Comprehensive Study of Load Characteristics of O-type Rotor Car Dumper Based on Measurements

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Abstract. The car dumper, an essential apparatus for unloading bulk materials, is increasingly critical across various sectors such as electricity generation, metallurgy, and operations at port terminals. This significance stems from its continuous operational capacity, which significantly boosts the efficiency of bulk material handling and optimizes the overall processes at industrial sites. This research paper delves into the power quality problems associated with car dumper applications, particularly focusing on the harmonic disturbances caused by inverters used within these systems. Such disturbances can degrade the quality of power within the industrial grid, potentially leading to inefficiencies and safety hazards. To address these issues, the paper proposes the use of parallel active power filters (APF). These filters are renowned for their efficiency in controlling and mitigating harmonic disruptions in electrical systems. The implementation of APFs has shown promising potential to stabilize power quality by filtering unwanted harmonic frequencies and allowing for a smoother power flow. Through detailed measurements conducted on an O-type rotor quad car dumper, the study systematically analyzes the operational characteristics of the dumper, thereby forming a comprehensive database. This database aids in the optimization of electrical control strategies and operational methodologies for car dumpers.The primary objectives of this research are to enhance the operational efficiency of car dumpers, minimize their energy consumption, and improve overall safety measures. By integrating advanced harmonic control technologies such as APF, this study not only addresses the immediate issues of power quality but also contributes to the broader goal of sustainable and efficient industrial practices. The findings are expected to influence future designs and operations of car dumpers, making them more energy-efficient and less prone to electrical disturbances, thereby ensuring a safer working environment in industries dependent on heavy machinery for bulk material handling.

Keywords: O-type rotor car dumper; actual measurement data; power quality; harmonic control.

1. Introduction

Car dumpers are essential components of modern bulk material unloading systems, renowned for their high efficiency and continuous operation. They play a critical role in the transportation of bulk goods and have become integral to the logistics chains of industries like electricity, metallurgy, and port terminals. The implementation of car dumpers not only enhances the efficiency of bulk material handling but also significantly optimizes the overall material handling process [1].

There are primarily two types of car dumpers [2,3]. The first is the rotor type, which employs a gear and rack transmission mechanism located on the end cover to rotate the entire machine for unloading bulk materials. The second type is the side-tiling type, with its axis fixed to the upper side edge of the open car, allowing for uploading by lifting and flipping the dumpers on the axis. Among these, the rotor-type car dumper is more commonly used due to its lower driving power requirements, higher unloading efficiency, and faster single unloading speed.

In particular, the rotor-type car dumpers can be categorized into two main types based on mechanical structure variations, namely the O-type and C-type are developed, as illustrated in Figure 1 [4]. Comparing to the relatively flexible structure of C-type, the O-type rotor car dumper comprises two O-shaped end rings, a load-bearing main beam, and additional front, rear beams, and rings for reinforcement. This design significantly enhances stability, load-bearing capacity, and the capability to perform multiple car unloading operations. Consequently, due to their superior unloading efficiency and stability, O-type rotor car dumpers are preferred in large-scale unloading environments such as port terminals [5,6].

(a) C-type rotor car dumpers (b) O-type rotor car dumpers

Figure 1: C-type and O-type rotor car dumpers

In the context of China’s rapid economic development, the substantial increase in energy demand has lead to a significant rise in coal transportation. As a result, there has been a corresponding increase in the demand for car dumpers to enhance the throughput of specific port coal terminals. However, the widespread utilization of these dumpers has introduced significant power quality issues that can harm the safety and stability of the electrical system. One common issue is the generation of harmonic currents in the inverters of car dumpers, which can cause overheating in the transformers and transmission lines, damage to motors and protective devices, and even malfunction of auxiliary electronic equipment [7,8].

This paper presents a comprehensive study of the load characteristics of car dumpers through systematic measurements, with the goal of mitigating harmonic content using active power filters. This approach not only enhances the operational efficiency of the dumpers and reduces energy consumption, but also improves operational safety. As such, this study holds significance for both theoretical understanding and practical applications.

2. Electrical Characteristics of the O-type Rotor Car Dumper

The car dumper equipment typically utilizes a three-phase five-wire power supply with its neutral point grounded [9]. At each end of the car dumper, a motor is linked, controlled by an 200 kW inverter connected to the low voltage side busbar of a 10/0.4kV transformer at a power supply substation. For smooth initiation, precise control, and stable deceleration of the O-type rotor car dumper under high-speed and high-torque conditions, each inverter consists of a four-quadrant rectifier, an intermediate DC circuit, and a three-phase PWM inverter. Specifically, the four-quadrant rectifier facilitates energy transfer with the grid side, directly impacting the current harmonic content and the associated power factor [10].

