Urban Rail Transit Energy Storage Based on Regenerative Braking Energy Utilization

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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 operation chart optimization, energy storage system recovery, and inverter system feedback are the main technical means for its implementation. At present, the recovery of energy storage systems includes supercapacitor type, battery type, and flywheel type energy storage devices. This paper focuses on the urban rail transit energy storage recycling method based on the utilization of regenerative braking energy, studies the basic working principle of the energy storage recovery device, and analyzes the different energy storage and recovery devices, and draws conclusions through comparison.

1. Introduction
By the end of 2018, a total of 185 urban rail transit (hereinafter referred to as urban rail transit) operating lines were opened in 35 cities in mainland China, with a total length of 5761.4 kilometers. The length of the newly added operation line was 728.7 kilometers. In 2018, the total passenger volume was 21.07 billion person-times, a year-on-year increase of 14%. With the expansion of the scale of each city's network and the increase in passenger traffic, the total energy consumption of urban rail transit in all cities increased in 2018 compared with the previous year. Although urban rail transit has the characteristics of protecting the environment and saving energy, its total power consumption is large, which is a veritable energy-consuming household. Taking Beijing as an example, from 2013 to 2018, the energy consumption of urban rail transit increased from 1.08 billion kilowatts to 1.89 billion kilowatts, accounting for 1.65% of the total electricity consumption in Beijing [1].

The urban rail traffic energy classification can be divided into five aspects: station, control center, vehicle segment and integrated base, line and road network. The energy consumption of the station includes energy consumption such as escalator system, power lighting system and environmental control system; the control center and the comprehensive base all contain energy consumption in terms of electric energy, heat, gas, gasoline, diesel, etc.; Traction energy consumption, comprehensive energy consumption, etc [2, 3, 4]. Obviously, power consumption is the most important energy consumption in urban rail transportation energy. It is mainly divided into two categories. One is traction energy consumption that supports train operation, including power consumption of main trains, power consumption of trains entering and leaving the warehouse, and train experiments. The power consumption of the test vehicle, etc.; the other is the station power lighting and other energy consumption that supports the power consumption of the station equipment, including the
environmental control ventilation system, the power lighting system, the escalator system and the water supply and drainage system. According to statistics, the traction power consumption of urban rail transit in Beijing accounts for 45% of the total energy consumption, and the energy consumption of train auxiliary systems (such as ventilation, air conditioning, lighting, control systems, etc.) accounts for 30%-40% of the energy consumption of trains; It consumes 55% of the total energy consumption, and the weak current system (communication, signal and FAS, BAS, etc.) accounts for 2% to 4%. Station ventilation and air conditioning systems, lighting systems, escalators and other energy consumption accounted for 70-80% of the station equipment system energy consumption, power consumption distribution as shown in Figure 1.

![Figure 1. Urban rail traffic energy distribution](image)

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 [5]. Based on the analysis of urban rail transit energy consumption, this paper focuses on urban rail transit energy storage devices that consider the use of regenerative braking energy. The structure of this paper is as follows: The first part analyzes the basic principle of energy storage components; the second part compares different energy storage components; the third part summarizes and analyzes the paper and draws conclusions.

2. Basic working principle of energy storage components
There are three types of urban rail transit energy storage components: supercapacitors, batteries and flywheel devices. This chapter will analyze the basic working principles of the three main energy storage components.

2.1. Supercapacitor
The capacity of a supercapacitor is much larger than a typical capacitor. Because of its large capacity, the external performance and the battery are the same, so there is also called "capacitor battery." The supercapacitor belongs to the electric double layer capacitor, which is the largest one among the world's electric double layer capacitors that have been put into mass production. The basic principle is the same as other types of electric double layer capacitors, which are composed of activated carbon porous electrode and electrolyte. The double layer structure has an extremely large capacity [6].

Electrochemical double layer capacitors (EDLC) are well known for their supercapacitors. Supercapacitors store energy by means of electrostatically polarized electrolytic solutions. Although it
is an electrochemical device, its energy storage mechanism does not involve chemical reactions at all. This mechanism is highly reversible, allowing supercapacitors to be charged and discharged up to 100,000 or even millions of times. A supercapacitor can be viewed as two mutually unrelated perforated plates separated by an electrolyte when voltage is applied to the two plates. The potential applied to the positive plate attracts negative ions in the electrolyte while the negative panel potential attracts positive ions. This effectively creates two charge reservoirs, separating one layer from the positive plate and separating the other from the negative plate.

Conventional electrolytic capacitor storage areas come from flat, thin sheets of conductive material. High capacitance is folded through a large amount of material. It is possible to further increase its surface area by further increasing its surface texture. In the past, conventional capacitors used dielectric separation electrodes, which were mostly plastic, paper or thin film ceramics. The thinner the dielectric, the more areas can be obtained in areas where space is limited. A definition of the surface area limitation of the thickness of the medium can be achieved.

