Analysis and Research on Energy Absorption and Utilization System of Regenerative Braking in Rail Transit Based on Super Capacitor

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Abstract. Since the 1950s, with the acceleration of urbanization in the world, the urban population has gradually increased. Due to the increase of floating population and road vehicles, urban traffic shows a rapid growth trend. As a mass and high-density public transport, urban rail transit has attracted worldwide attention, and three-dimensional rapid rail transit has been adopted to solve the worsening urban traffic problems. As a mass, fast and punctual public transport, urban rail transit needs frequent start-up and braking. As the traditional traction power supply substation cannot absorb energy in reverse direction, the excess energy generated during vehicle regenerative braking cannot be reused, resulting in energy waste. Therefore, this paper studies the regenerative braking energy absorption and utilization technology based on supercapacitor, and stores the excess energy generated during vehicle regenerative braking into the supercapacitor energy storage system. And the energy in the supercapacitor energy storage system is released when the vehicle starts to accelerate, so that the regenerative braking energy is fully and effectively utilized.

1. Introduction
With the continuous development of China's economy and the flourishing of various undertakings, the people live and work in peace and contentment [1]. The communication and communication between people are increasingly frequent, the development of the city is expanding outward, and the urbanization process is accelerating [2]. Therefore, the demand for transportation is increasing day by day. In order to better solve the problem of urban traffic congestion, countries are constantly exploring new urban traffic modes [3]. Whether a city has rail transportation is often a symbol of modernization and competitiveness. As a representative of large-scale modern transportation, urban rail transit has been developed and applied rapidly in our country. How to improve the construction level of urban rail transit, improve the utilization rate of energy and reduce the operating cost to meet the national policy requirements of energy conservation, environmental protection and low-carbon economy are several key issues to be solved in the construction and development of urban rail transit [4]. At present, regenerative braking technology is generally used for urban rail trains. If regenerative braking energy is not absorbed in time, it will cause the voltage of traction network to rise and affect the safe operation of power network and trains [5].

Urban rail transit system, as a modern metropolitan trunk city with a population of more than one million people, has good benefits and has received extensive attention due to its large volume and high density [6]. The train generates a considerable amount of braking energy during frequent starting and braking, and rational use of it can save energy. According to statistics, the braking energy of urban rail transit can reach 20% to 40% of the traction energy [7]. The rapid urbanization process makes the energy saving and consumption reduction of the urban rail system very huge, and the requirements of energy
saving and consumption reduction policies and technology upgrades are more urgent for the feedback of vehicle braking energy [8]. Therefore, the regenerative braking energy absorption utilization system is applied in the urban rail transit field, and the energy generated by the locomotive braking is fed back to the AC power grid to achieve comprehensive utilization of energy, thereby achieving the purpose of energy saving and consumption reduction [9]. The energy-saving effect is obvious, resulting in significant economic and social benefits. It is of practical significance to promote the recovery of braking energy of urban rail trains into commercialization and application [10].

2. Energy Absorption and Utilization Technology of Regenerative Braking

2.1. Braking modes of urban rail transit vehicles
At present, variable voltage variable frequency emu trains are widely used in rail transit vehicles, and their braking modes can be divided into friction braking mode and power braking mode according to kinetic energy transfer mode. At present, electric brake and air brake are used for vehicle braking, with electric brake as the main brake and air brake as the auxiliary brake in operation. During the operation of the train, due to the short distance between stations, the train starts and brakes frequently and the braking energy is considerable. The electric energy generated by regenerative braking of rail transit vehicles is supplied to the DC traction power supply network. If other vehicles are running in the same power supply interval, the electric energy generated by regenerative braking may be absorbed and utilized by other vehicles. Since the rail transit rectifier uses a diode rectifier that can only be supplied in one direction, these excess regenerative braking energy will cause the DC grid voltage to rise above the allowable voltage range. The 750V DC power supply of the subway may rise to 1000V when the train is braking. The 1500V DC power supply may rise above 1800V during train braking, which will endanger the safety of the rail vehicles and the rectifiers.