2.1 Four-Quadrant Rectifier

The four-quadrant rectifier, available in two-level and three-level configurations, offers several key advantages, including high power factor, low harmonic content, and bidirectional energy flow [11]. The schematic of a single-phase two-level four-quadrant rectifier used in the car dumper is shown in Figure 2, where T1 to T4 are switch devices, each comprising two IGBTs in parallel to handle the required current carrying capacity. The corresponding AC side equivalent circuit of the four-quadrant rectifier and the fundamental wave vector diagram (when the power factor is 1) is shown in Figure 3.

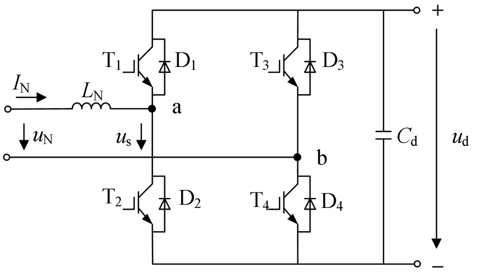


Figure 2: Schematic diagram of four-quadrant rectifier

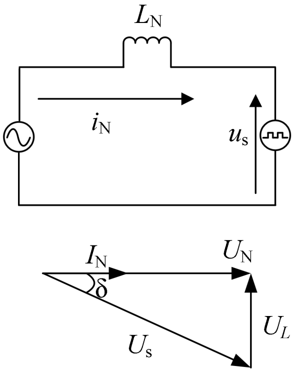


Figure 3: AC Side Equivalent Circuit and Fundamental Wave Phasor Diagram

The generated current iN can be described by Equation 1.

$$i_N = \frac{\sqrt{(MU_d)^2 - 2U_N^2}}{\sqrt{2}\omega L_N}\cos(\omega t+\beta) + \sum_{m=2,4\ldots}^{\infty} \sum_{\substack{n=\pm1,\pm3\ldots \\ m\pi L_N(m\omega_c+n\omega)}}^{\infty} J_n\left(\frac{mM\pi}{2}\right)\sin\frac{n}{2}\pi\sin\left(m\omega_c t+n\omega t+n\beta+m\alpha\right) \qquad (1)$$

where U_d represents the DC-side voltage of the rectifier, ω_c denotes the frequency of the SPWM-modulated triangular carrier, and M represents the modulation index. It is observed that i_N comprises the fundamental and odd harmonic components, while lacking DC and even harmonics components [12]. Furthermore, the use of carrier phase-shifting technology in the locomotive's independent four-quadrant rectifiers helps compensate for the phase shift caused by harmonics. These harmonics are then reflected through the main transformer into the primary network flow, further suppressing current harmonics [14].

2.2 Analysis of Actual Measurement Data for O-type Rotor Car Dumper

For a car dumper operating in a specific testing port, the voltage and current waveforms corresponding to one hour of operation (from 16:45 to 17:45), are shown in Figure 4. The voltage fluctuations range from 5.84 to 6.18 kV, and frequent current surges with amplitudes reaching almost 50 A are observed. These surges are mainly attributed to the high torque required during the low-speed start of the car dumper, resulting in continuous current shock to the motor.

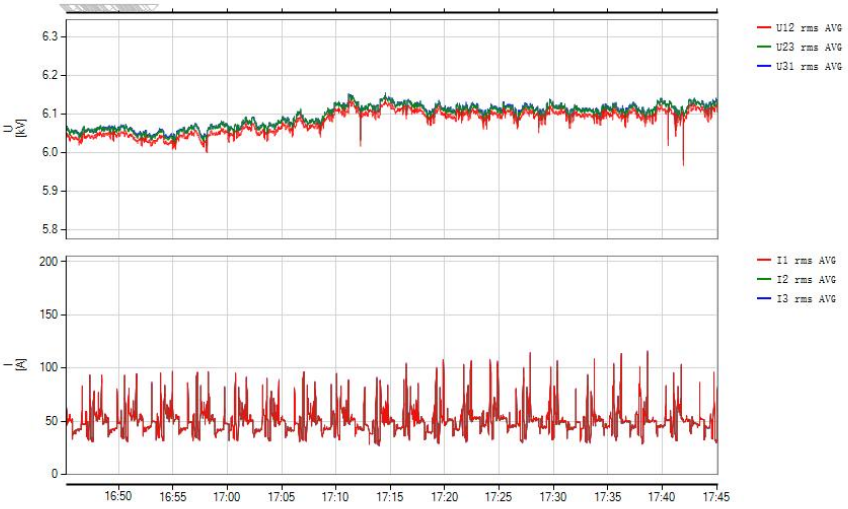


Figure 4: Car dumper voltage and current waveforms

The active power, reactive power, and power factor curves of the car dumper during this testing period is depicted in Figure 5.

