In a multilevel rectifier, different levels can achieve different effects with different levels of layers. Five-level and seven-level are discussed below.

3.1.1 Five levels

To address the capacitor voltage balance issue without adding more switches, a linked inductor-based single-phase five-level rectifier is suggested whose topology diagram is shown in figure 3. The figure is composed of 6 IGBT power switch tubes, with two coupling inductors connected in the middle. C is the support capacitor and R is the equivalent resistance [7].

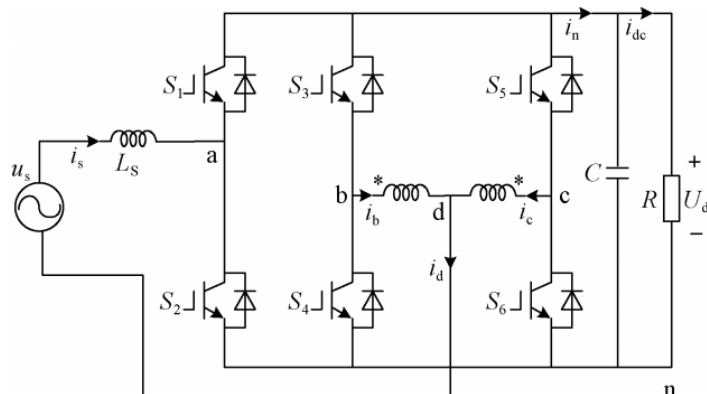


Fig. 3 Single-phase five-level rectifier topology diagram [7]

The following is the mathematical model of the single-phase five-level rectifier, ignoring the impact of the grid-side equivalent resistance:

$$L_s \frac{di_s}{dt} = u_s - SU_{dc} \quad (4)$$

A sliding mode PIR control method is suggested, which has superior dynamic performance during system startup and load mutation, in order to substantially enhance the management efficiency of the rectifier device built on the five-level rectifier [8].

3.1.2 Seven levels

In the operation of electric locomotives, in order to improve the problems of the traditional traction inverter being bulky and expensive, a single-phase seven-level rectifier has been proposed, which can convert single-phase alternating current into direct current, thereby replacing the traction inverter. The single-phase seven-level rectifier, as depicted in Figure 4, is primarily made up of 12 IGBT power switch tubes arranged in three groups. Each group consists of 4 IGBT power switch tubes, a support capacitor, and an equivalent resistor [9].

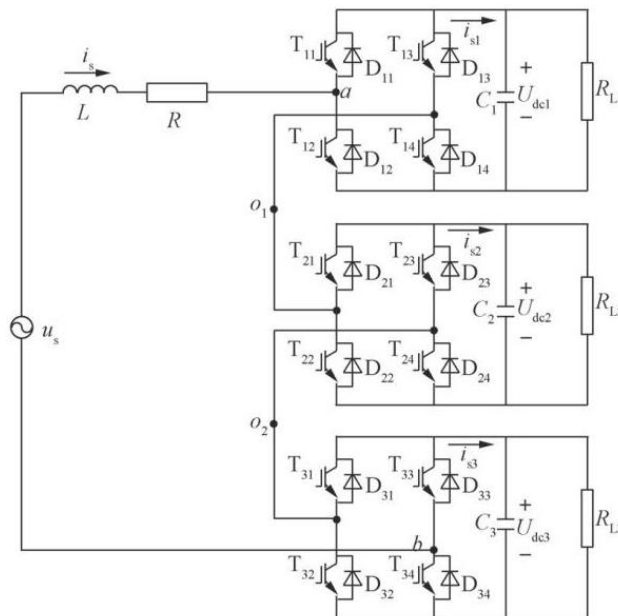


Fig. 4 Single-phase seven-level rectifier topology diagram [9]

The single-phase seven-level rectifier has capacitor voltage imbalance caused by control signal delay, system self-consumption, output power differences, etc resulting in unstable output power. To weaken the above problems, and under the condition that each device remains unchanged, a PI regulator is proposed to ensure the capacitor voltage balance under the PI-DPC control strategy [10].

