

Control strategy and capacity optimization of energy-storage-based railway power conditioner

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Abstract. Electrified railroad has the characteristics of high safety factors, high comfort, large transportation capacity, and less time-consuming, which is an effective means to solve traffic congestion. However, with the rapid development of China's electrified railroad, harmonic, negative sequence and other power quality problems have also been widely concerned, while more and more regenerative braking energy in the traction power supply system can not be effectively utilized. The input of railroad power regulators makes the power quality problem be solved effectively, this paper studies the control strategy of traditional railroad power regulators. Combined with the actual working conditions of railroad vehicles, the simulation model of traction network, vehicles, and railroad power conditioner is established, and the load characteristics of traction substation are simulated by this model. Secondly, for a domestic substation field collection data processing to obtain the actual train operation load changes, to the battery energy storage device life within the maximum economic returns as the optimization goal, for the peak load reduction judgment threshold and the capacity of the battery energy storage device through the genetic algorithm to process the data of previous years to optimize the design.

Keywords: Electrified railroads, Railway power conditioners, Peak loads, Energy storage systems, Regenerative braking.

1 Background of the study

Nowadays, the electrified railroad is developing rapidly and the flow of people and materials is accelerated. The rapid development of electrified railroads has continuously brought increasing pressure on electric power quality, energy consumption, ecological environment and economic operation, and has become one of the important factors affecting or restricting the development of transportation [1].

At present, the main ways of regenerative braking energy utilization are energy-consuming, energy-feeding, and energy storage, of which the energy storage technology is widely used because it is not only energy-saving and environmentally friendly, simple in structure, but also has high reliability of power supply. However, there are fewer studies at home and abroad based on energy storage systems to recycle regenerative braking energy and reduce load peak in electrified railroads, and basically, they are centered around DC power supply systems such as subways and streetcars to carry out research on control strategies and

optimization aspects, to achieve peak load regulation and the use of regenerative braking energy, but AC power supply systems are different, which not only need to consider the load characteristics for the selection of the energy storage system, However, the AC power supply system is different, not only need to consider the load characteristics for the selection of the energy storage system, and the use of appropriate control strategy, but also consider the negative sequence, harmonics, and other system power quality management issues.

With the increase in operating mileage and a large number of railroad load inputs, the amount of electricity costs faced by the railroad sector is also increasing, and it becomes particularly important to improve the economic operation of the system. As the traction load has the characteristics of fluctuating random, frequent action and large load peaks, it will not only bring a series of power quality problems but also lead to a large amount of regenerative braking energy back to the grid, resulting in a huge load impact [2]. In compliance with the principle of two-part tariff charging, the regenerative braking energy fed back to the grid is not counted inversely, and the large load peaks and long durations directly lead to additional expenses.

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For the power grid, improving power quality, increasing the utilization rate of regenerative braking energy, and improving the peak-to-valley difference of loads can effectively improve the utilization rate of the equipment, reduce the expenditure on electricity, reduce the investment in system equipment, and make the electric power system operate stably, efficiently and economically. Therefore, how to improve power quality, increasing regenerative braking energy utilization, and reducing peak load in the system becomes especially critical [3].

At present, there are two main methods to improve the regenerative braking energy utilization rate of electrified railroads:

1. Optimize the traveling organization to improve the utilization rate of regenerative braking energy between Locomotives [4]. Taking into account constraints such as line conditions, weather conditions, locomotive operating nodes, and train traction/braking power, optimize the train operation organization to minimize energy consumption throughout the entire process [5].
2. External energy storage and energy feedback device, regenerative braking energy storage, or energy feedback utilization [6]. At present, there are related studies on the devices regenerative braking energy storage [7] and load peak [8, 9] processing of electrified railroads. By connecting the intermediate DC link of RPC to the energy storage device, regenerative braking energy storage and utilization can be achieved, optimizing the load peak judgment point to limit the input area of the energy storage device, and carrying out load peak processing.

At this stage, energy storage technology is mainly used in electric vehicles, new energy generation, microgrids [10–12], etc. The power quality management effect of RPC, capacity configuration technology, and energy management. The strategy of the energy storage system has been the research hotspot in recent years [13, 14], and the characteristics of the two-way flow of RPC energy also provide the possibility of regenerative braking energy utilization for energy storage devices.

Various research for conventional RPC have been matured. Literature [15] analyzed the negative sequence and harmonic compensation principle of RPC, focusing on the effect of hysteresis loop control switching frequency on the closed-loop tracking capability to improve the stability of the system. Literature [16] simplified the modular multi-level RPC to improve the flexibility and robustness of the system and control the compensation arm current by hysteresis loop control, this control strategy is simple to control, fast response is robust and few debugging parameters. Literature [17] analyzes the principle of incomplete compensation for the transient under-power problem existing in high-speed RPC operation, and proposes a compensation strategy under overload to realize the incomplete compensation of RPC. Literature [18] proposed a new type of power quality management scheme for traction power supply systems consisting of RPC and high-pass filter,

which can simultaneously realize the functions of negative sequence management, network voltage stabilization, power factor enhancement, broadband harmonic suppression, etc., and comprehensively solved the power quality problem of traction power supply system. Literature [19] studied the LPF technology and decoupling strategy for grid phase-locking, and analyzed the performance of resonant phase-locked loop and reduced-order resonant phase-locked loop in discrete domain, at the same time, a series-connected structure of LPF is proposed, which can effectively improve the speed and quality of the extraction of active and reactive command signals. Literature [20] proposed a multilevel RPC system based on a YNvd balancing transformer, analyzed the topology, equivalent model, and compensation principle of the system, and proposed a hierarchical control strategy consisting of three layers with command current tracking, circulating current suppression, and link voltage balancing according to the compensation principle. Literature [21] for railroad power quality capacity optimization problem, using energy optimization method for RPC control, to achieve optimal compensation, RPC compensation capacity reduction, and to meet the power quality requirements, verifying the rationality and economy of the algorithm. Literature [22] takes the negative sequence voltage unbalance degree and power factor as the constraints and proposes an RPC capacity optimization design method, which effectively makes the RPC capacity utilization rate reach the optimal effect. Literature [23] analyzes the basic principle of RPC dynamic compensation of power quality and proposes an RPC control strategy taking into account the energy storage device, which can recycle and utilize the regenerative braking energy generated by the traction power supply system, and also well solve the problem of negative-sequence and harmonic current compensation of the energy storage device after it is connected to the traction power supply system. Literature [24] proposed a new type of RPC based on supercapacitor energy storage, an in-depth study of the power transfer characteristics between the supercapacitor and the RPC, through the construction of the equivalent circuit of the two control modes, comparative analysis of the accuracy of the two control modes and the supercapacitor discharge out of control problems, and then put forward a new type of RPC coordinated control strategy based on the supercapacitor energy storage.

