

# An Overview on Braking Energy Regeneration Technologies in Chinese Urban Railway Transportation

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**Abstract**— In order to prevent the failure of regeneration and reduce energy consumption, making full use of regenerative energy has been widely recognized as an important issue by Chinese urban railway transportation community. This paper provides an overview on the technologies of regenerative energy braking in China. It is first explained that why the ground resistor is popular in China in order to prevent the failure of regeneration. Alternative technology using regenerative inverter and ground supercapacitor is then introduced including main circuit, working mechanism and existing problems. Next, the simulation, status quo and experimental results of the ground supercapacitor energy storage system are discussed in detail for a 200kW prototype system developed in China. Finally, future improvements are mentioned for Chinese braking energy regeneration technology.

**Keywords**— Regenerative Braking, Regenerative Inverter, Super Capacitor, Urban Railway Transportation.

## I. INTRODUCTION

With the continuous and rapid development of Chinese economy, the numbers of passenger cars and urban population significantly increased in recent years. Traffic jam and pollution are now serious social problems in Chinese big cities such as Beijing, Shanghai and Guangzhou. It is a national-wide consensus to mitigate traffic jam and improve air quality through developing energy saving and punctual mass transportation systems such as the urban railway system. Under this basic consideration, China is now leading the world in the development of the urban railway transportation system. By the end of 2012, there are 2,008 km urban railways in operation in 17 Chinese cities. In addition, 80 lines are under construction, whose total length is about 2,000km. And more than 400 lines are being planned with total length of over 14,000km.

The two biggest advantages of the railway transportation over other means of transportations are its small rolling resistance and the capability of braking energy regeneration. However, the regenerated energy is not able to return to the grid through traction substation due to the DC power supply of the urban railway systems. While the train is regenerating the braking energy, if there is no other train absorbing the energy, the pantograph voltage will sharply increase that may cause

the traction motor incapable to work as a generator any more. This situation is the so-called failure of regeneration. Then the train's kinetic energy can only be converted into heat and dissipated in air through mechanical braking or braking resistor. It received a considerable attention in recent years to prevent the regeneration failure, and thus reduce energy consumption and improve train's performance by making full use of the regenerative braking energy [1].

This paper introduces the current situation and problems of the braking energy regeneration technology in Chinese urban railway transportation systems. Then a detailed discussion is provided on the development of regenerative energy storage system using ground supercapacitors. The system will be implemented in Beijing subway Line 10.

## II. REGENERATIVE ENERGY RECOVERY TECHNOLOGIES IN CHINA

Urban railway transportation has developed for over 40 years in China since the first line, Line 1 from Beijing railway station to Pingguoyuan opened in 1969. The power supply system of Chinese urban railway transportation system is either 750V DC or 1500V DC. Ground and viaduct lines usually receive electrical power from overhead wires, while underground lines are commonly powered by a third rail. The urban railway systems in China are significantly diversified in recent years including subway, monorail, linear motor metro, LRT (light rail transit) and so on. In terms of size of the car, there are two types in China, type A with 20m long and 3.0m wide, and type B with 18m long and 2.8m wide. Type A railway cars are widely used in Shanghai and Guangzhou. Type B ones mainly operate in Beijing now, while the adoption of type A cars is under discussion and may also be introduced in Beijing in the future. In addition, AC electric driving has totally replaced the DC electric driving in Chinese railway trains since 1990s.

As an important sub-system of urban railway cars, the performance of braking system directly influences driving safety, energy consumption, riding comfort, and temperature rise in tunnels. In Chinese urban railway cars, the electro-pneumatic blending brake is usually adopted,

in which the regenerative braking plays a major role and the air braking only serves as an auxiliary brake. As shown in Table 1, there are multiple technologies to absorb the regenerative energy when regeneration failure occurs, such as on-board resistor, ground resistor, the combination of ground resistor and regenerative inverters, regenerative inverters, ground supercapacitors [2]. It is obvious that on-board and ground resistors are only able to dissipate energy instead of the recycle and reuse of the regenerative energy. However, since the way using resistor to consume the regenerative energy is easy to control and maintain with low cost, it is now a major technology in China to prevent the regeneration failure. Therefore, this technology is also briefly reviewed in this paper.