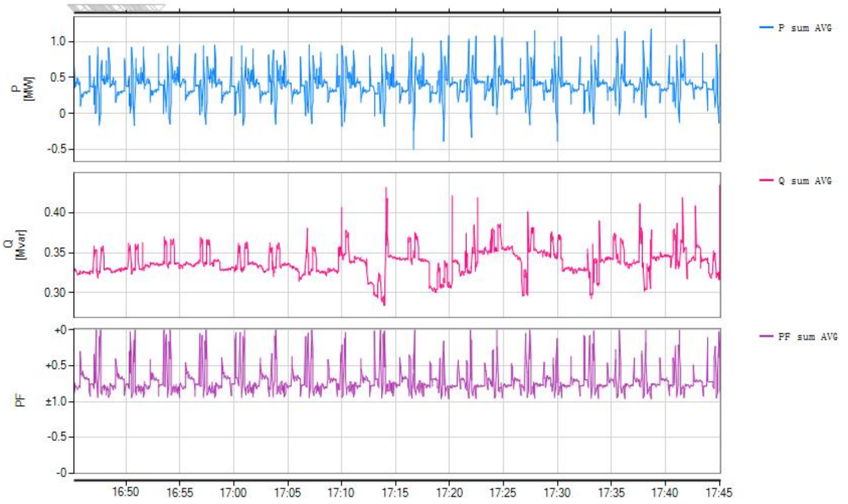


Figure 5: Active power, reactive power, and power factor curves

The presence of both positive and negative values of the active power indicates that the operational period of the car dumper includes three main phases: traction, coasting, and regenerative braking. Consequently, a typical work cycle can be divided into two main stages: positioning car traction and car dumper overturning. A typical work cycle of an O-type rotor car dumper is illustrated in Figure 6.

The primary function of the positioning car is to propel the train forward or backward, positioning it properly for subsequent unloading operations [13]. In addition to providing adequate traction to manage heavy vehicles under full load conditions, a high-precision control system is required to ensure accurate train positioning within the loading area of the car dumpers. After the unloading operation, the empty car is pushed out of the car dumper for continuous operations.