2 RPC structure and compensation principle based on V-v transformer

V-v transformers are widely used in electrified railroads because they not only have a simple wiring form, but also have a high capacity utilization rate, so V-v wiring transformers are widely used in electrified railroads, but the access of V-v transformers also create a power supply environment in electrified railroads that has single-phase power supply and serious negative sequences, and since RPC can be a good solution to all kinds of power quality problems, this chapter will analyze the traditional RPC compensation system under V-v transformers [25].

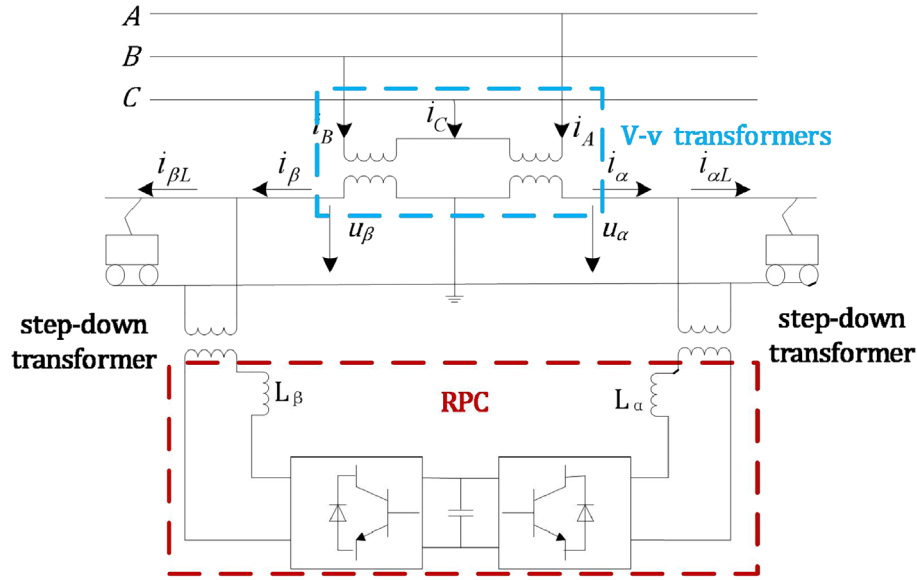


Figure 1. RPC topology.

2.1 V-v transformer and RPC system architecture

The structure of the compensation system based on the V-v transformer RPC is shown in Figure 1, and the left and right power supply arms are power supply arms respectively. The three-phase 110 kV voltage is converted to single-phase 27.5 kV voltage by a V-v transformer to supply power to electric locomotives on both sides of the power supply arms, and both sides of the power supply arms are connected to DC side support capacitors through step-down transformers to convert 27.5 kV voltage to 1 kV voltage by RPC converters on both sides.

2.2 Compensation principle of RPC based on V-v transformer

Assuming that the system is in an ideal state, the AC/DC voltage-type converter power factor angles on both supply arms are θ_a and θ_b , and U_A , U_B , U_C are the three-phase AC voltages on the primary side of the V-v traction transformer, and for and both sides of the power supply arm voltage, and for and both sides of the power supply arm current. and are the electric locomotive fundamental currents of the power supply arms on both sides, respectively, and harmonics are not considered for the time being.

Because the AC drive electrified railroad locomotive generally uses four-quadrant pulse-width modulation rectifier control, the power factor is approximated as 1. Taking the A-phase voltage as the reference, and the two-phase power supply arm of the fundamental current i

$$\begin{cases} \dot{I}_{\alpha L} = I_{\alpha Lf} e^{-j30^\circ} \\ \dot{I}_{\beta L} = I_{\beta Lf} e^{-j90^\circ} \end{cases} \quad (1)$$

Where, $I_{\alpha Lf}$ and $I_{\beta Lf}$ is the rms value of the base wave current of the supply arms of the α and β phases. Assuming

that, at this time, the three-phase current is shown in Figure 2.

In the figure, $\dot{I}_A$, $\dot{I}_B$, $\dot{I}_C$ for V-v transformer three-phase side phase current phase quantity, $\dot{U}_A$, $\dot{U}_B$, $\dot{U}_C$ for three-phase side phase voltage phase quantity. At this time, A, B, C three-phase current values are not equal in size, A, B two-phase current lags and exceeds the A, B two-phase voltage, respectively, three-phase current contains negative sequence current. If the RPC will be, half of the difference between the phase load current active current from phase to phase transfer, the two-phase active current component size is equal, so the A, B two-phase current amplitude is equal, at this time the three-phase current as shown in Figure 3.

At this time, the three-phase current A, B phase current size is equal, but the C-phase current and A, B-phase current are not equal to the three-phase current in the negative sequence and positive sequence current ratio of 50%, the phase A, B-phase current lagging behind and ahead of the A, B-phase voltage, respectively, and the C-phase current and voltage in phase with the same. At this time, it is necessary to carry out reactive current compensation for, phase, so as to make A, B phase current and A, B phase voltage phase consistent, the three-phase current compensation for three-phase symmetrical current.

According to Figure 3, it can be seen that the size of the reactive current to be compensated by the α , β two-phase converter is:

$$I_{\alpha cq} = I_{\beta cq} = \frac{1}{2} (I_{\alpha Lf} + I_{\beta Lf}) \tan 30^\circ \quad (2)$$

Where α and β phases transfer reactive power to the phase, after reactive power compensation, the three-phase current phase diagram is shown in Figure 4.

From Figure 4, it can be seen that after active and reactive power compensation of RPC, the three-phase currents have been completely symmetrical, and the three-phase

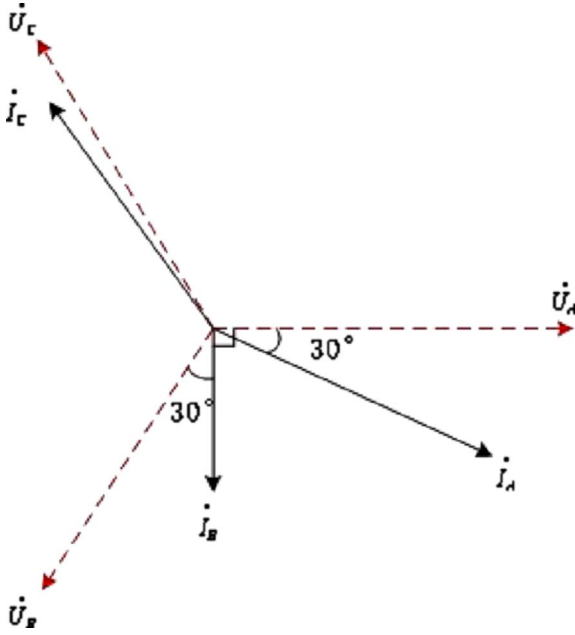


Figure 2. Compensate the first three-phase current vector diagram.