TABLE 1  
EXAMPLES OF METRO REGENERATIVE BRAKING ENERGY ABSORBING TECHNOLOGIES IN CHINA

ABSORBING TECHNOLOGIES	APPLIED LINES (YEAR OF OPERATION)		
ON-BOARD RESISTOR	LINE 1 IN BEIJING SUBWAY(1969)	LINE 1 IN SHANGHAI METRO(1993)	LINE 1 IN GUANGZHOU METRO(1997)
GROUND RESISTOR	LINE 4 IN GUANGZHOU METRO(2005)	LINE 6 IN BEIJING SUBWAY(2012)	-
GROUND RESISTOR AND REGENERATIVE INVERTER	LINE 14 IN BEIJING SUBWAY(2013)	LINE 5 IN GUANGZHOU METRO(2009)	LINE 9 IN BEIJING SUBWAY(2011)
REGENERATIVE INVERTER	LINE 10 IN BEIJING SUBWAY(2008)	LINE 14 IN BEIJING SUBWAY (2013)	-
SUPER CAPACITOR	LINE 5 IN BEIJING SUBWAY(2007)	-	-

### III. RESISTOR BRAKING

There are two ways of rheostatic braking that are widely used in China, braking using on-board resistor and ground resistor, respectively. It is a long-term controversy on the capacity of the on-board braking resistor in China. The controversy focuses on if the braking resistor is required to absorb all or part of the regenerative energy from the maximum speed to zero speed [3]. As a practical solution, the A type railway cars absorb all the regenerated energy by the on-board resistor such as Line 1 of Guangzhou Metro, while considering the reduction of weight the B type cars only absorb part of the regenerative energy through the on-board resistor such as Line 13 of Beijing Subway. For example, the maximum speed of Line 13 is 80km/h, but the capacity of its braking resistor was determined to absorb the regenerative energy with the initial braking speed of 50km/h. This leads to the reduction of both the space and weight of braking resistor. The difference between the capacities of the type A and type B cars is due to the different understanding on the amount of regenerative energy that need be absorbed during the regeneration failure.

Line 2 of Chongqing monorail and Line 4 of Guangzhou linear motor metro started in 2005 and 2006, respectively. The ground resistor developed by Hunan Hengxin Electric corporation are being applied in the above two lines for same reasons: (1) from the operation experience of Line 2 of Guangzhou Metro, the on-board brake choppers and resistor weight 500kg in a single car. Thus for the 4M2T formation, the total weight is increased by 2t. But both the monorail and linear motor cars strictly require the lightweight design. The weight of cars will increase if on-board resistor is used. (2) The installation space under floor is limited. (3) Since Chongqing and Guangzhou are hot in summer, it is undesirable to use on-board resistor that will raise the tunnel temperature. In addition to the above two lines, Beijing Fangshan Line, Guangzhou Line 4 and Tianjin Line 1 use ground braking resistor, as shown in Figure 1.

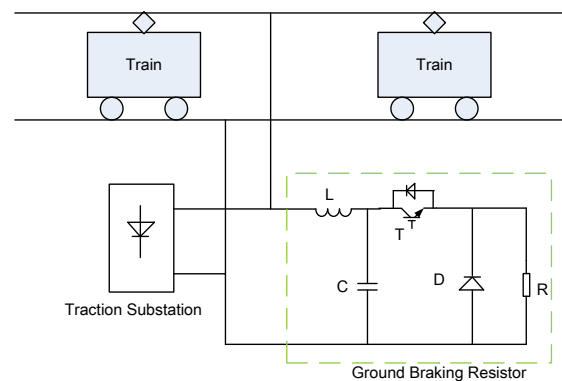


Fig. 1. The schematic diagram of the ground braking resistor

The combination of ground resistor and regenerative inverter has been adopted in Line 1 of Tianjin subway in Oct. 2007. The system absorbs the peak power of regenerative energy by resistor, and converts the left energy from DC to 380V AC in order to supply electric power for lighting, fans and other auxiliary equipment. However, this system is currently not widely applied [4].

### IV. INVERTER FEEDBACK APPROACH

Although the rheostatic braking is simple with low-cost, it can only dissipate the regenerated energy into heat, thus fails to reuse the energy and follow the energy saving policy advocated by Chinese government. Therefore, China started the development of the regenerative inverter, which has been in trail operation at the 2nd stage of Beijing subway Line 10 in December 2012 and Line 14 in May 2013 [5].