The area of the supercapacitor comes from a porous carbon-based electrode material. The porous structure of this material allows its area to be close to 2000 square meters per gram, much larger than by using plastic or thin film ceramics. The charging distance of the supercapacitor depends on the amount of charged ions in the electrolyte that are attracted to the electrodes. This distance (less than 10 angstroms) is much smaller than the distance through the use of conventional dielectric materials. The combination of huge surface area and extremely small charging distance make supercapacitors superior to conventional capacitors [7].

2.2. Battery

1) Lithium battery working principle

Cathode material: LiMn$_2$O$_4$, Anode material: graphite

Li$^+$ of the positive electrode during charging and Li$^+$ in the electrolytic solution are aggregated to the negative electrode to obtain electrons, which are reduced to a carbon material in which Li is embedded in the negative electrode. Li, which is embedded in the negative carbon material during discharge, loses electrons and enters the electrolyte, and Li$^+$ in the electrolyte moves to the positive electrode.

![Figure 2. Lithium battery working principle](image)

2) Charge and discharge process

The power supply charges the battery. At this time, the electron e on the positive electrode runs from the external circuit to the negative electrode, and the positive lithium ion Li$^+$ “jumps” into the electrolyte from the positive electrode, “crawling” through the curved hole on the diaphragm, “swim "Get to the negative pole and combine with the electronics that have been running long ago.” The reaction that takes place on the positive electrode is:

LiMn$_2$O$_4$ $\rightarrow$ Li$_{1-x}$Mn$_2$O$_4$ + $x$Li$^+$ + $xe$

The reaction occurring on the negative electrode is:

6C + $x$Li$^+$ + $xe$ $\rightarrow$ Li$_x$C$_6$
The battery is discharged. At this time, the electron $e$ on the negative electrode runs from the external circuit to the positive electrode, and the positive lithium ion $Li^+$ “jumps” into the electrolyte from the negative electrode, “crawls” through the curved hole on the diaphragm, and “swims” to arrive. The positive pole is combined with the electrons that have long since run. The reaction that takes place on the positive electrode is:

$$Li_{1-x}Mn_2O_4+xLi^++xe=LiMn_2O_4$$

The reaction occurring on the negative electrode is:

$$Li_xC_6 = 6C+xLi+xe$$

2.3. Flywheel

Flywheel energy storage system (FESS) is also called flywheel battery. Its structure is shown in the figure. It is mainly composed of flywheel rotor, integrated electric/generator, bearing system, high vacuum and safety cover [8].

![Figure 3. Flywheel energy storage system composition and structure](image)

FESS stores electrical energy in the form of mechanical energy in a high-speed rotating flywheel, which is converted by the generator into electrical energy for use by the generator or fed back to the grid when needed. Since the flywheel is rotated at a high speed around the central axis, according to the basic knowledge of physics, when the flywheel is rotated at an angular velocity $\omega$, the expression of the energy $E$ stored in the flywheel is:

$$E = \frac{1}{2} J \omega^2$$

(1)

$J$—Moment of inertia of the flywheel rotor

$\omega$—Angular speed of the flywheel rotor

It can be seen from the above formula that there are two ways to increase the capacity of the flywheel energy storage system: one is to increase the moment of inertia of the flywheel, and the other is to speed up the rotation speed of the flywheel. Flywheels with large moments of inertia are generally large in size, often referred to as low-speed flywheels. Flywheels with fast rotational speeds are called high-speed flywheels. From equation (1), high-speed flywheels store much more energy than low-speed flywheels. However, the greater the rotational speed of the flywheel, the greater the centrifugal force, and therefore the high tensile strength of the flywheel rotor material. When the flywheel is controlled to rotate between a preset maximum angular velocity $\omega_{max}$ and a minimum angular velocity $\omega_{min}$, the maximum energy $\Delta E$ that can be exchanged is:

$$\Delta E = \frac{1}{2} J (\omega_{max}^2 - \omega_{min}^2)$$

(2)
If the loss is not counted, the effective power of the flywheel is:

$$P = \frac{dE}{dt} = \frac{d}{dt}\left(\frac{1}{2}J\omega^2\right) = J\frac{d\omega}{dt} = M\omega$$  \hspace{1cm} (3)

As can be seen from the above, the energy conversion of FESS is realized according to the change of the rotational speed of the flywheel rotor. It has three working modes: charging (storage) mode, discharge (release) mode, and standby (energy retention) mode. When charging, the grid power is driven by the power electronic energy conversion device to drive the flywheel motor to accelerate the energy storage. When the speed reaches the given maximum speed $\omega_{\text{max}}$, the charging (storage) process ends, and then enters the standby (energy retention) mode. At this point, the flywheel is in the vacuum chamber, to minimize energy loss, and disconnect it from the power converter by disabling all gating signals. During discharge, the mechanical energy stored in the flywheel is output by the energy conversion device for use by the load. When the flywheel speed drops to a given speed $\omega_{\text{min}}$, the discharge (release) process ends.