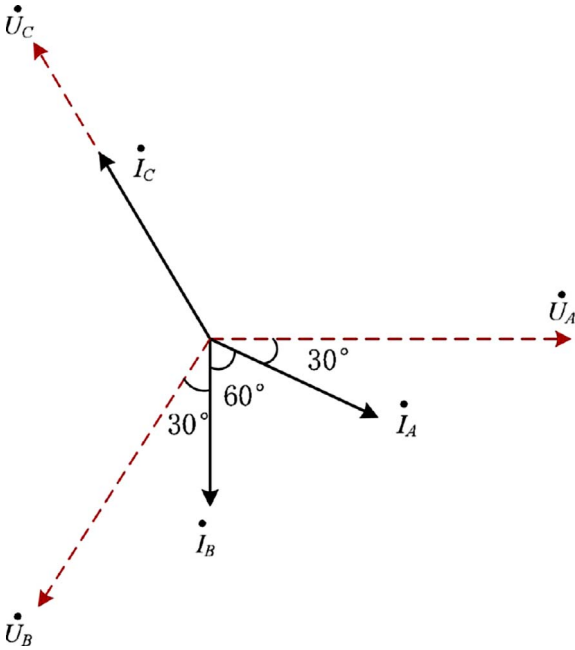


Figure 3. Three-phase current vector diagram after active power compensation.

power factor is 1. When the situation is similar to the above, the value of the negative sequence compensation current of the converter on both sides of the RPC in the general case is:

$$\dot{I}_{\alpha cf} = \frac{1}{2} (I_{\beta Lf} - I_{\alpha Lf}) e^{-j30^\circ} + \frac{1}{2\sqrt{3}} (I_{\alpha Lf} + I_{\beta Lf}) e^{j60^\circ}$$

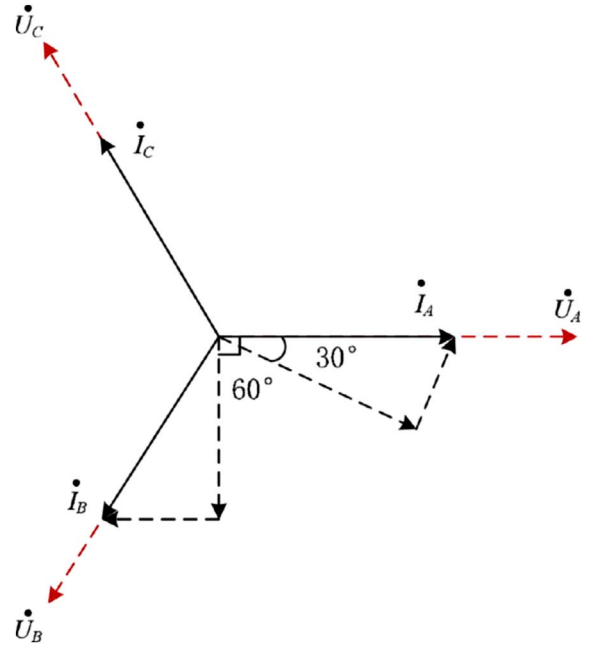


Figure 4. Three-phase current vector diagram after active and reactive power compensation.

$$\dot{I}_{\beta cf} = \frac{1}{2} (I_{\alpha Lf} - I_{\beta Lf}) e^{-j90^\circ} + \frac{1}{2\sqrt{3}} (I_{\alpha Lf} + I_{\beta Lf}) e^{-j180^\circ} \quad (3)$$

In the formula, $\dot{I}_{\alpha cf}$ and $\dot{I}_{\beta cf}$ are the equivalent currents in the RPC, a two-phase converter in the supply arm side, sets the direction of flow to flow into the RPC for the positive direction.

Since the load of an AC-driven electrified railroad locomotive generates harmonics, the RPC also needs to carry out harmonic suppression. the RPC needs to generate and load harmonic currents equal in size and opposite in phase, to offset the harmonics generated by the locomotive. Assuming that the harmonic currents of the power supply arms on both sides of α and β are $\dot{I}_{\alpha Lh}$ and $\dot{I}_{\beta Lh}$, the harmonic suppression current generated by the RPC can be obtained as:

$$\begin{cases} \dot{I}_{\alpha ch} = -\dot{I}_{\alpha Lh} \\ \dot{I}_{\beta ch} = -\dot{I}_{\beta Lh} \end{cases} \quad (4)$$

The converter compensation current on both sides of the RPC is:

$$\begin{cases} \dot{I}_{\alpha c} = \frac{1}{2} (I_{\beta Lf} - I_{\alpha Lf}) e^{-j30^\circ} + \frac{1}{2\sqrt{3}} (I_{\alpha Lf} + I_{\beta Lf}) e^{j60^\circ} - \dot{I}_{\alpha Lh} \\ \dot{I}_{\beta c} = \frac{1}{2} (I_{\alpha Lf} - I_{\beta Lf}) e^{-j90^\circ} + \frac{1}{2\sqrt{3}} (I_{\alpha Lf} + I_{\beta Lf}) e^{-j180^\circ} - \dot{I}_{\beta Lh} \end{cases} \quad (5)$$

As the current generated by the converter on both sides of the RPC has to pass through the step-down transformer, set the step-down transformer ratio as k . Multiply equation (5) by the transformer ratio k to obtain the compensation

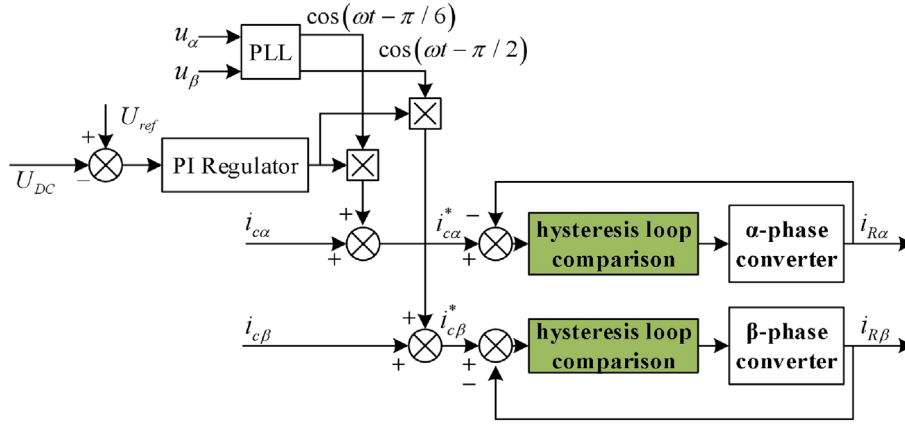


Figure 5. RPC double closed-loop control strategy.

current of the converter on both sides of the RPC on the low-voltage side.