There are two types of regenerative inverters using SCR and PWM mechanism (IGBT or the other full-controlled power electronic devices is adopted) [6]. Disadvantages of the SCR inverters are the strong high harmonic components and the large distortion of the AC electric power. It is not suitable to directly connect with the grid. The PWM inverter has small harmonic components, small distortion and good dynamic performance. Therefore, Beijing Subway Operation Corporation decided to develop the PWM regenerative inverter in the future.

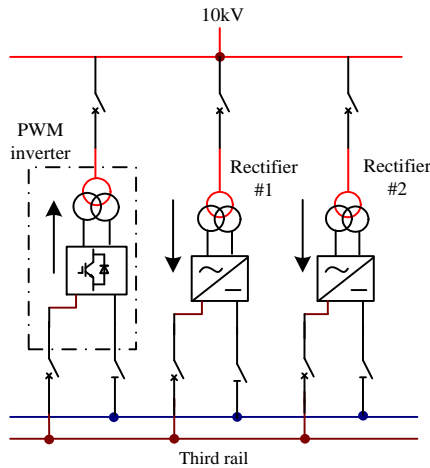


Fig.2 The schematic diagram of PWM regenerative inverter

Figure 2 shows the schematic diagram of the PWM regenerative inverter system that has been applied at the 2nd stage of Beijing subway Line 10. The regenerative inverter system consists of transformer, low-voltage switchgear cabinet and the PWM inverter (see Figures 3 and 4). There are two substations installing the PWM regenerative inverter system. The rated voltage of the AC side is 10kV and the operating range of DC voltage is 750V~1000V. The inverter uses 1700V/2400A IGBT, and the rated power of every inverter is 2MW. Line 10 uses 750V DC power supply. When the DC bus voltage is higher than 880V, the inverter is activated to send the regenerative energy to the grid. The highest allowed voltage is 1000V. And there are two power supply modes, 750V DC and 1500V DC, in Beijing subway system. Different series-parallel connections of the DC-link of the PWM inverter correspond to the two different power supply modes (see Figure 3).

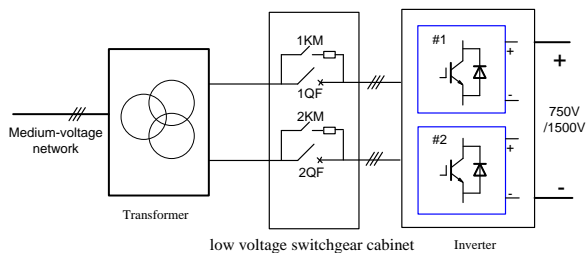


Fig.3 Series-parallel connection of PWM inverter DC-link



Fig.4 Photo of the PWM regenerative inverter system

After the initial operation of the PWM regenerative inverter system, there were several protection malfunctions (caused by improper setting of the overvoltage and overcurrent protection parameters) and communication malfunctions occurring at the beginning. After fixing the malfunctions, the system was able to work properly. Figure 5 shows the statistical results of the feedback power of PWM inverter in a week. It can be seen that the average daily electricity saving is 1772kWh using the PWM regenerative inverter system.

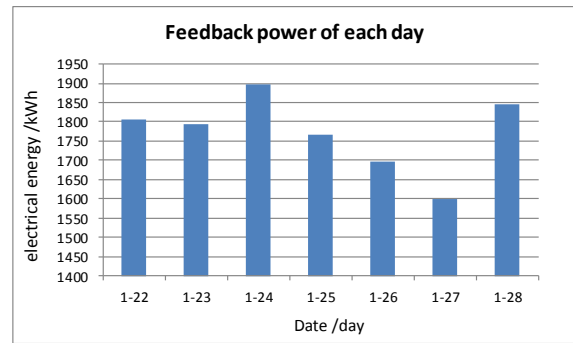


Fig.5 The statistical results of the feedback power in a week

However, the electric power of Chinese urban railway systems is supplied by SGCC (State Grid Corporation of China). SGCC is worrying about the influences of the feedback power to grid stability and other electrical equipment. It is critically important to work with SGCC together to make the PWM regenerative inverter system a general technology that could be widely applied in China [7]. The AC medium voltage network uses decentralized power supply system. Since the peak power of the inverter cannot be completely consumed by the subway system, the left power has to be sent to the grid, which need be proved by SGCC. While for the centralized power supply system, the above problem does not exist because of its large capacity and more loads.

