Research on Energy-saving Operation Optimization of Urban Rail Transit Trains

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Abstract. In order to better realize the energy saving operation of urban rail transit trains, considering the use of regenerative braking energy has become the focus of current academic research. Train timetable optimization, energy storage system recovery, and inverter system feedback are the main technical means to achieve it. At present, train operation chart optimization is mainly divided into static timetable optimization and dynamic timetable optimization. The energy storage system recovery includes super capacitor type, battery type and flywheel type energy storage device. This paper introduces three technical methods based on the use of regenerative braking energy, and compares the advantages and disadvantages of different energy storage and recovery devices, and finally come to a conclusion.

1. Introduction

With the rapid development of China's economic level and the continuous improvement of people's living standards, by the end of 2018, the number of motor vehicles in China has increased by more than 15 million compared with the end of 2017, reaching 300 million. While promoting urban development, it also brings about problems such as urban traffic congestion, frequent accidents, and energy shortages. Therefore, in recent years, urban rail transit with characteristics of large volume, low pollution, all-weather, and punctuality has developed rapidly. Statistics show that as of the end of 2017, the total track mileage of the national rail transit totaled more than 4,000 kilometers, and more than 2,700 stations have been built. According to the plan, the future mileage of the national subway will reach 14,000 kilometers, involving 80 cities. With the rapid development of urban rail transit, solving the problem of increased energy consumption has become the top priority.

Generally, the energy consumption of urban rail transit system is mainly distributed in multiple subsystems such as power supply system, escalator, ventilation and air conditioning, lighting, and drainage. Figure 1 shows the proportion of energy consumption in each part. As shown in the figure, the energy consumption of the urban rail transit traction power supply system accounts for 40% of the total system energy consumption. Therefore, it is of certain significance to study the energy consumption of traction power supply in urban rail transit systems [1].

Due to the short distance between urban rail transit stations, the starting and braking of trains are frequent, so there are certain requirements for the starting braking performance of the system. At present, the urban rail transit system mainly adopts the combined electric and electric braking method. Under normal circumstances, the electric braking can meet the braking requirements of the vehicle;
when the electric braking cannot meet the requirements of the vehicle, the air braking can achieve a smooth switching, and Replenish in time. When the train adopts electric braking, the traction motor is in the generator mode at this time, and the kinetic energy of the train can be converted into electric energy. If the generated electric energy is returned to the contact net, it is called regenerative braking. Since most of the traction substations use diode rectification, energy can only achieve one-way flow. If the braking energy returned to the catenary is not effectively absorbed, the traction network voltage will rise. After reaching the network voltage limit, the train will cut off the electric brake and cause regeneration failure, resulting in waste of energy. In order to suppress this phenomenon, urban rail trains are generally equipped with vehicle-mounted or ground-type braking resistors. When the traction grid voltage exceeds the limit value, the braking resistor is activated, and the regenerative braking generated by the train can be converted into heat by the resistor, but in this mode, there is a large amount of heat generation, which will cause problems such as tunnel heat dissipation. Therefore, considering the utilization of regenerative braking energy has become a hot research topic, and it is of great significance to realize energy-saving optimization of urban rail transit system.

![Figure 1. Operating energy distribution of urban rail system](image)