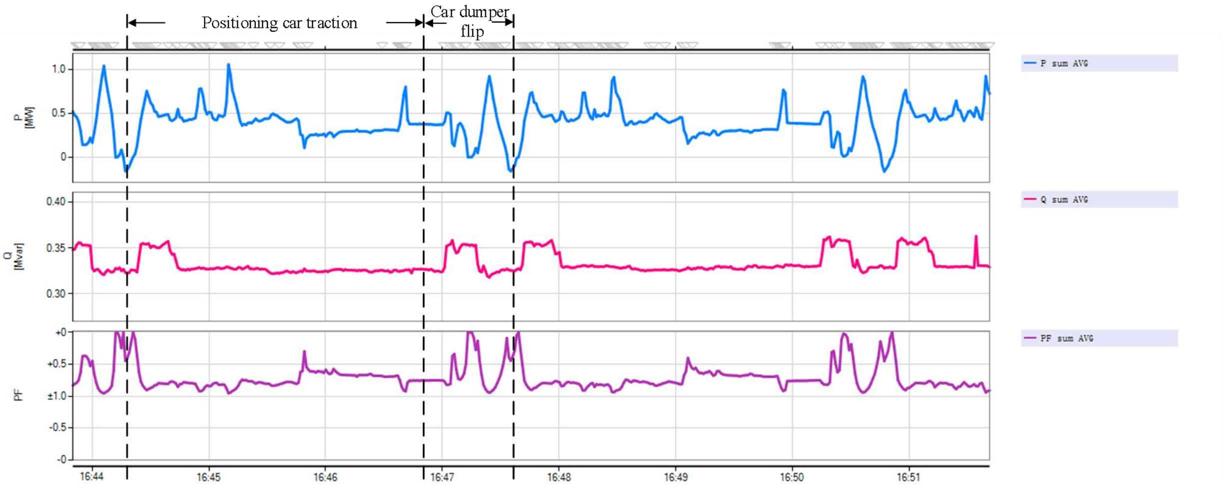


Figure 6: A typical working cycle of the car dumper

The typical voltage and current waveforms of the car dumper's traction and overturning conditions, along with their current harmonic spectra, are depicted in Figures 7 and 8, respectively. During the initial stages of both the traction process and the overturning processes, significant fluctuations in the current result in a somewhat distorted current waveform. The harmonic spectrum reveals that the primary characteristic harmonics of the current are odd harmonics such as the 3rd, 5th, 7th, 9th, and 11th, consistent with the theoretical analysis derived from Equation 1, as discussed earlier [14].

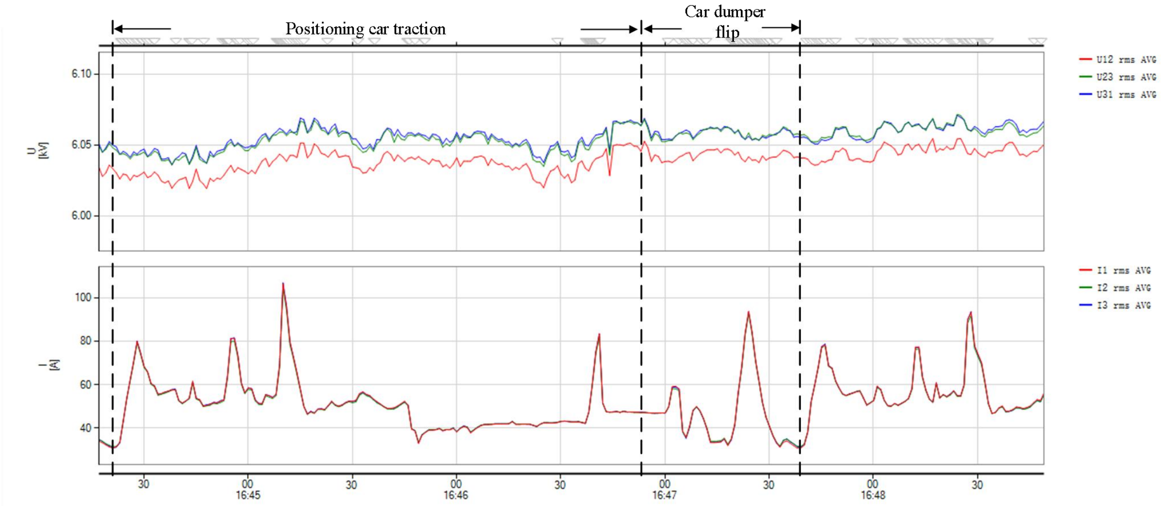
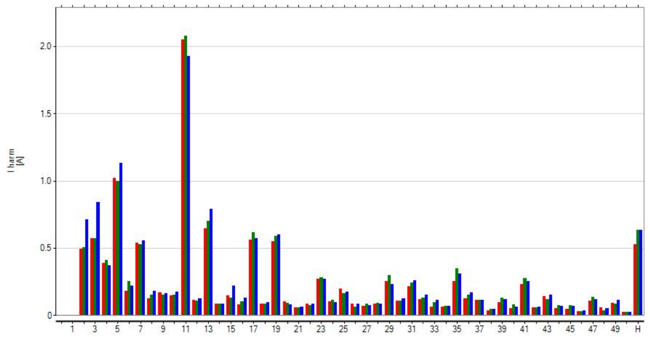
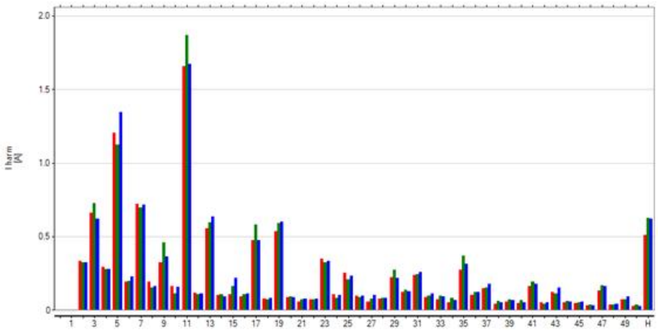


Figure 7: Voltage and current waveforms for car dumper traction and overturning conditions