## V. STATIONARY SUPER CAPACITOR ENERGY STORAGE

With the rapid development of secondary battery, flywheel, supercapacitor and other energy storage devices in recent years, utilizing energy storage devices to absorb the regenerative energy has been gradually applied in urban railway systems. Total length of 27.6 km of Beijing subway Line 5 was opened in October 2007. 4 SITRAS-SEC supercapacitor energy storage devices (provided by Siemens) have been installed in 4 substations, which are used to absorb regenerative energy in order to prevent regeneration failure and mitigate fluctuations of power supply voltage. The Line 5 is the first subway line to adopt supercapacitor in China [8].

There are two major reasons for the Line 5 to adopt the stationary ground supercapacitor: 1) supercapacitor works by physical reaction. Compared to Lithium-ion batteries or other secondary batteries, its advantages are long cycle life, high power density, fast charging and discharging, etc. Supercapacitor is suitable for absorbing and releasing the highly dynamic regenerative braking energy; 2) the usage of the stationary ground supercapacitor avoids the

space and weight problems compared to the on-board one.

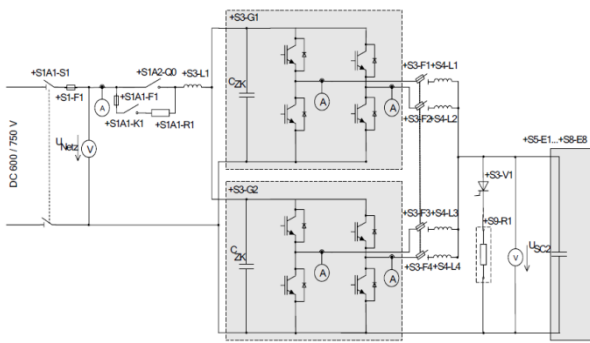


Fig.6 The schematic diagram of the supercapacitor system in Line 5

Figure 6 shows the diagram of the main circuit in the supercapacitor energy storage system of Line 5. The system can be applied to a subway system with a voltage level of 600V or 750V. The bi-directional converter is connected with a 4-bridge arm in parallel. The total capacitance is 94F and the energy storage capacity is 2.5kWh. The system can work by two modes, energy saving mode and constant voltage model. In the energy saving mode, the regenerative braking energy is stored and reused; while in the constant voltage model, the energy storage system is charged by the traction network or release the energy back to the network in order to stabilize the voltage and improve the train performance. Figure 7 shows the SES system from Siemens.



Fig.7 SES system from Siemens

If the similar energy storage system is adopted by other Chinese urban railway lines as Line 5 in Beijing, two issues have to be addressed. One is that how to choose the location for installation and capacity of the supercapacitor; the other is developing home-made energy storage systems [9]. Beijing Subway Operation Corporation is now working with universities, research institutes and other companies to solve the two issues.

The supercapacitor energy storage system innovates the traditional power supply system for urban railway. Developers should consider simultaneously the energy storage capacity, control strategy, charging and discharging power. The subway operation corporations

also want to exactly know the energy-saving effect, the maintenance of a constant DC bus voltage and quantitative results on the improvement of railway car performance after the implementation of the system.

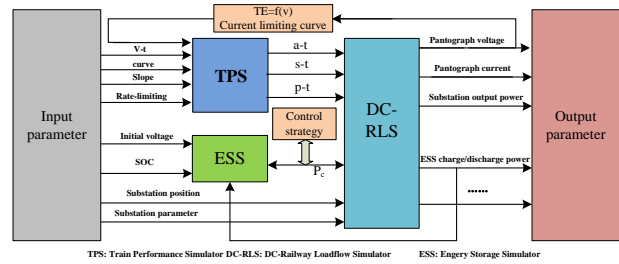


Fig.8 The system simulation flow chart

In Figure 8, the simulation model of the supercapacitor energy storage system is shown consisting of traction calculation module (TPS), DC line power flow simulation module (DC-RLS) and energy storage module (ESS). This simulation model can evaluate energy-saving effect, optimize and configure the capacity and position of the energy storage system. The departure interval, charging and discharging threshold voltages are also represented in the model.