Due to the short distance between urban rail transit stations, the train starts and brakes frequently, it requires large starting acceleration and braking deceleration, stable braking, and good starting and braking performance. At present, in the common braking mode of the subway system, electric braking and air braking are generally activated. Generally 8km/h or less, the electric brake can meet the requirements of vehicle braking; when the electric brake cannot meet the requirements, the air brake can be smoothly switched and quickly replenished, and the kinetic energy of the electric train is combined with the electric brake. Converted to electrical energy, fed back to the grid, and sent to the contact network is called regenerative braking. If the generated regenerative braking energy cannot be effectively absorbed, the traction network pressure will increase, the urban rail train will regenerate the regenerative braking, and the air brake will be used, resulting in the occurrence of regeneration failure, and the kinetic energy of the train will be consumed by the air brake. In order to prevent regeneration failure, the train is generally equipped with ground or vehicle braking resistor. When the traction network pressure reaches the limit, the braking resistor is input, and the generated electric energy will be wasted by the resistance absorption, and the resistance is absorbed and a large amount is generated. The heat, which brings problems such as heat dissipation in the greenhouse, it is necessary to consider the use of regenerative braking energy [2].
Generally, the electric energy generated by regenerative braking can be used to draw nearby trains, realize energy interaction of multiple trains, increase the energy interaction between trains by adjusting train operation maps, or store them in energy storage devices for trains next time. Traction or other equipment in the car operates; it can also be reverted back to the grid. Therefore, the effective use of regenerative braking energy has significant significance for energy-saving optimization of urban rail transit systems. Xu Wei [3] and other measurements on the traction and braking energy consumption of urban rail trains. Through the test and analysis of the energy consumption of Shanghai Metro Line 3 and Line 4, the energy consumed by the subway vehicle in the braking process accounts for 34.93%~55.71% of the traction energy, so the braking energy is fed back. Or the way of storage is used, and its energy-saving effect is of great significance to the sustainable development of our country.

2. Regenerative braking energy utilization technology

According to the flow direction of the regenerative braking energy of the urban rail transit system, when the train is towed, the traction substation and the energy storage device simultaneously release energy to the traction net, the train obtains energy, one part is for the train to draw, and the other part is used for the train auxiliary power supply system. When the train brakes, part of the regenerative braking energy generated by the train is used for the auxiliary power supply system of the train, and the other part is returned to the traction net through the pantograph or the third rail. The energy returned to the traction net is preferentially supplied to the adjacent train for traction. The regenerative braking energy is fed back to the AC network through the energy storage absorption recovery or inverter system. There is a loss in the entire energy flow process. At present, the regenerative braking energy utilization technology is mainly divided into the following three types: train operation map optimization, energy storage system recovery, and inverter system feedback. This chapter provides a brief overview of these three technologies.

2.1. Train timetable optimization

Train timetable optimization is to increase the energy interaction between trains, thereby increasing the utilization of regenerative braking energy. This is also the most direct and effective way [4]. Train timetable optimization can be divided into static operation chart optimization and dynamic operation chart optimization.

The train timetable uses the coordinate principle to describe the time and space relationship of the train running on the track line, and visually shows a graphical form of the train parking or passing in each station (vehicle section) and running in each section.

In the representation mode, the abscissa in the operation chart indicates the time, and the time division is performed according to the requirement with a certain ratio; the ordinate indicates the distance, and according to the actual mileage of the interval, the specified ratio is used to divide the position of the center line of the station; The horizontal line and the vertical line respectively indicate the position and time of each station center line; the diagonal line in the figure represents the train running line, which is the trajectory of the planned running of the train. Generally, the following diagonal line indicates the descending train, and the upward line indicates Upstream train; the intersection of the train running line and the station on the operation map is the time of arrival, departure, or passage of the train, and each train has a different number of running trains. Generally speaking, the upper behavior is even, and the next behavior is odd. 2 is the train operation map.
The static optimization of the train timetable is to optimize the offline operation of the train's timetable, adjust the train running time, stop time and departure interval and other factors affecting the train operation, and adjust the train operation status as a whole to realize the multi-train energy-saving operation research.

Figure 2. Train timetable

Figure 3. The optimization of operation chart
By adjusting the influencing factors such as train running time, stop time and departure interval, the overlapping ratio of traction energy and braking energy is increased, and the energy interaction of the train is realized as much as possible. Figure 3 is a schematic diagram of static adjustment of the train. The running curve of the train 2, the proper adjustment of the train stop time increases the overlapping area of the braking power and the traction power between the train 1 and the train 2, and improves the utilization of the regenerative braking energy.