(a) Current spectrum diagram under traction conditions



(b) Current spectrum diagram under overturning conditions

Figure 8: Current spectrum diagram

Harmonic currents in the car dumper's electrical system primarily originate from the non-linear characteristics of the inverter and its control strategy. The inverter, using power electronics technology, converts alternating current (AC) to direct current (DC) through methods such as Pulse Width Modulation (PWM), and then converts the DC back to AC with an adjustable frequency to control the motor's speed. This process involves the rapid switching of power semiconductor components like thyristors or Insulated Gate Bipolar Transistors (IGBTs), whose non-linear switching behavior introduces harmonic components. In three-phase AC systems, harmonic currents are predominantly odd harmonics, specifically the 3rd, 5th, 7th, 9th, and 11th harmonics. This phenomenon can be partially attributed to the system's symmetry, where the symmetric load characteristics of three-phase systems lead to the cancellation of even harmonics, while odd harmonics are emphasized due to their phase differences. Furthermore, the impedance characteristics of the power grid and the car dumper system respond differently to harmonics of varying frequencies, potentially amplifying specific frequency harmonics, particularly multiples of 3, due to their unique reinforcing effect in three-phase systems.

Harmonic currents significantly affect power quality and system efficiency, leading to issues such as transformer and transmission line overheating, shortened motor insulation lifespans, mis-triggering of protection devices, and interference with other electrical equipment. Therefore, reducing harmonic levels is crucial for enhancing the overall performance and reliability of the car dumper and its electrical system during operation and maintenance.

3. Harmonic Mitigation for the O-type Quad Car Dumper

To enhance operational efficiency, reduce energy consumption, and improve safety, it is essential to mitigate the high level odd harmonics observed in the measurements of the O-type rotor quad car dumper. Traditional methods of harmonic mitigation involve the implementation of LC filters, leveraging their simple structure and low investment. However, these filters are limited in their ability to compensate for harmonics at fixed frequencies, resulting in less than optimal effects.

Active Power Filters (APF) utilize a dynamic real-time tracking and compensation method to filter out grid harmonics [15].They detect current waveforms generated by nonlinear loads, separate the fundamental wave from the harmonics, and generate a current through an inverter that counteracts the load harmonic current. This nullifies the total harmonic current from the source, achieving real-time harmonic current compensation. The basic principle of APF is depicted in Figure 9. APFs offer greater flexibility and a wider range of applications compared to traditional passive filters, making them particularly suitable for managing harmonics generated by variable frequency equipment. They can compensate for harmonics with varying frequencies and amplitudes in real-time, and their compensation characteristics are not affected by grid impedance, thereby providing enhanced adaptability to changing grid conditions.

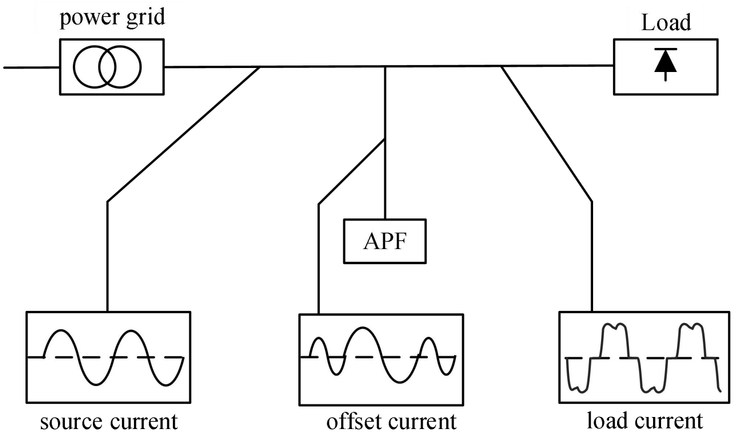


Figure 9: The basic working principle diagram of APF

The technology of parallel-connected Active Power Filters (APF) is relatively mature and easy to maintain and expand. If the car dumper system introduces additional variable frequency devices or other harmonic-generating loads in the future, more efficient harmonic compensation can be achieved by increasing the capacity or number of parallel-connected APFs. This would simplify the selection and application process for system designers and operational personnel. Consequently, this project utilizes parallel-connected APF for harmonic mitigation.