3.2. Silicon carbide devices

A novel high-efficiency single-phase three-level three-leg converter based on SiC MOSFET is presented to efficiently reduce the need of power switching devices and reduce conduction losses. Compared with the mid-point clamped three-level bridge arm, its T-shaped three-level bridge arm can effectively reduce the use of power switching devices and has the advantage of reducing conduction losses, as shown in figure 5 [11].

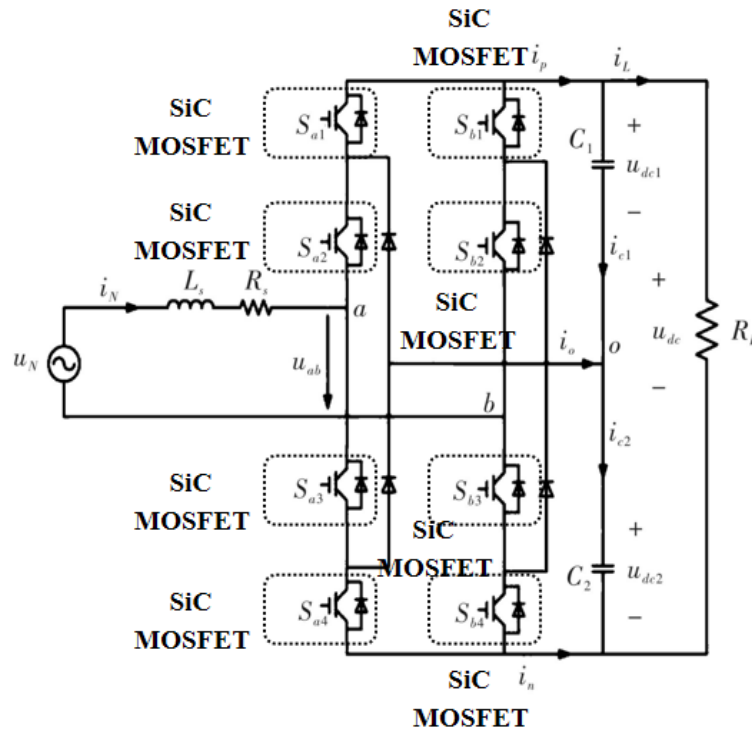


Fig. 5 New SiC single-phase three-level rectifier topology diagram [11]

Compared with Si MOSFET, SiC MOSFET has high breakdown voltage, low loss, and high thermal conductivity. It offers a wide range of potential applications and can be employed in high voltage, high switching frequency, and high-power density situations. With the growth of mass production, the price/performance ratio tends to be more reasonable, and the utilization rate is higher. By using SiC MOSFET instead of Si MOSFET to reduce switching losses, the new converter can achieve high efficiency and can also operate at higher switching frequencies with better harmonic performance.

3.3. Current harmonic suppression

According to Figure 1, the following formula can be derived. It can be seen that i_N under ideal conditions, there will be a secondary voltage ripple on the DC side of the three-level rectifier. The increase in the harmonic content of the side current, especially the low-order harmonic content, reduces the performance of the system.

The neutral point potential will wander as a result of the three-level rectifier's topological nature, which could hurt the switching device and increase grid-side current harmonics [12].

$$u_{dc} = U_d + \frac{U_N I_N \sin(2\omega t - \theta)}{2\omega C_d U_{dc}} \quad (5)$$

It is suggested to suppress low-order harmonics of grid-side current by using an N-order trap and multiplexed quasi-proportional resonant controllers in a double closed-loop control method. This will control the neutral point potential of a single-phase three-level rectifier, lower the harmonic content of the grid-side current, and further improve the control performance. It also combines a neutral point balance control algorithm based on hysteresis adjustment, as shown in figure 6.