The dynamic adjustment and optimization of the train's timetable is based on the optimization study of the inter-station running curve of the centralized data system, which can realize offline or online optimization, based on the energy interaction between multiple trains, to improve the regenerative braking of the brake train. The utilization of energy, adjust the operating state of other trains, and improve the energy interaction between multiple trains.

In order to absorb the regenerative braking energy of the adjacent trains, the traction running condition is increased during the running of the train, or the traction running condition of the train is extended when the traction train ends the traction. By changing only the traction force, the train acceleration time is shortened, and the acceleration is increased. The high-power operating condition absorbs the regenerative braking energy of the train; the braking force can also be changed, the braking process becomes longer, and the braking is made. The power is slowly released, reducing the influence of the instantaneous change of the regenerative braking power on the traction network pressure, and prolonging the train traction time, which can absorb the regenerative braking energy of the adjacent train; and changing the traction force also changes the braking force. There is also a traction condition added in the middle idle running condition, and the traction and braking forces may change. Dynamic adjustment needs to be based on communication between trains, and needs to be properly configured and adjusted according to the real-time running status of the train.

2.2. Energy storage system recycling
The regenerative braking energy of the train can be recovered by an energy storage device. It can be used alone or in combination with train operation chart optimization. When acting alone, the train brakes, the regenerative energy is stored in the energy storage device for the next train's traction or the operation of other equipment in the vehicle. When combined with the train timetable optimization, the remaining regenerative braking energy of the train is absorbed. The energy storage device can be divided into an on-board type and a wayside type according to the installation position, and can be classified into a supercapacitor type, a battery type, and a flywheel type according to different energy storage mediums.

2.3. Inverter feedback
Inverter feedback generally consists of a system consisting of an inverter device and a step-up transformer in parallel with the existing step-down transformer and rectifier unit of the traction substation; when the braking energy is returned to the traction network, the bus voltage rises above the set value. When the system starts and absorbs current from the traction net, the braking energy is completed to feed back to the grid; in other states, the system is in standby [5]. Inverter feedback type generally has two types: medium voltage inverter feedback type and low voltage inverter feedback type. There is a new type of inverter + energy storage feedback device, which uses inverter + energy storage hybrid regenerative braking energy.

The absorption device, the DC bus braking energy is connected to the 400 V station low-voltage distribution system through the inverter, and the super capacitor is connected in parallel to the DC bus through the DC/DC bidirectional converter, and the relatively stable braking power is directly transmitted to the station via the inverter. Load power supply, large peak power is absorbed by super capacitor, and then used for load or vehicle start acceleration [6].

Through the introduction of the regenerative braking energy utilization technology of the first three sections, the operation optimization of multiple trains is adopted, the traction and braking time of the train are adjusted, and the parameters such as the train departure interval and stop time are optimized.
to effectively utilize the regenerative braking energy and reduce the system. Energy consumption is the easiest and most effective way. At the same time, the energy recovery device or the inverter feedback device is used to absorb the remaining regenerative braking energy, which further improves the utilization rate of the regenerative braking energy [7, 8]. Table 1 compares three types of regenerative braking energy absorbing devices.

| Table 1. Comparison of regenerative braking energy absorption devices |
|---------------------------------------------------------------|
| **Device** | **energy saving effect** | **Equipment cost** | **Impact on the system** | **Can it meet the characteristics of urban rail transit regenerative energy load?** |
| Resistance type | None | Low | None | Yes |
| Energy storage | Good | High | None | Limited capacity, need multiple sets of parallel |
| Inverter feedback type | Good | High | Harmonic influence | Yes |

3. Conclusion
This paper studies the energy-saving operation of urban rail transit trains considering the use of regenerative braking energy. Three technical methods based on regenerative braking energy utilization are introduced. The train operation diagram operation method is studied in detail. The train operation diagram method is the most direct utilization method. At the same time, the energy storage system recovery device is introduced, and the advantages and disadvantages of different energy storage and recovery devices are compared. Finally, the inverter feedback device is studied. Afterwards, in-depth analysis will be carried out using different energy-saving technologies in combination with the characteristics of urban rail transit trains.

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