The configuration of a typical usage of parallel-connected Active Power Filter (APF) in the system is depicted in Figure 10. Here, the power source es supplies energy to the load via the traction power supply system, while the nonlinear load, primarily the car dumper, is the principal source of harmonics in the system. The APF system is primarily composed of two components: the command current calculation circuit and the compensation current generation circuit. The command current calculation circuit, also known as the harmonic current detection circuit, is designed to detect the harmonic components in the load current. The compensation current generation circuit encompasses the current tracking control circuit, the drive circuit, and the main APF circuit. This circuit generates a compensation current based on the harmonic current detected in the command current generation circuit [16].

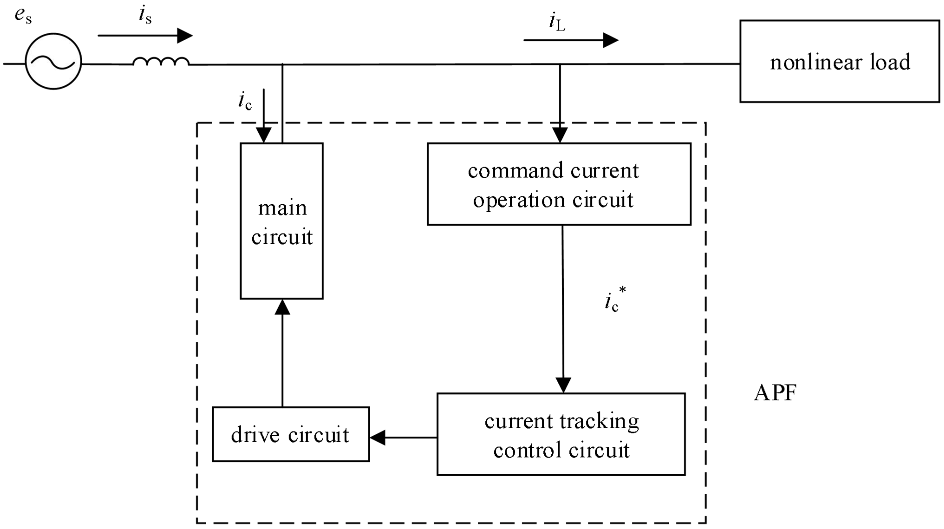


Figure 10: Parallel active power filter system diagram

Figure 11 presents a system structure diagram of a three-phase three-wire parallel-connected Active Power Filter, illustrating the APF's role in harmonic compensation within the electrical grid. In this setup, the APF is positioned in parallel between the load and the grid [17]. By continuously monitoring the grid current's harmonic components and generating corresponding compensation currents, it effectively mitigates the harmonic currents caused by nonlinear loads.

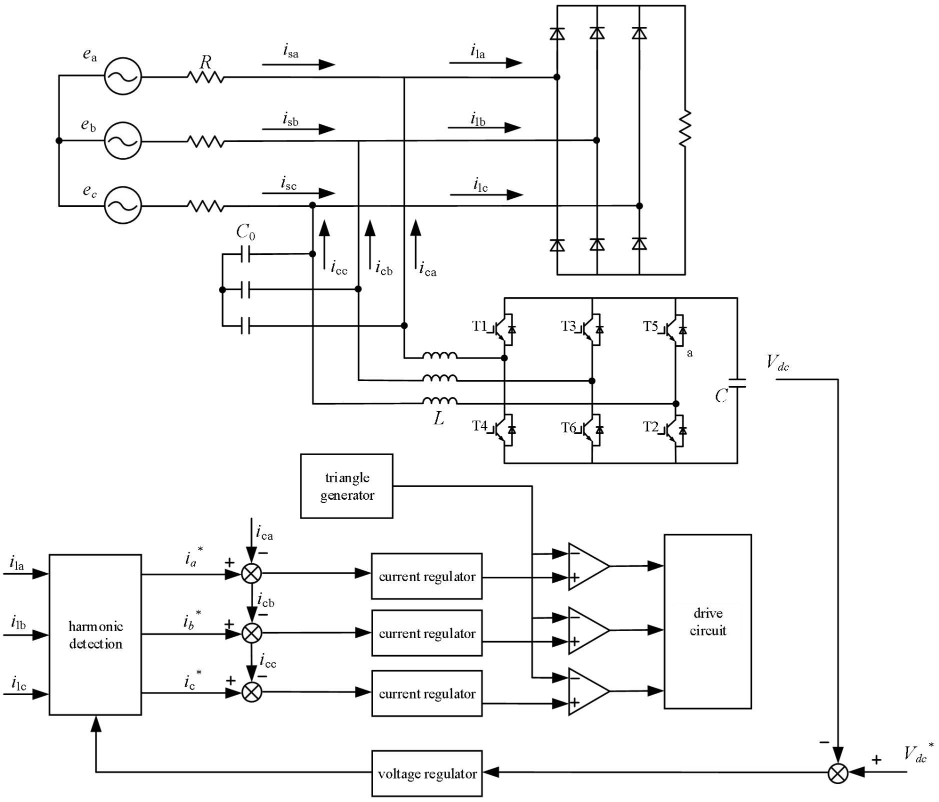


Figure 11: Three-phase three-wire shunt active power filter system structure diagram