3 Control strategy for RPC

RPC can realize the comprehensive management of negative sequence, reactive power, and harmonic power quality problems in electrified railroads after command current extraction, but in order to ensure that RPC can work stably, it also needs a suitable control strategy, as shown in Figure 5, which is the double-loop control strategy diagram of RPC.

A stable intermediate DC link voltage is necessary for the converter on both sides of the RPC to work stably. Therefore, a double closed-loop control strategy with the outer loop as the voltage loop and the inner loop as the current loop is used.

1. Voltage outer loop: The amount of energy that needs to be stored in the DC side support capacitor determines the DC side voltage. In order to maintain a stable DC side voltage, it is necessary to ensure that the energy flowing in and out of both ends of the RPC is equal. The difference between the DC voltage reference value and the actual DC voltage value is processed by the error of the PI regulator to obtain the active current command value for DC-side voltage control. The current command value is multiplied by the voltage synchronization signals of the power supply arms on both sides, and the control phase is the same as that of the power supply arm voltages to obtain the DC side voltage control signals of the converters on both sides of the RPC. By superposition of the current integrated compensation reference signal command extracted from the detection link, the reference command of the actual current of the converters on both sides of the RPC is obtained. The power flow of the converters on both sides can work together to maintain the stability of the DC-side voltage, thus ensuring the balance of the active components on both sides of the RPC.

2. Current inner loop: from the above analysis, it can be obtained that in order to get the stable intermediate DC link voltage, there are two parts of the actual compensation current reference instruction for the converters on both sides of the RPC. The first part is the integrated current reference instruction of negative sequence, reactive power, and harmonics, and the second part is the active current instruction of DC side stable voltage control.

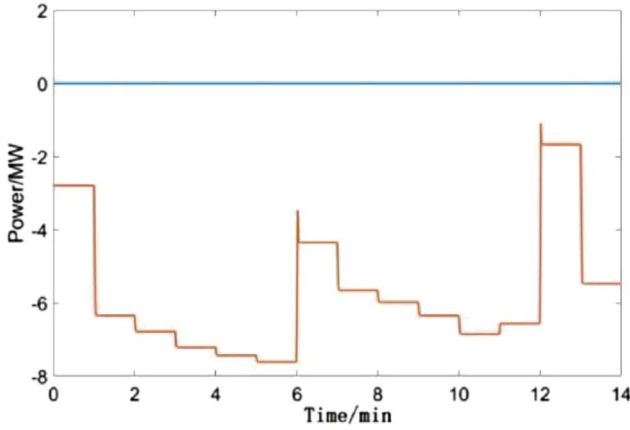
In order to realize the fast-tracking of the current command value, the current hysteresis loop comparison tracking control is adopted to control the converter on both sides of the RPC to ensure that the converter has a fast response speed. The final reference current command is used to generate the control signal through the regulation effect of hysteresis loop comparison tracking control, and then the switching tubes of both sides of the converter are controlled by the PWM generator module to realize the control of both sides of the RPC converter.

4 Analysis of simulation results

Define both sides of the bridge armload of the total active power as positive, that is, the line train as a whole is in traction, and the whole from the traction network absorbs energy; both sides of the bridge armload of the total active power is negative means that the train as a whole is in the braking state, the excess regenerative braking energy is released into the traction network. In order to better analyze the effect of RPC governance, a sampling frequency of 0.001 s is used to sample the voltage and current at the converter cabinet transformer of an actual substation, and the active power of the data is decomposed into a change value of one per minute through Fourier decomposition. In order to verify the compensation effect of RPC under the double-closed-loop control strategy described in subsection 2.2, this chapter screens the data collected and processed in the actual substation under several typical operating conditions and uses MATLAB/SIMULINK to perform the RPC compensation simulation verification,

Table 1. System simulation parameters.

Parameters	Value
Grid-side three-phase voltage/kV	110
Grid-side Frequency/Hz	50
V-v Traction Transformer ratio	110/27.5
Step-down transformer ratio	27.5/1
Output inductance of AC side of converter/mH	0.01
DC side capacitance/mF	20
DC side reference voltage/kV	1650

**Figure 6.** Operating condition– Active load on both arms before compensation.

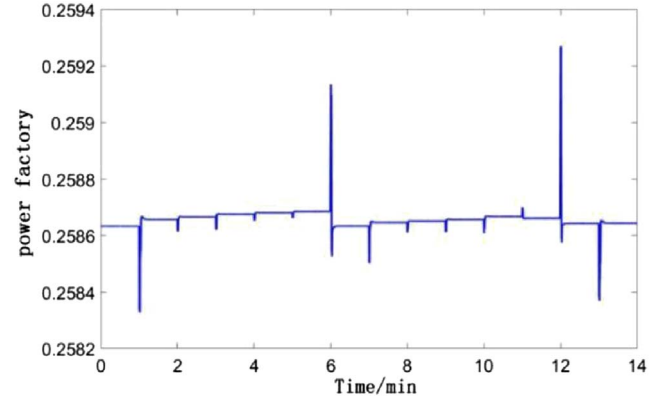
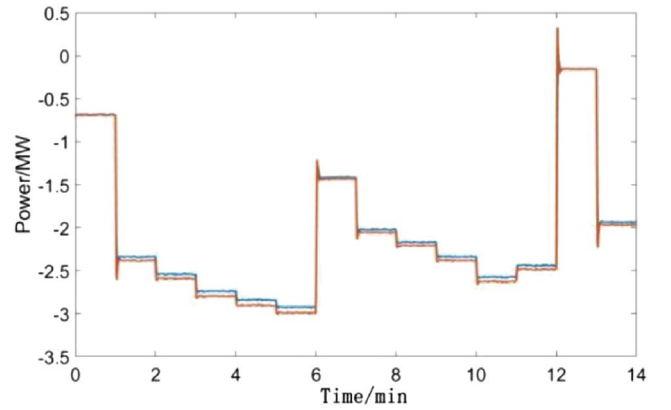
and Table 1 shows the simulation parameters of the RPC system.