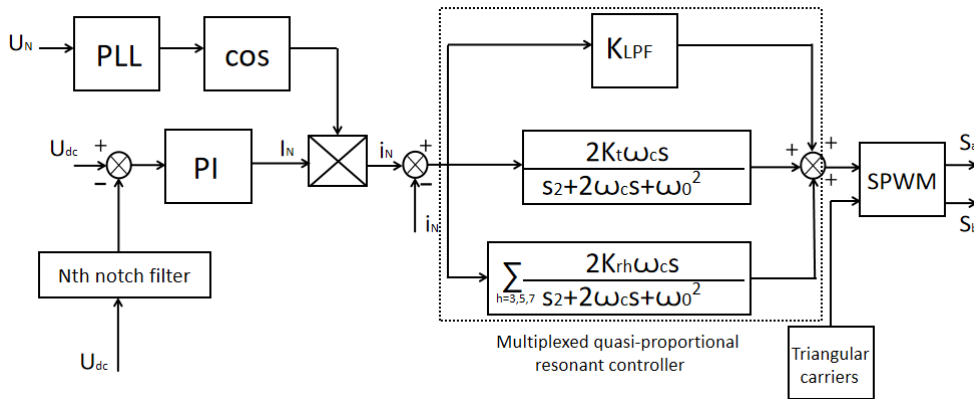


Fig. 6 Control algorithm based on N-order notch filter and M-Q-PR controller (Photo/Picture credit: Original)

To sum up, there are many optimization solutions for single-phase multi-level rectifiers, each with advantages and disadvantages. For example, although the single-phase seven-level rectifier has stable performance, it adds too many switches, which increases the loss and the risk of failure; new devices SiC manufacturing issues and more. The following table 2 is summarized based on the above scheme.

Table 2. Comparison

Option		Benefits	Drawbacks
Number of level layers	Single-phase three-level rectifier	Suitable for most scenarios	Special scenarios do not meet the requirements
	Single-phase five-level rectifier	Solve the problem of capacitor voltage balance	Introducing inductance affects response
	Single-phase seven-level rectifier	Stable performance, suitable for motor vehicle operation	More levels, greater loss
SiC material rectifier		Loss reduction	New materials are complex to produce
Current harmonic suppression optimization		Interference weakening	Adding new systems can easily introduce new interference

4. Application scenarios

Since the single-phase multi-level rectifier needs to withstand a smaller voltage when the switch tube is turned off, it is suitable for fields with higher voltage and larger capacity; Because the circuit's actual switching frequency is lower than its equivalent switching frequency, harmonic performance and radiation interference are improved, and the filter's size can be decreased; The circuit's power density is improved and it is widely used in many fields since the loss during switching of the circuit is significantly decreased as a result of the switching frequency being lowered.

4.1. Electric locomotives

My nation has constructed the largest high-speed railway network in the world thanks to the quick development of high-speed rail. The traction transfer system, consisting of a pantograph, traction converter, traction engine, and geared transmission, usually uses a "AC-DC-AC" drive arrangement. The multi-level rectifier is a crucial component of the traction converter, which is made up of a grid-side single-phase pulse rectifier, an intermediate DC loop, and a three-phase traction inverter [13].

At present, my country's traction converters mainly use two topological structures: two-level and three-level. Among them, the two-level structure is mainly used in CRH1, CRH3 and CRH5 EMU, and the three-level structure traction converter is mainly used in Among my country's CRH2 EMU. The high-speed railway routes in my nation primarily use CRH2 high-speed trains among them. The single-phase three-level rectifier, a crucial component of the CRH2 high-speed train traction system, transforms the secondary winding of the high-speed train traction transformer's 1500 V/50 Hz output. The single-phase alternating current is converted into 2600-3000 V direct current through power devices, and the direct current is transmitted to the traction inverter through the intermediate DC loop. Since the three-level structure has a large supporting capacitor on the DC side, the secondary resonance filter circuit in the intermediate DC link is eliminated, effectively increasing the power density of the traction converter, and achieving a lightweight system [14].

4.2. Wind power generation

The development of large-capacity offshore wind power has become one of the important ways for my country to achieve the goals of "carbon peak" and "carbon neutrality". Offshore wind power is close to load centers and rich in resources and has become the focus of wind power development in recent years. As the scale of offshore wind farms becomes larger and larger, in order to improve economic benefits, the capacity of a single unit of offshore wind power has also shown an increasing trend. At present, offshore wind farms mainly use high-voltage AC transmission and connection to the grid. However, as the distance from the wind farm increases, the inefficiency of submarine cables should make DC transmission the first choice for large-capacity long-distance offshore wind power transmission. Modular multilevel converters (MMC) have the characteristics of modularity, low harmonics, and low losses, and are the mainstream topology of DC converters, in which rectifiers play an important role in wind power generation [15].