2.2. Types of Energy Absorbing Devices for Regenerative Braking
The braking resistor absorption device adopts a constant voltage absorption mode in which a multiphase chopper and an absorption resistor are matched, and the conduction ratio of the chopper is adjusted according to the change state of the DC bus voltage during regenerative braking. So as to change the absorption power, keep the direct current voltage in a certain set range, and consume the braking energy on the absorption resistor. The conventional on-board braking resistor adopts the mode of "braking resistor+braking chopper" and is installed in each power car dispersedly. During regenerative braking, if the converted electric energy is not absorbed by other running trains, the traction network voltage will rise. When the network voltage rises to the upper limit, the traction system starts the brake chopper to consume excessive electric energy on the vehicle-mounted brake resistor. The resistance energy-consuming absorption device is simple and intuitive to control, and the one-time investment is small. However, its disadvantage is that the regenerative braking energy is consumed on the absorption resistor, which does not really realize the reuse of electric energy. However, it is only the centralized treatment of heat energy, and the resistance heat dissipation causes the ambient temperature to rise. Therefore, the device is generally installed on the ground and needs to occupy a certain amount of land.

The device energy storage type regenerative braking energy absorbing device mainly uses a large-capacity energy storage device to absorb and store the train regenerative braking energy. When there is a train starting and accelerating in the power supply section, the device releases the stored electric energy and reuses it. It mainly has two kinds of static energy storage devices and dynamic energy storage devices. The structure of the dynamic energy storage device is too complicated, and the maintenance is difficult, the cost is high, and it is rarely used. Capacitor energy storage type is currently used more, and its electrical system mainly includes energy storage capacitor bank, chopper, DC fast circuit breaker, electric isolation switch, sensor and microcomputer control unit. Capacitor energy storage type energy absorbing device has the advantages of fast charging and discharging speed, large instantaneous power, low maintenance cost and long service life. When the traction network voltage is low, the device can also be put into a voltage regulation working state, thereby improving the power quality of the traction
network. The disadvantage is that the energy storage is small and the storage braking energy cannot be completely absorbed. The heat generation is large, and it is advisable to use independent installation space and install an environmentally controlled ventilation system.

3. New Energy Absorption Device for Regenerative Braking

3.1. Inverter and Resistor Mixed Type
Inverter feedback regenerative braking energy absorption device has two types: medium voltage inverter feedback type and low voltage inverter feedback type. The medium voltage inverter feedback type directly adopts a PWM (pulse width modulation) traction rectifier inverter device running in four quadrants, combines controllable rectifier and controllable inverter, and energy can flow in two directions. The low-voltage inverter feedback type connects the inverter device in parallel on the station traction bus on the line that has adopted uncontrollable rectification power supply to convert the braking electric energy into alternating current and feed it back to the low-voltage 400 V power distribution system. The inverter + resistance hybrid regenerative braking energy absorbing device is composed of an inverter device and a resistance absorbing device. When the regenerative braking causes the DC voltage to exceed the specified value, it is first inverted to the station 400 V low-voltage distribution system, which is absorbed by the station power and lighting equipment. When the absorbed power is insufficient, the resistance is input and the excess energy is absorbed by the resistor. The device combines the advantages of inverters and resistors, and inverters to low-voltage 400 V distribution systems can avoid harmonic effects on the system to a certain extent.

3.2. Hybrid Inverter and Energy Storage
Considering the vehicle characteristics, the national energy conservation and emission reduction policies, as well as the current application and technical development direction of various regenerative braking energy absorption devices, an inverter (400 V)+ energy storage hybrid energy absorption device is adopted. In the structure of the device, DC/AC inverters are connected in parallel to the traction DC bus and connected to the 400 V low-voltage distribution system of the station through an isolation transformer. The super capacitor energy storage device is connected in parallel on the DC side through a bidirectional DC/DC converter. The feedback distance of inverter energy in the device to the low-voltage distribution system is short, and the energy can be utilized in time. At the same time, the DC/DC bidirectional converter has the energy bidirectional flow function to charge the super capacitor when the train brakes. The supercapacitor energy storage device is used to absorb the short-term impact power, discharge the super capacitor when needed, and release the stored energy. The inverter + energy storage hybrid absorption device is installed in the traction substation. It can not only solve the limitation that supercapacitor can not store large capacity, but also make full use of its advantages of fast charge and discharge speed and absorption of spike power, and solve the impact power and harmonic problem of inverter feedback.