Figure 9 and Figure 10 show the results of the maximum power and energy storage capacity of supercapacitor charging and discharging under 10min/5min departure intervals, respectively [10]. In Figure 9, with a 10min departure interval, the maximum power (800kW) and energy storage capacity (2.5kWh) of the supercapacitor is the largest at station 12. In Figure 10, with a 5min departure interval, energy exchange among the nearby trains becomes more frequent. The maximum power (550kW) and energy storage capacity (2.3kWh) of the supercapacitor reach the largest at station 12 and 13, which are smaller than the results in Figure 9.

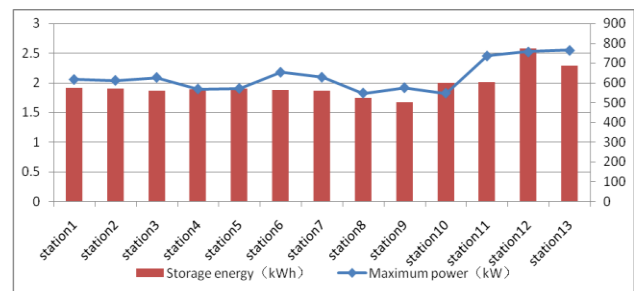


Fig.9 The maximum power and energy storage capacity under 10min departure interval

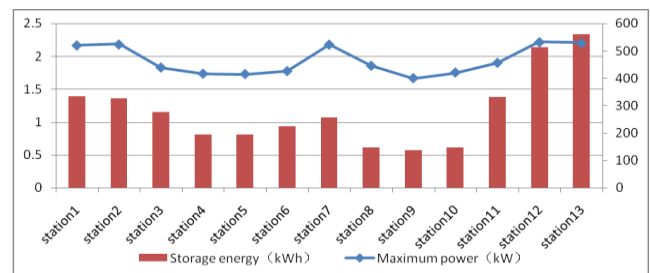


Fig.10 The maximum power and energy storage capacity under 5min departure interval

In order to verify effects of energy saving and constant voltage maintenance of the supercapacitor energy storage system in house, the authors developed a 200kW experimental platform that emulates the subway regenerative energy recovery system. A megawatt-level prototype system will also be developed in the future, which is close to the real practical systems.

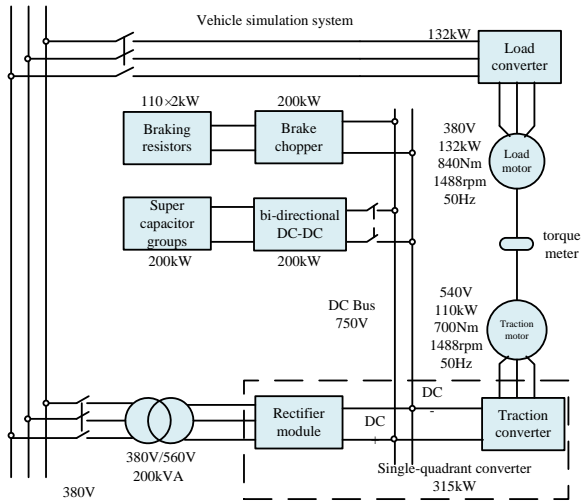


Fig.11 The experimental platform for subway regenerative energy recovery

Figure 11 shows the schematic diagram of 200kW experimental platform. The 380V AC is boosted and rectified to 750V DC through boosting transformer and diode rectifier. The output voltage 750V DC is the DC bus voltage. The traction converter and traction motor emulate the subway traction driving system; while the load motor and load converter emulate the subway train. The supercapacitor energy storage device is connected with the DC bus in parallel.



Fig.12 The experimental platform physical appearance

Figure 12 shows the physical appearance of the experimental platform, after adding super capacitor energy storage system, when the simulated train is accelerating, DC line voltage drops, super capacitor

group discharges, and supplies the electrical power together with the rectifier; during the braking, energy comes back to DC line, and the voltage start to rise up, super capacitor group start to take in the regenerative energy, and if the braking energy power level is higher than the maximum power super capacitor group can withstand, the remaining energy will be consumed by the braking resistor, the energy flow is shown in figure 13 [11-13].