4.1 Negative sequence compensation simulation

The working condition is that one side of the bridge arm is in the braking condition and the other bridge arm is in the no-load condition, which has the largest negative sequence current and the most serious three-phase unbalance. The simulation results before adding RPC control are shown in Figure 6.

At this time, the bridge arm is unloaded, the bridge arm is in the braking condition, and the active power is not balanced, because the active and reactive components of the system are not compensated. The voltage and current phases are not equal. As shown in Figure 7, the A-phase power factor is very low, the size of which varies between 0.25 and 0.26, and the power factor fluctuates more gently. At this time, because there is no addition of the RPC compensator, the three-phase current magnitudes and phases are not balanced, and the three-phase current imbalance is 99.29%. The degree of imbalance can reach 99.29%.

After adding the RPC compensation device, the two sides of the bridge arm through the RPC compensation device for the active component transfer, after the transfer of the two sides of the bridge arm active power situation is shown in Figure 8.

**Figure 7.** Operating condition – Power factor condition before compensation.**Figure 8.** Operating condition – Active load on both arms after compensation.

The phase A voltage and current phases are just equal after the RPC device. After the RPC device management power factor is close to 1, the fluctuation is 0.998 or so. At this time the A-phase power factor is shown in Figure 9.

4.2 Harmonic compensation

Assume that there are locomotive loads on both the left and right supply arms with unequal power. The locomotive load is replaced by a resistive harmonic source, which contains only the 3rd, 5th, 7th, 9th, and 11th lower harmonics. The RPC compensation device is added for harmonic compensation simulation, and the current command detection method and control strategy are the same as above. The simulation results before and after adding the RPC compensation device are shown in Figure 10 to Figure 11.

IA, IB, and IC are the primary side A, B, C three-phase currents of the traction transformer. It can be seen that the three-phase currents of A, B and C contain a certain amount of harmonics before compensation, and the harmonic content of the primary-side current is significantly reduced after compensation. The measured distortion rate of the primary side A-phase current is reduced from 17.17% to 1.39%, which proves that the traditional RPC

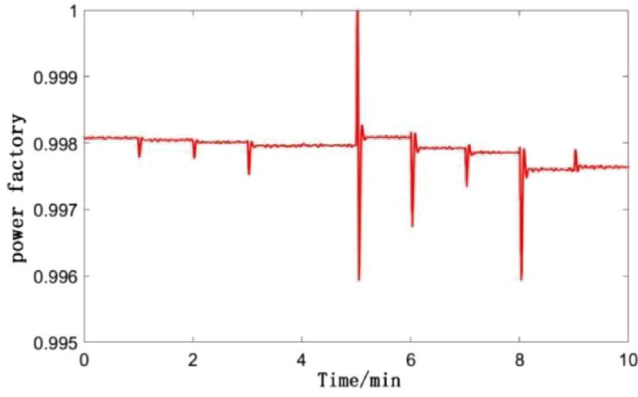


Figure 9. Operating condition – Power factor condition after compensation.

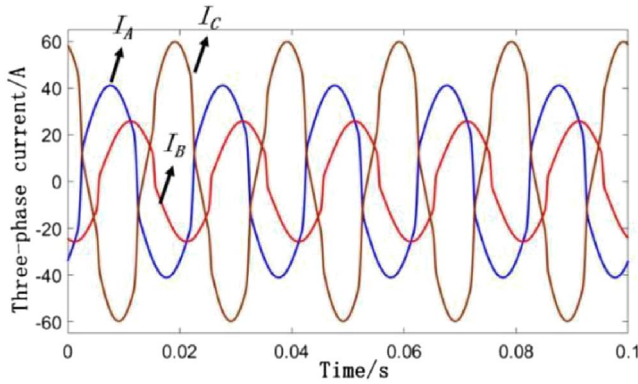


Figure 10. Three-phase current before harmonic compensation.

has better harmonic suppression ability by using this control strategy.

5 Optimization of energy storage device capacity and its peak shaving thresholds

According to the measured load change analysis in a substation, the load peak value is large, the duration is long, it will produce a large demand value, and the maximum value of the demand within a certain period of time will be the maximum demand. Demand is the average value of active power within a specified time interval, and the specified time interval is the period of demand. The energy storage device needs to be discharged during the peak load duration to reduce the maximum demand. The maximum demand of a substation is obtained by the slip measurement method as shown in Figure 12. The maximum demand value is 24.727 MW. suitable algorithms need to be selected to optimize the capacity configuration of the energy storage device and the peak shaving threshold.

5.1 Optimization algorithm

A genetic algorithm is a computational model of the biological evolution process that simulates the genetic principle of survival of the fittest and survival of the fittest in natural

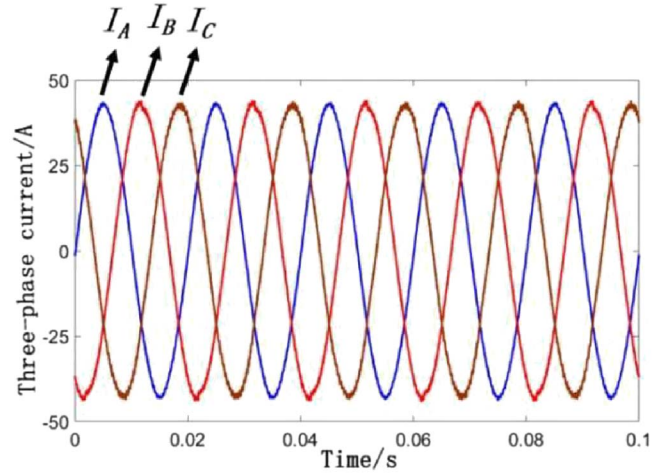


Figure 11. Three-phase current after harmonic compensation.

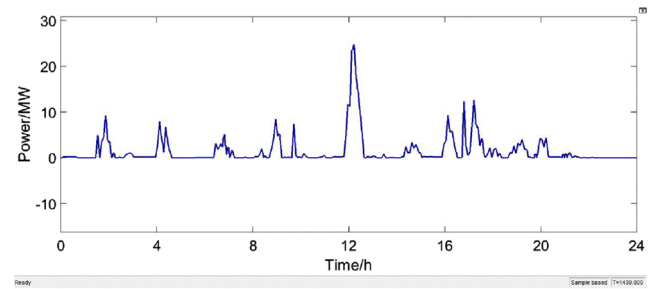


Figure 12. Demand curve on the day when the peak load of substation appears.

selection in Darwin's theory of biological evolution and achieves the computation of optimal solution by simulating the evolution process of nature. The features mainly lie in the fact that it can directly process the structural objects without special qualifications, and has good global optimization seeking ability. At the same time, it can automatically obtain and guide the optimization interval and automatically adjust the optimization direction without determining the rules. These characteristics also further indicate that genetic algorithms can be widely used in many fields such as combinatorial optimization, machine learning, automatic control, and artificial intelligence. For the problem of optimizing the objective in the algorithm, it can be generally established by equation (6):

$$\begin{cases} \max f(x) \text{ or } \min f(x) \\ x \in R \\ R \subset U \end{cases} \quad (6)$$

Where, x is the decision variable, $\max f(x)$ and $\min f(x)$ is the objective function, and are the constraints of the system, the set of solutions that satisfy the constraints is the set of feasible solutions.