The two most common topologies of wind power converters nowadays are two-level and three-level converters. With the trend of offshore wind turbines developing towards ultra-large capacities of 20 MW, converter solutions with lower levels are facing huge limitations. First, when the number of levels is low, the voltage level increase of the converter is limited, making it difficult to meet the demand for large capacity. In addition, converters with a lower number of levels have disadvantages such as large harmonics, high dv/dt , and difficulty in output filter design. Improve the capacity, voltage, efficiency, and harmonic performance of wind power converters through multi-level converter technology. Among the existing full-power wind power converter solutions, one uses a back-to-back two-stage pulse width modulation (PWM) voltage source converter, and the other uses a diode rectifier on the machine side. MMC has the advantages of high voltage capacity level, low loss, and small harmonics. However, its application in wind power converters faces great challenges due to its large number of switching devices and large capacitance usage. The application of MMC in wind power converters is discussed. A single-stage multi-level switching converter scheme is proposed based on WDC-MMC, and the two-stage conversion functions of DC/DC and DC/AC are realized in the first-level WDC-MMC. The advantages of MMC-based solutions are greatly improved by reducing the one-stage switching converter link [16].

4.3. Pumped hydro storage

With the large-scale grid-connected operation of renewable energy generation such as wind power and photovoltaics, the stability of the power system is facing increasingly severe challenges. Energy storage systems used to adjust the active power balance of the system are playing an increasingly important role. Compared with chemical battery energy storage, air compression energy storage, superconducting energy storage and other methods, pumped hydro energy storage has many advantages such as large capacity, low maintenance cost, safety, and efficiency. Since doubly fed motors have the advantages of variable speed and constant frequency and power decoupling capabilities, pumped storage units based on doubly fed motors can not only improve the operating efficiency of pump turbines, improve operating conditions, and improve the ability of independent

frequency regulation under pump operating conditions. The stability of the system can also be improved through rapid adjustment of active and reactive power. The neutral point clamped (NPC) is a more commonly used topology [17].

However, NPC three-level converters use a lot of power devices, and the current flow path during the switching process is complex, resulting in device loss and uneven heat distribution. Power devices that generate serious heat will affect the operational reliability and service life of the converter. At the same time, the unit-side converter of the doubly fed pumped storage unit has been operating at low frequency for a long time, the power device has a longer operating cycle, the loss and uneven heat distribution have increased, and the switching of operating conditions of the unit is complicated. The power converter losses and junction temperature changes more drastically. Therefore, reducing the serious power device loss due to heat generation in the NPC three-level converter used in doubly fed pumped storage units is of great significance for improving the operational reliability of the converter and increasing its service life. A modulation method based on redundant vector improvement for NPC three-level converter optimization of power device loss due to severe heating is also proposed [18].

5. Conclusion

Through the analysis and discussion of existing literature, this article fully explores the working principle of single-phase multi-level rectifiers and elaborates on its optimization scheme and analyzes its advantages and disadvantages. Single-phase three-level rectifiers can be widely used in various fields, but they still have problems of insufficient efficiency and substandard demand in some situations. The single-phase five-level rectifier solves the problem of capacitor voltage balance but introducing inductance affects response. Single-phase seven-level is stable performance, suitable for motor vehicle operation, but introducing too many levels increases system losses. SiC new materials can effectively reduce system losses, but the high cost of SiC itself and the complexity of production are also important issues. By adding new systems, harmonic interference can be effectively reduced, and output efficiency improved, but the addition of new systems is also accompanied by the introduction of new interference.

Single-phase multi-level rectifiers are widely used in electric locomotives, wind power, water storage and other fields, which illustrates their importance. However, the current optimization of single-phase multi-level is reflected in complicating the topology structure in order to improve the output efficiency. Although the efficiency is improved, it also increases the maintenance pressure, and once a failure occurs, the loss will increase.