4. Super Capacitor Technology

4.1. Working Principle of Super Capacitor
Supercapacitors are also called electric double layer capacitors, gold capacitors and farad capacitors. High specific surface area carbon materials or noble metal oxides such as RuO2 are used as electrodes, and electric energy is stored by using an interface electric double layer capacitor formed between the electrodes and electrolyte. The principle of electric double layer was put forward by Helmholz in 1879. The metal electrode is inserted into the electrolyte. When a voltage is applied to the metal electrode, the net charge on the electrode surface will attract some irregularly distributed ions with different charges from the electrolyte. At the electrode-electrolyte interface, one side of the electrolyte at a certain distance from the electrode is arranged in a row to form an interface layer with the same charge quantity and opposite sign as the remaining charge quantity on the electrode surface. This interfacial layer consists
of two charge layers, one on the electrode and the other in the electrolyte, thus forming an electric double layer. Since there is a barrier on the interface, the two layers of charge can not neutralize each other across the boundary. According to the capacitor principle, a plate capacitor is formed. The two electrodes form an interface layer respectively, so the total capacitance of the capacitor is positive and negative. Sum.

4.2. Characteristics of supercapacitors
At room temperature, the number of charge-discharge cycles of supercapacitor during deep charge-discharge can reach more than 500,000, or 90,000 hours of operation. As an energy storage device, its service life is equivalent to or even longer than that of power converters, controllers and other devices in the system, which can be regarded as permanent devices in many applications. The equivalent series internal resistance of supercapacitor is very small, and the energy loss in the charging and discharging process is small, so it has very high charging and discharging efficiency, and its charging and discharging cycle efficiency can reach more than 90%. In the case of energy loss including power converter, the charge and discharge cycle loss of the supercapacitor is about 10%, and the battery is 20%~30%. The supercapacitor does not undergo an electrochemical reaction during the exchange of energy, and the dependence on the ambient temperature is greatly weakened, and has good high and low temperature performance. Supercapacitors can operate normally from -40 °C to +70 °C without significant performance degradation. The materials used in the electric double layer supercapacitors are safe, non-toxic and environmentally friendly. It will not pollute the environment and will not cause harm to production or users.

Table 1. Performance Index Comparison of Supercapacitors, Batteries and Common Capacitors

| Performance                      | Supercapacitor | Lead acid battery | Electrolytic Capacitor |
|----------------------------------|----------------|-------------------|------------------------|
| Cyclic life (secondary)          | >500,000       | 1000-2000         | >10^6                  |
| Charging and discharging efficiency | 85-90%         | 75-85%            | ≈100%                  |
| Charging time                    | SEC level      | Hours             | 10^-6-10^-3 seconds    |
| Temperature range                | -40-70°C       | Room temperature  | -40-105°C              |
| Energy density                   | 6-12           | 20-40             | <0.2                   |
| Power density                    | 2-12           | 0.1-0.5           | 20-1000                |

As a new energy storage component, supercapacitor has the advantages of high energy density of storage battery and high power density of common electrolytic capacitor. Table 1 shows the comparison of performance indexes of supercapacitor, lead-acid storage battery and common electrolytic capacitor.

4.3. Problems to be solved in supercapacitor energy storage
The energy density of supercapacitors is lower than that of batteries, which is about 30% of that of lead-acid batteries. Under the same energy demand condition, its volume and weight are much larger than that of the battery pack, and its application scope is restricted. It is not suitable for large-capacity energy storage systems. However, due to the continuous progress of technology in recent years, its energy density has increased rapidly. Some countries that started earlier in research, such as Japan and other countries, have developed supercapacitors with energy density reaching the battery level. The terminal voltage of a supercapacitor fluctuates greatly with the change of stored energy, and it will continuously rise or fall during the charging and discharging process. However, the DC power supply network of the urban rail transit power supply system requires voltage stability during the working process, thus requiring supercapacitors. A converter is arranged between the DC power supply grid to achieve the purpose of voltage regulation. Supercapacitors have low cell voltages and low storage energy. Generally,
series and parallel combinations are required to achieve the required voltage level and energy storage capacity. Therefore, series voltage equalization processing is required to improve the capacity utilization and safety of the capacitor.