According to the introduction of the above algorithm, this paper takes the peak shaving threshold of the actual battery energy storage device put into the system in the

traction substation and the actual energy storage capacity S of the battery energy storage device as the optimization variables, and integrates the peak load curve data collected and analyzed in the actual substation into the optimal configuration of the capacity and peak shaving threshold, so that the flowchart of the genetic algorithm for solving the problem of the capacity configuration of the battery energy storage device in the traction substation and the load shaving threshold at the time of putting into operation is designed as shown in Figure 13.

In order to cope with the situation when the maximum demand value appears (peak shaving condition), it is necessary to add a battery storage device to discharge during the time when the maximum demand appears to reduce the demand value, because the lithium iron phosphate battery is not only lower cost and higher safety performance, but also multiplicative discharge, this chapter takes the optimization of the lithium iron phosphate battery storage system with a fixed power of 2 MW as a prerequisite, and in the interval of 0.5~4.0c multiplicative discharge for the lithium iron phosphate battery model to optimize the configuration.

First, the battery energy storage device needs to work during the maximum demand period, so the objective function of maximizing the battery's return over its lifetime is established and two assumptions are made about the model.

1. Assumption one: ignore the battery climb rate constraint;
2. Assumption two: ignore the internal losses of the battery pack.

The main purpose of a lithium iron phosphate battery energy storage device is to control peak shaving on the load profile. The objective of battery storage capacity configuration in traction substation is to maximize the total benefit value of the battery storage device in the lifetime under the condition of meeting the peak shaving demand of the maximum output power. Therefore, the objective function of the capacity allocation model, as shown in equation (7):

$$f_{\max} = C_{ep} + C_{bp} - C_{bat} \quad (7)$$

Where C_{eq} is the battery life cycle kWh tariff benefit, C_{bp} is the battery life cycle basic tariff benefit and C_{bat} the total investment cost of the battery energy storage device.

According to the objective function, the charging and discharging time constraints, the battery constant power charging and discharging mode output power magnitude constraints, the battery charging and discharging capacity and SOC range constraints, and the battery constant power charging and discharging mode reduction of the maximum demand value constraints will be used as the constraints.

1. Charge and discharge time constraints

The starting and ending time of the discharge cycle is selected as follows: according to the load active power curve and the size of the peak shaving threshold, all load intervals above the peak shaving threshold are discharging intervals

$$1 \leq T_{start}(1) \quad (8)$$

$$T_{start}(i) < T_{stop}(i), \quad i = 1, 2, \dots, n \quad (9)$$

$$T_{stop}(i) < T_{start}(i+1), \quad i = 1, 2, \dots, n \quad (10)$$

$$T_{stop}(n) \leq n_p \quad (11)$$

where $T_{start}(i)$ is the start time of a discharge interval, $T_{stop}(i)$ is the termination time of a discharge interval, and n_p is the cutoff time. The schematic diagram of the discharge interval is shown in Figure 14.

As shown in the above figure, the battery discharge interval changes as the peak shaving threshold rises and falls, and all the intervals where the total system load active power value is greater than the peak shaving threshold are battery discharge intervals. All intervals where the total load active power is less than -600 kW are charging intervals until the battery is charged to the highest allowable SOC value.

2. Charging and discharging power constraints

Since the battery storage device only participates in the discharge processing under peak shaving conditions, the battery storage device needs to output at maximum power when the total load active power of the entire line is greater than a set value and remain in constant power mode to ensure maximum basic tariff revenue. The battery charging power is shown in equation (12).

$$p_c = 0.2p(i) \quad (12)$$

3. Capacity and SOC constraints

$$\begin{aligned} S \cdot SOC_{\min} &< S_{initial} + \sum_{i=1}^k [(T_{stop}(i) - T_{start}(i))p(i)] \\ &< S \cdot SOC_{\max} \end{aligned} \quad (13)$$

$$S_{initial} + \sum_{i=1}^k [(T_{stop}(i) - T_{start}(i))p(i)] = S_{final} \quad (14)$$

Where S is the capacity of the battery energy storage device, $SOC_{\min}$ is the minimum limit value of the battery SOC, and $SOC_{\max}$ is the maximum limit value of the battery SOC, and controlling the battery SOC within this range can effectively extend the service life of the battery, $S_{initial}$ is the starting capacity value of the battery, and S_{final} is the final capacity value of the battery.

4. Maximum demand constraint

Since the battery energy storage device always works in constant power mode, the battery is required to minimize the maximum demand value, the maximum demand constraint equation is as follows:

$$\Delta P = p(i) \quad (15)$$

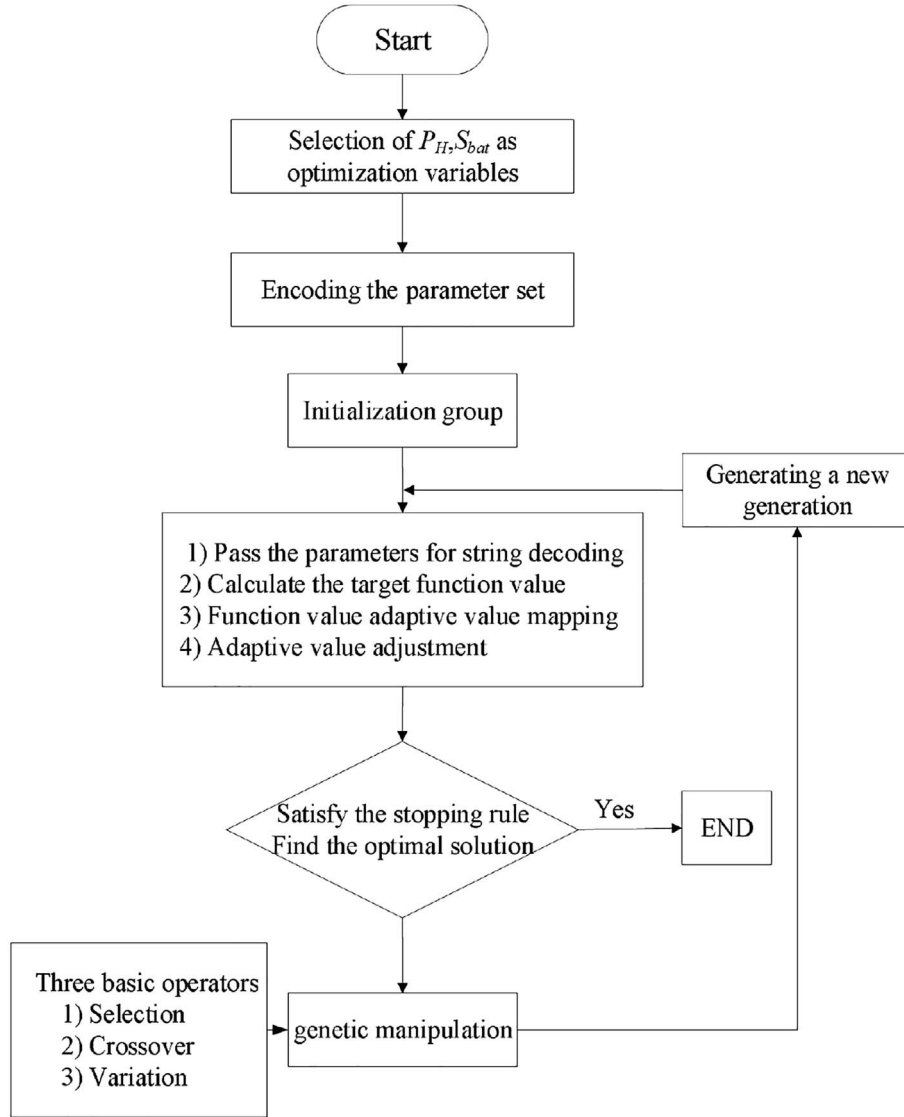


Figure 13. Genetic algorithm flow.

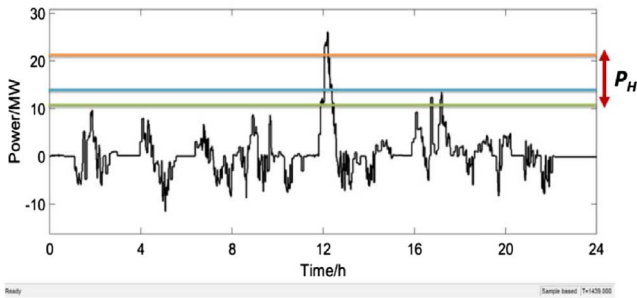


Figure 14. Schematic diagram of discharge interval of battery storage device.

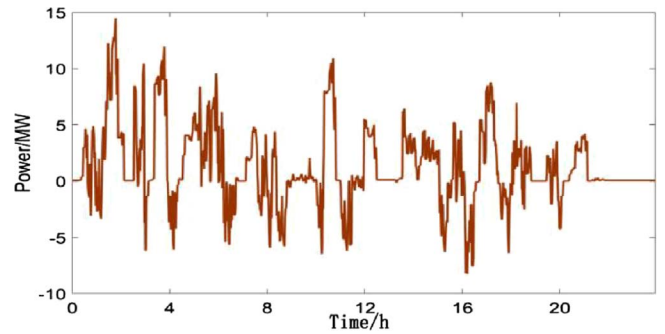


Figure 15. Total active power curve of a substation at a normal time of the month.

Where ΔP is the maximum demand drop value, is the maximum discharge power of the battery in constant power mode, to ensure the maximum utilization of the battery, and reduce the basic electricity cost.

5.2 Optimization algorithm

According to the applicability of the energy storage scheme, the measured data of the traction substation in [Figure 15](#)

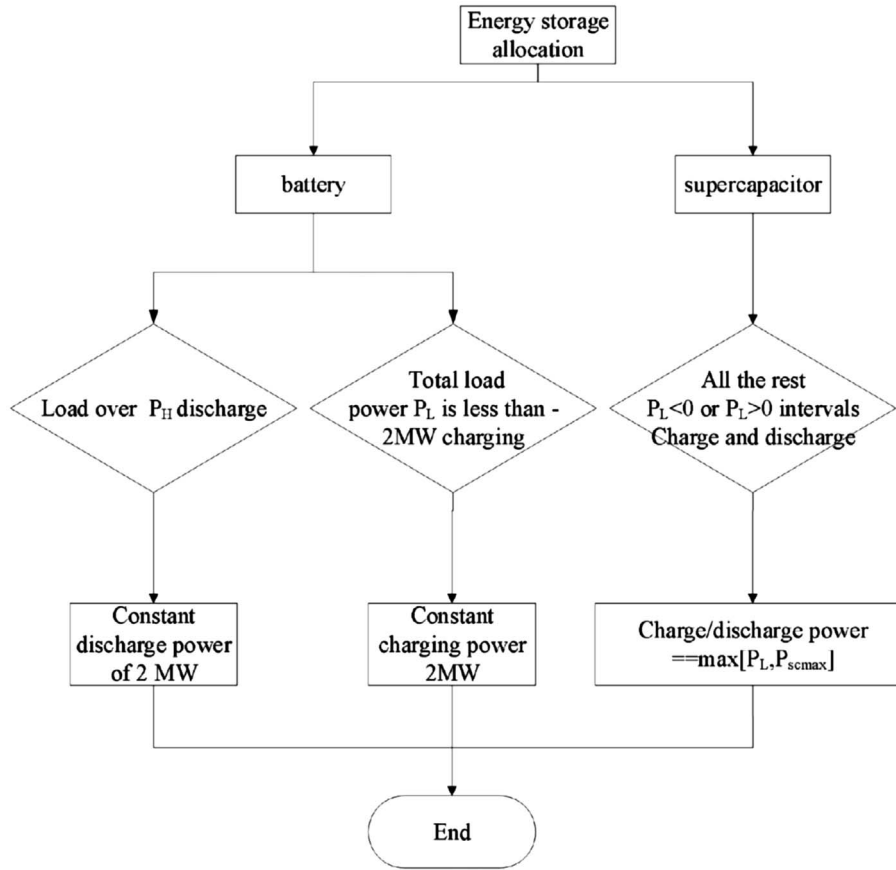


Figure 16. Energy storage system distribution.

Table 2. Energy storage system investment analysis I.