It is hoped that in future research, on the premise of improving output efficiency, the topology can be simplified, and the negative impact caused by faults can be prevented. Through continuous optimization and innovation, the power system will be made more stable and efficient, making greater contributions to the power industry.

References

- [1] Salmon J, Knight A, Ewanchuk J, et al. multi-level single phase boost rectifiers using coupled inductors. 2008 IEEE Power Electronics Specialists Conference. IEEE, 2008: 3156-3163
- [2] Tsang K M, Chan W L. Multi-level multi-output single-phase active rectifier using cascaded H-bridge converter. IET Power Electronics, 2014, 7(4): 784-794.
- [3] Ma H, Han X, Wu P, et al. A novel single-phase five-level hybrid rectifier using two active switches. IET Power Electronics, 2021, 14(1): 158-168.
- [4] Vu T T, Young G. Implementation of multi-level bridgeless PFC rectifiers for mid-power single phase applications. 2016 IEEE Applied Power Electronics Conference and Exposition (APEC). IEEE, 2016: 1835-1841.

- [5] Rocha F V, Jacobina C B, Queiroz A P D, et al. Single-phase multilevel rectifier based on series and parallel connections. 2020 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE, 2020: 4143-4150.
- [6] Peng Xu. Research on voltage equalization strategy of cascade rectifiers for vehicle power electronic transformers. Southwest Jiaotong University, 2018.
- [7] Zhu Yifeng, Jia Xiaolei, Zhou Feishan, et al. No-delay power observation control method of single-phase five-level rectifier. *Journal of Electronic Measurement and Instrumentation*, 2023, 37(7): 156.
- [8] Zhu Yifeng, Wu Dangjian, Bai Bingyang, et al. Sliding mode proportional integral resonance control of single-phase five-level pulse rectifier. *Journal of Zhejiang University: Engineering Edition*, 2020, 54(8): 1578-1586.
- [9] Zhang Di, Cui Jing. Cascade H-bridge multi-level converter scheme for electric locomotives. *Science and Technology Wind*, 2021.
- [10] Li Jiaqi, Zheng Hui. Research on direct power model predictive control of single-phase multi-level cascade H-bridge converter. *Electric Locomotive and Urban Rail Vehicles*, 2020, 43(6): 49-54.
- [11] Chen Xiao, Zhao Yadong, Zhang Yu. Design of single-phase three-level converter based on SiC MOSFET. *Journal of Power Supply*, 2021, 19(2): 57-65.
- [12] Sheng Guoyu, Liu Wensheng. Research on grid-side current harmonic suppression of single-phase three-level rectifiers. *Micromotors*, 2019, 52(4): 52-58.
- [13] Liu Jinyan. Research on optimal control of single-phase three-level rectifiers in traction locomotives. Dalian Maritime University, 2022.
- [14] Xu Shuiqing, Wang Jian, Hu Youqiang, et al. Single-phase three-level rectifier open-circuit fault diagnosis of high-speed railway traction system based on adaptive sliding mode observer. *Control Theory & Applications/Kongzhi Lilun Yu Yinyong*, 2023, 40(11).
- [15] Fang Zixi, Cai Xu, Shi Xianqiang, et al. Topology optimization and control of hybrid offshore wind power DC converter. *Chinese Journal of Electrical Engineering*, 2021, 41(24): 8546-8559.
- [16] Song Qiang, Wang Yunfei, Zhao Biao, et al. Ultra-large-capacity offshore wind power converter based on single-stage multi-level switching conversion. *Electric Power Automation Equipment*, 2021.
- [17] Fan Boran, Wang Kui, Li Yongdong, et al. Adjustable speed pumped storage system based on modular multi-level matrix converter. *Journal of Electrical Engineering*, 2018, 33(zk2): 511-518.
- [18] Li Hui, Song Erbing, Liu Haitao, et al. Loss analysis of three-level converter devices for doubly fed pumped storage units and its improved modulation strategy. *Journal of Solar Energy*, 2019, 40(5): 1217-1224.