5. Regenerative Braking Energy Absorption and Utilization System Based on Super Capacitor

5.1. Modular Energy Storage System
The whole system consists of four identical energy storage modules connected in series. Each energy storage module includes a bidirectional DC/DC converter and a group of super capacitors. Each bidirectional DC/DC converter consists of multiple channels connected in parallel, the controller of the bidirectional DC/DC converter communicates with an external console through a CAN bus, and each group of super capacitor groups consists of a certain number of super capacitor monomers connected in series and in parallel. The system has four main advantages. First, the modular design is adopted to facilitate the increase or decrease of the number of modules and can be flexibly applied to various occasions. Second, the converter outputs of each module are independent of each other, which facilitates the adjustment of the system structure. Only standard modules need to be designed, thus not only reducing the equipment manufacturing cost but also saving the system upgrade time. Third, the load power and power loss are shared by multiple modules, which can reduce the thermal stress of power semiconductor devices. Redundancy is easy to realize, and the system reliability and power density are greatly improved. 4. The output of the low voltage side of the system is dispersed into a plurality of super capacitor groups, the maximum working voltage of the system is reduced, the number of super capacitors connected in series in the group can be reduced, and the reliability of the super capacitor groups is improved.

Fig.1. Converter Bidirectional Conversion Efficiency Curve

When the inputs of multiple energy storage modules are connected in series, the input voltages of their bidirectional converters are unbalanced in Buck mode. Fig. 1 shows the curve of efficiency versus load when the bidirectional DC/DC converter works in Buck and Boost modes respectively.

5.2. Single Module Energy Storage System
Since the regenerative braking energy absorption and utilization system adopts a modular structure, and each module adopts the same structure and control principle, the structure and parameter design of a single module system can be carried out first, and then a plurality of modules are combined to form the whole energy storage system. In the structural block diagram of the single module energy storage system, the charge and discharge controller is the internal controller of the bidirectional DC/DC converter. Its
main function is to control the power circuit of the bidirectional DC/DC converter to manage the charge and discharge of the super capacitor. The main function of the external controller is to manually set the maximum charging current and maximum discharging current of the super capacitor group by the outside and send them to CDM. The operator can adjust the maximum charge and discharge current value of the super capacitor group according to the state of the ultra-super capacitor group. The auxiliary power supply provides operating power to the CDM and LCD. The main function of the LCD is to display the working information of the current converter (including operating mode, ambient temperature, input high voltage side voltage, super capacitor group voltage and current parameters). CDM, OCM, and LCD transmit data through the CAN communication bus.

6. Conclusion
Building urban rail transit is an inevitable trend of urban development and an inevitable choice for building a resource-saving and environment-friendly society. It is the only way to change the mode of growth and promote the adjustment of economic structure, and it is also an inevitable requirement for building a national innovative city. We need to continuously introduce advanced international technologies to improve our independent innovation ability, which will help to promote the process of localization. In this paper, a regenerative braking energy absorption system for rail transit vehicles based on supercapacitor energy storage is studied, and a modular energy storage scheme is proposed. Four energy storage modules are connected in series to adapt to high input voltage applications. The voltage equalization circuit with modular structure is used to realize the voltage equalization of the cells in the ultracapacitor group. The converter has simple control method and high efficiency, and is suitable for high power applications. For a single module energy storage system, the greater the power, the greater the number of parallel channels. Due to the difference in parameters of each channel, the current distribution of each channel is uneven, resulting in excessive current of individual channels and loss of power switching tubes. Therefore, it is necessary to use current sharing control for parallel channels.

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