3. **Comparison of energy storage components**

The regenerative braking of the train can achieve the purpose of energy saving, but the regenerative braking energy cannot be absorbed by the nearby traction train, and the rest is consumed on the train braking resistor and converted into heat energy and emitted into the air. Although the vehicle adopts the resistance braking method to absorb the electric energy is relatively stable, the braking energy consumption is not applicable to the electric resistance, and the overall arrangement of the under-vehicle equipment is difficult due to the installation of the large-capacity braking resistor on the vehicle, and the weight of the vehicle body is increased with the increase of the train traction power consumption, but also increased environmental pollution. In order to reduce the dissipation of braking energy on the braking resistance of the train, suppress the increase of the temperature in the subway tunnel and reduce the on-board equipment, the energy storage system recovery device absorbs the residual regenerative braking energy during train braking, which is mainly divided into super Capacitive, battery and flywheel.

3.1. **Super capacitor energy storage device**

The energy storage medium of the device is a high-power capacitor, and the absorption and discharge principle of the capacitor is used to realize the absorption and utilization of the remaining regenerative braking energy of the train. When there is a train in the power supply section that needs to take the flow, the stored energy is released for use by the required train. Selecting the charge and discharge threshold of the supercapacitor energy storage system is the key to study the utilization of the remaining regenerative braking energy. At present, scholars have discussed the charging and discharging threshold selection principle of supercapacitor energy storage system based on maximum energy saving, and proposed the control strategy of urban rail transit supercapacitor energy storage system based on dynamic threshold adjustment [9].

3.2. **Battery energy storage device**

The device absorbs the remaining braking energy in the battery medium. When the train needs to take the flow in the power supply interval, the stored energy is released for use by the required train. The device is large in volume, and frequent charging and discharging will affect the service life of the battery, so its energy storage capacity is small. Currently, the types of batteries commonly used for energy storage include lithium-ion batteries.
3.3. Flywheel energy storage device
The flywheel energy storage device consists of three parts: control isolation, chopper, and flywheel energy storage. The flywheel energy storage is a kind of physical energy storage mode, which uses the kinetic energy of the rotating body to rotate at high speed to store energy. Table 1 compares several energy storage recovery devices.

| Storage device       | Energy Density (Wh/kg) | Power Density (W/kg) | Service life (number of cycles) | Work efficiency (%) |
|----------------------|------------------------|----------------------|---------------------------------|--------------------|
| Lithium battery      | 70~250                 | 1000                 | >1000                           | 95                 |
| Supercapacitor       | 2~10                   | 5000~15000           | >100000                         | >95                |
| Super high speed flywheel | 10~100               | 2000~10000           | 106                             | 90~95              |

It can be seen from the above table that the super capacitor has a fast charging and discharging speed; the instantaneous power is large; the maintenance cost is low; the service life is long; combined with the short distance between the urban rail train station and the frequent starting braking, the super capacitor device is preferentially used to absorb the remaining regenerative braking of the train energy. When the traction network voltage is low, the device can also be put into the voltage regulation working state, thereby improving the power quality of the traction network.

4. Conclusion
This paper focuses on the basic working principle and characteristics of three energy storage devices for urban rail transit. It can be seen from the comparison that the supercapacitor is more in line with the characteristics of frequent start-up braking of urban rail trains, so it will focus on the use of supercapacitors or multiple combinations in the future. The energy storage component is used as a regenerative braking energy recovery device for urban rail transit.

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References
[1] Linli Xu, Wei Liu, Jun Liao, Measurement and Analysis of Traction and Braking Energy Consumption of Urban Rail Transit Trains [J]. Journal of Railway Science and Engineering, 2016, 13(9): 1819-1824.
[2] Huanyu Wang. Study on Energy System Analysis and Energy Saving Measures of Power System of Urban Rail Transit Station [D]. Beijing Jiaotong University, 2018.
[3] Ning Sun, Zhaoxing Li, Huapeng Dai. Research on Urban Rail Transit Energy Consumption Index System and Energy Saving Measures——Innovative Practice of Equipment Supervision in Energy Saving and Emission Reduction [J]. Equipment supervision, 2011(01): 15-18+22.
[4] Huaming Dai, Jie Song, Zhaoxing Li. Investigation and Analysis of Urban Rail Transit Energy Consumption in Beijing [J]. Equipment supervision, 2015(3): 36-40.
[5] Zhihong Yang. Research on train energy-saving operation based on multi-train energy interaction and energy storage system optimization control [D]. Beijing Jiaotong University, 2018.
[6] Yanzheng Wang, Pengcheng Su. Absorption and utilization of renewable energy in urban rail transit [J]. China Rail Transit Research, 2007(6): 42-45.
[7] Yingying Zhao. Research on energy-saving operation of urban rail transit multi-train considering the utilization of regenerative braking energy [D]. Beijing Jiaotong University,
2015.

[8] Zhixin He. Recycling of Regenerative Braking Energy of Urban Rail Transit Vehicles [J]. China Rail Transit Research, 2013(8): 49-58

[9] Qi Yu. Research on new type of rail transit regenerative braking energy absorption device [J]. China Rail Transit Research, 2017(7): 14-1