In this study, we constructed a comprehensive simulation model using MATLAB/Simulink software to replicate the operation and performance of a parallel-connected three-phase three-wire active power filter, as depicted in Figure 12. To ensure the model's precision and applicability, a diode-clamped inverter structure was chosen as the central design for the inverter's primary circuit. This structure is widely used in actual power systems due to its high efficiency and stability. This simulation model serves as a simulated reference for harmonic mitigation in O-type rotor car dumpers and provides theoretical support for further analysis and management of power quality issues related to O-type rotor car dumpers.

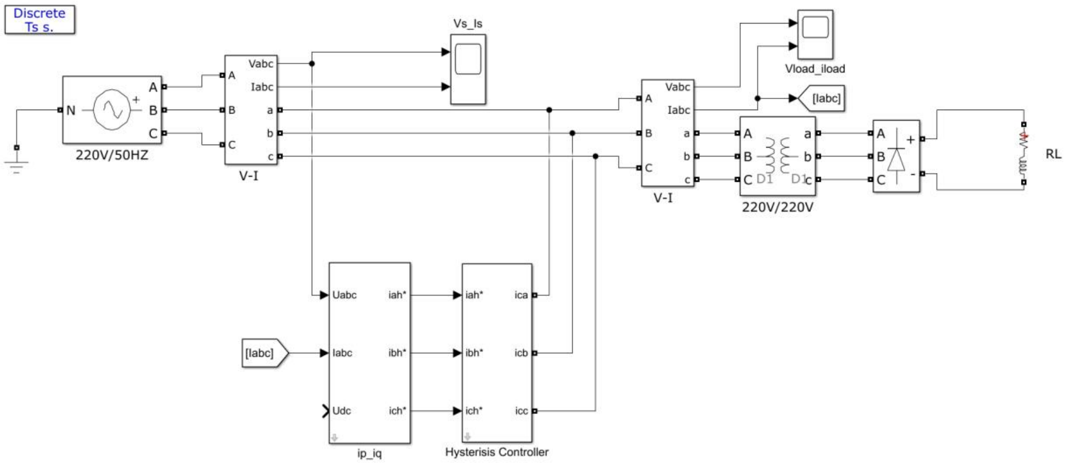


Figure 12: Simulation topology diagram

The system simulation outcomes, depicted in Figure 13, illustrate the impact of harmonic compensation executed by the APF. The figure clearly demonstrates that following compensation, the current waveform of the O-type rotor car dumper becomes significantly smoother, eliminating irregular spikes and burrs. The waveform after APF compensation closely aligns with the ideal sinusoidal waveform. These simulation results validate the accuracy and efficacy of the simulation model and the compensation strategy employed, thus establishing a solid foundation for the subsequent practical application of harmonic mitigation in car dumpers.