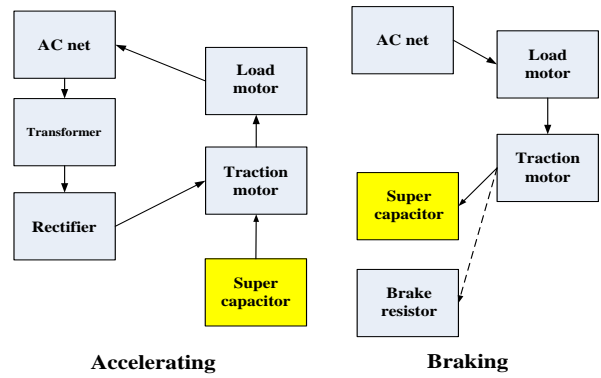


Fig.13 The experimental platform energy flow chart

Figure 14 [14-16] shows the main circuit of the supercapacitor energy storage system. It uses Maxwell 63F/125V module. A bigger module, the 31.5F/500V supercapacitor module consists of 4 series and 2 parallel connection of the 63F/125V modules. The peak power is 200kW and the energy storage capacity is 1kWh. Figure 15 shows the photos of the system.

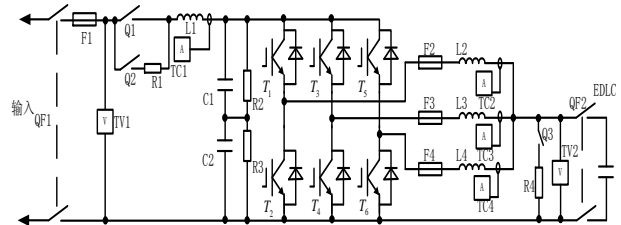


Fig.14 The main circuit of the supercapacitor energy storage system



Fig.15 200kW supercapacitor energy storage system

The platform can emulate the traction, coasting and braking of the trains that cause DC bus voltage fluctuations. Figure 16 shows the experimental results of

speed and torque. As shown in Figure 17, with the supercapacitor energy storage system, the decline of the DC bus voltage is limited in the first duration because using the power released by supercapacitor can reduce the output power of the diode rectifier. In the second duration, the supercapacitors do not absorb or release energy because DC bus voltage is in its normal operation range. While in the third duration, the supercapacitor absorbs the regenerative braking energy in order to suppress the rise of the DC bus voltage. The authors' group is now developing a megawatt-level prototype system that is expected to perform online test running in October 2014.

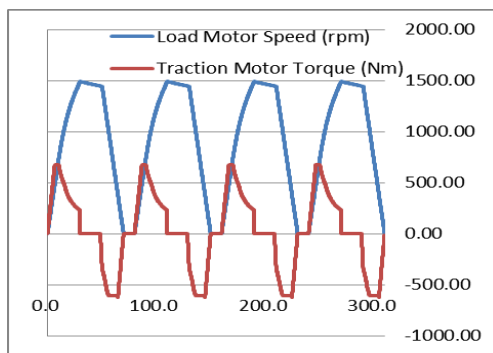


Fig.16 Experimental results of speed and torque

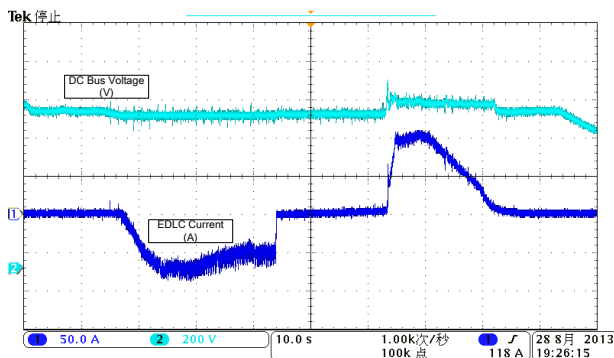


Fig.17 Experimental results of supercapacitor energy storage system

## VI. CONCLUSIONS

This paper introduces the regenerative energy recovery technologies in China. For the conventional on-board resistor, it is needed to determine a correct capacity considering the space and weight limitations. Although ground resistor is widely used in China, it will become obsolete due to its incapability of energy saving and reuse. Currently the regenerative inverters and supercapacitors are not widely used. In addition to the cost, the operating companies are asking for the proof of the energy-efficiency and reliability of the technology. Quantitative studies are needed to validate its energy-saving effect, stabilization of the DC bus voltage and improvement of train operation. It is also important for China to develop home-made high performance energy storage devices

such as secondary battery, supercapacitor and flywheel.

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