Parameters	Value	Ratio
Reduced maximum demand/kW	2000	8.09%
Regenerative braking energy saved by supercapacitor/kWh	530.78	2.26%
Battery saving regenerative braking energy/kWh	233.33	0.99%
Power transfer saving regenerative braking energy/kWh	4429.77	18.88%
Supercapacitor charge/discharge times	50	—

are selected to analyze the energy-saving effect and economy of the scheme. The traction substation consumes 34.54 MWh of electricity in 24 h, generates regenerative braking energy of 23.465 MWh, and has a maximum demand of 24.727 MW. The charging and discharging power threshold of the energy storage system is 19.545 MW, and the capacity of the batteries is 662 kWh, regardless of the size of the RPC capacity. Although the battery only participates in the peak shaving condition processing, the peak shaving condition processing is essentially also the utilization of regenerative braking energy. According to the most ideal situation (at this time the battery charging and discharging are in accordance with the maximum power, supercapacitor in the load total power is negative when charging, positive discharge) considering the battery and supercapacitor charging and discharging, the

battery and supercapacitor for the load peak and regenerative braking energy utilization processing in accordance with the rules shown in Figure 16.

1. Equipped with a 15 kWh supercapacitor, the supercapacitor only participates in the utilization of the remaining regenerative braking energy, and the supercapacitor maximum charging and discharging power $P_{sc_max} = 2$ MW. Real-time charging and discharging analysis of the measured data and the energy-saving effect is shown in Table 2.

From Table 2, it can be seen that after the energy storage system is built, the maximum demand of the traction substation is reduced by 2 MW, which is 8.09% lower compared to the peak value. In terms of regenerative braking energy

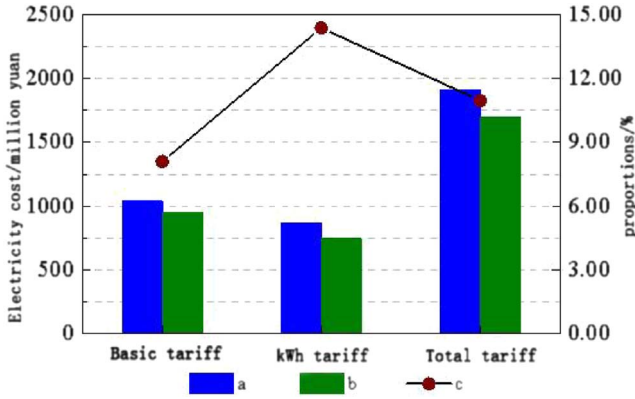


Figure 17. Comparison of returns of energy storage system before and after investment I.

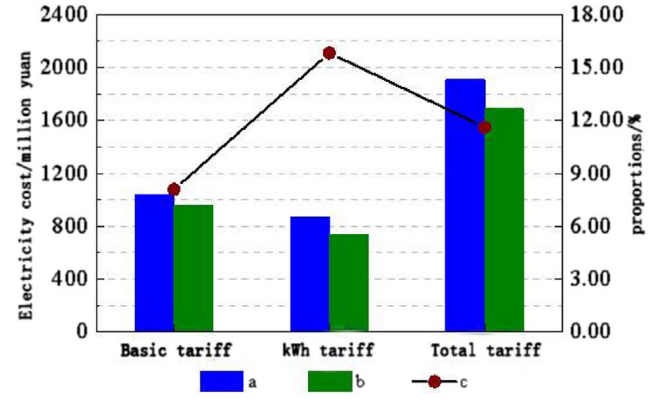


Figure 18. Comparison of returns of energy storage system before and after investment II.

Table 3. Energy storage system investment analysis II.

Parameters	Value	Ratio
Reduced maximum demand/kW	2000	8.09%
Regenerative braking energy saved by supercapacitor/kWh	1.031	4.39%
Battery saving regenerative braking energy/kWh	233.33	0.99%
Power transfer saving regenerative braking energy/kWh	4429.77	18.88%
Supercapacitor charge/discharge times	50	—

utilization, the traction substation can save regenerative braking energy of 530.78 kWh by super capacitor energy storage device on the same day, and the battery energy storage device can save regenerative braking energy of 233.33 kWh, which reduces energy consumption by 2.26% and 0.99% compared with that before adding the energy storage device, and the energy-saving effect of the traction substation through the power transfer is the same as that of the single-battery energy storage.

According to the data of the substation shown in Table 2, the annual electricity cost savings of the station are calculated. The energy-saving situation is shown in Figure 17.

According to the two-part tariff standard, the comparison of the electricity cost before and after adding the energy storage system to the traction transformer substation can show that, after adding the battery energy storage device, the basic tariff, kWh tariff, and the total tariff have been reduced by 8.09%, 14.38%, and 10.96%, respectively.

- Equipped with 50 kWh supercapacitors, the supercapacitors only participate in the utilization of remaining regenerative braking energy, and the maximum charging and discharging power P_{sc_max} of the supercapacitors is 6.7 MW. Real-time charge and discharge analysis was conducted on the measured data, and the energy-saving effect is shown in Table 3.

From Table 3, it can be seen that after the completion of the energy storage system, the maximum demand of the traction substation has decreased by 2 MW, which is

8.09% lower than the peak value. In terms of regenerative braking energy utilization, the supercapacitor energy storage device in the traction substation can save 1.031 MWh of regenerative braking energy on the same day, and the battery energy storage device can save 233.33 kWh of regenerative braking energy. Compared with before adding the energy storage device, the energy consumption is reduced by 4.39% and 0.99%. The energy-saving effect of the traction substation through power transfer is the same as that of single-battery energy storage.

According to the data of the substation shown in Table 3, the annual electricity cost savings of the station are calculated. The energy-saving situation is shown in Figure 18.

According to the two-part electricity tariff, the comparison of electricity cost before and after adding the energy storage system to the traction substation shows that after adding the energy storage device, the basic tariff, kWh tariff, and total tariff are reduced by 8.09%, 15.83%, and 11.62%, respectively.

6 Conclusion

The electrified railroad has the advantages of high speed, large capacity, high safety factor, etc. However, a large amount of negative sequence, reactive power, and harmonics will be generated in the traction transformer substation, and at the same time, a large amount of regenerative braking energy will be generated by the constant change of load power of an electric locomotive. The use of an energy

storage system and RPC compensation device can not only effectively solve all kinds of power quality problems in the substation, but also reduce the peak load, reduce the impact, stabilize the DC side network voltage, and improve the utilization rate of regenerative braking energy. In this paper, the RPC with energy storage in the traction substation is studied in terms of control strategy and optimization of the working interval of the energy storage part to verify its effectiveness.

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