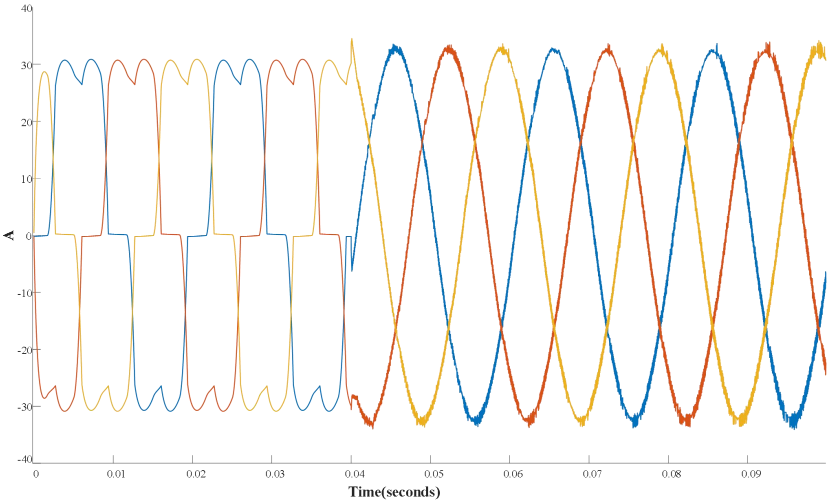
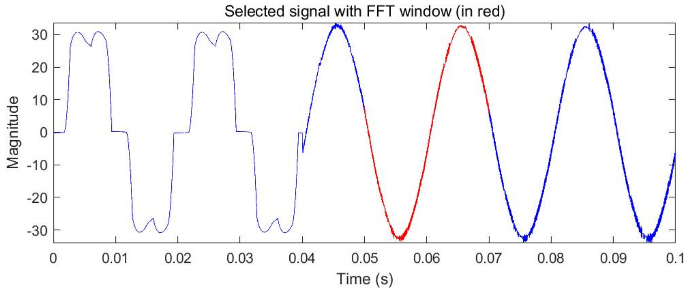
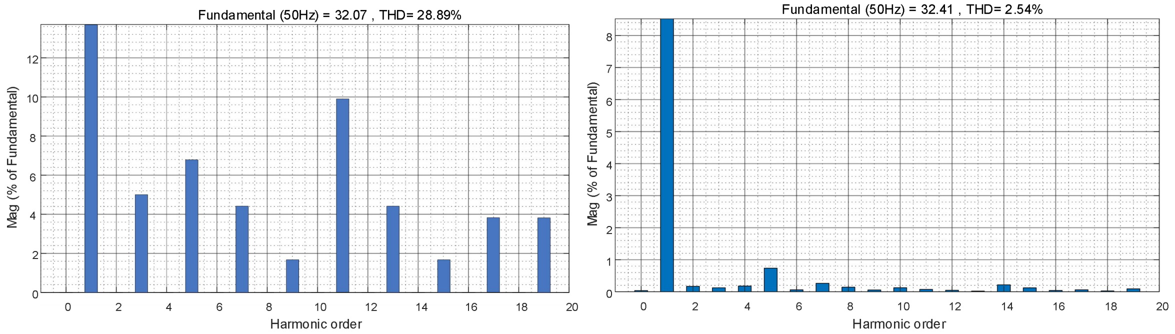


Figure 13: System simulation result diagram

The FFT (Fast Fourier Transform) spectrum analysis results, depicted in Figure 14, indicate a significant reduction in odd harmonics under the influence of the APF. Prior to the APF intervention, the total harmonic distortion (THD) of the current was as high as 28.89% [18]. However, this was reduced to merely 2.54% post-APF intervention. This substantial improvement not only substantiates the APF's capability in attenuating and eliminating harmonics in practical operations but also underscores its importance in enhancing power quality and ensuring stable electrical system operation.



(a) Select the part of current analysis



(b) Before APF intervention (c) After APF intervention

Figure 14: Dumper current FFT analysis diagram

This result further bolsters the APF's effectiveness as a solution for harmonic mitigation, particularly when addressing harmonic issues emanating from large industrial equipment such as the O-type rotor car dumper [19]. The considerable reduction in total current harmonic distortion aids in minimizing energy loss, enhancing energy efficiency, and extending the lifespan of electrical equipment while reducing maintenance costs. Furthermore, the improved current waveform also indicates enhanced voltage quality in the grid, thereby benefiting operational efficiency and reliability of the entire power system. Therefore, this finding is not only significant for theoretical research but also provides invaluable reference and guidance for the application of harmonic mitigation technologies in industrial practice.

4. Summary

This paper focuses on the power quality issues caused by car dumpers, particularly harmonic problems, and proposes an effective mitigation strategy. Simulation analysis has shown that the use of parallel-connected Active Power Filters (APF) can effectively compensate for the harmonics generated by car dumpers, significantly improving power quality and reducing the Total Harmonic Distortion (THD) of current to 2.34%. This adjustment brings the grid-side current closer to a standard sinusoidal waveform, validating the application value of parallel-connected APF in car dumper systems. As technological advancements continue and the demand for power quality management increases, the application of advanced power electronic devices like APFs will become more prevalent. This will provide more reliable and efficient power quality assurance for large industrial equipment such as car dumpers. Ongoing technological innovation and optimized design are expected to result in higher operational efficiency and better energy utilization efficiency in car dumper systems, contributing to the sustainable development of industrial production [20,21].

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