

Review of Regenerative Braking Energy Storage and Utilization Technology in Urban Rail Transit



Lesheng Xing and Xin Li

Abstract Due to the short distance between urban rail transit stations, a large amount of regenerative electric energy will be generated. Studying how to recuperate regenerative braking energy and control the voltage fluctuation of the traction network within allowable range can result in economic as well as environmental merits, which has important practical significance in alleviating energy shortage at home and abroad. According to the differences in energy process, regenerating energy absorbing modes can be divided as follows: energy-consuming mode, energy-feeding back mode, energy-storing mode. In this comprehensive paper, for the regenerative braking energy recuperation during the train operation, various method and technology have been analyzed. First of all, three methods of storage and utilization of regenerative braking energy are briefly introduced respectively. Then, the advantages and disadvantages of these three methods are summarized. Finally, based on the current research situation, the storage and utilization of regenerative braking energy in urban rail transit is prospected.

Keywords Urban rail transit · Train timetable optimization · Energy storage system · Reversible substation

1 Introduction

As an important part of urban public transport, urban rail transit has become an effective way to solve urban traffic congestion and air pollution because of its excellent characteristics, such as energy-saving, environmental protection, safety and fast, etc. Urban rail transit has become an effective way to solve traffic congestion and air

L. Xing
School of Automation and Electrical Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China
e-mail: 2304526035@qq.com

X. Li (✉)
School of New Energy and Power Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China
e-mail: lixinzdh@lzjtu.edu.cn

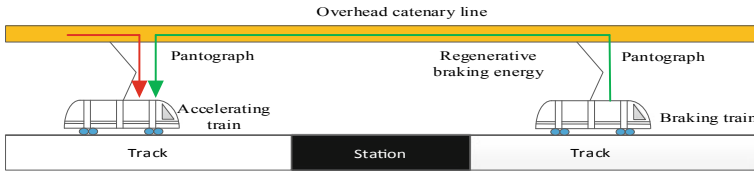


Fig. 1 Diagram of exchange of regenerative braking energy between trains

pollution, and has been rapidly developed in major cities in the world, however, with the acceleration of urbanization process, the traditional overhead catenary power supply mode adopted by urban rail vehicles can not meet the demand anymore in the beauty of landscape, the simplicity of facilities and the efficiency of power supply, thereby a novel power supply mode is promoting, which is energy storage and energy feedback traction supply system [1, 2]. In a city with a large population, the distance between passenger stations is usually short, and a train acceleration/braking is very frequent, which generates a considerable amount of regenerative braking energy [3]. In locomotives with traction motors, when the train is braking, the motor reverses and acts as a generator to generate electrical energy, which can be used by the accelerating train.

The process of regenerative energy flowing from braking train to accelerating train is shown in Fig. 1. Regenerative energy is fed back into the overhead contact line, which can be immediately used by accelerating other trains located in the same electricity supply interval.

In order to maximize the use of regenerative braking energy, there are three solutions have been proposed: (1) Train operation timetable optimization, by synchronizing the operation of other trains in the same power supply interval, the regenerative braking energy produced by the braking train is absorbed by the train in the acceleration condition. (2) Energy storage system (ESS), regenerative braking energy is stored in an electric storage medium, such as batteries, super capacitors, flywheels, and is released to the overhead catenary line or the third rail when needed. (3) Regenerative braking energy feedback, which means a branch provided for regenerative braking energy to feed back to the main AC power grid.

2 Train Timetable Optimization

Train timetable optimization has been proposed as one of the most direct and effective ways to increase the utilization rate of regenerative braking energy, without the need for additional equipment. Timetable optimization aims at finding the optimal timetable such that the regenerative energy can be furthest used to accelerate other trains. In this method, the regenerative energy from the braking trains can simultaneously be used by the accelerating trains, by synchronizing accelerating and braking times of trains in the same supply interval.

The optimization problem may be summarized as how to maximize the use of regenerative braking energy. As an example, if a set of arrival times is considered as:

$$a = \{a_n^i, 1 \leq i \leq I, 1 \leq n \leq N\} \tag{1}$$

where a_n^i means the time that train i arrives at station n , I and N are the number of trains and stations, respectively; and departure times are defined as:

$$d = \{d_n^i, 1 \leq i \leq I, 1 \leq n \leq N\} \tag{2}$$

where d_n^i means the time that train i departs station n . The total objective function aimed at maximizing the utilization of regenerative braking energy can be summarized as follows:

$$F(a, d) = \sum_{t=1}^T \sum_{s=1}^{N_s} \min \left\{ \sum_{i=1}^I \omega_i(a, d, t) \lambda(i, t, s) \times \sum_{i=1}^I f_i(a, d, t) \lambda(i, t, s) \right\} \tag{3}$$

where T is the total operation time, N_s is the number of electricity supply substations, $\omega_i(a, d, t)$ is the energy produced by train i during the time unit $[t, t + 1]$, $f_i(a, d, t)$ is the required energy for accelerating train i during time unit $[t, t + 1]$, and $\lambda(i, t, s)$ means whether the train i is located in the electricity supply interval s at time t or not [4, 5].

In general, most of the train timetable optimization models aim at maximizing the overall utilization rate of regenerative braking energy $F(a, d)$.

According to optimization goals, studies on timetable optimization can be divided into two strategies: limiting the peak power demand, and maximizing the utilization of regenerative braking energy. In real-world systems, the overhead catenary line is set to a threshold voltage for ensuring the safety of the rail transit power network. During the trains' braking progress, the overhead catenary voltage is increasing continually. If the voltage reaches and exceeds the pre-fixed threshold, regenerative braking will be removed and replaced by mechanical braking [4].

In the early stages of timetable optimization studies, the focus is on reducing peak power requirements. For instance, in [6], taking the Kaohsiung mass rapid transit (MRT) system as an example, the author uses genetic algorithms to optimize train scheduling to avoid excessively accelerating trains at the same time resulting in extremely high peak traction power. In [7], Gordon and Lehrer designed a control algorithm to reduce the peak power demand, through coordinating the operation of multiple trains, to avoid grid vibration and reduce peak power demand.

In recent years, researchers began to formulate the optimization model to maximize the utilization of regenerative energy directly. In [8], some scholars established a mathematical model to adjust the train departure interval. The simulation results show that before and after the adjustment, the peak traction power of the train is reduced by 41%, and the traction energy consumption is reduced by 5%. In [9],

based on the actual operation data of the Beijing subway, a comprehensive optimization method is proposed. The results show that this method can reduce the overall energy consumption by 21.17%.

3 Energy Storage System for Urban Rail

A properly designed energy storage system can store regenerative braking energy and release energy back to the grid when needed, thereby saving the cost of resistance cabinets and ventilation systems. Generally speaking, energy storage equipment is installed on board vehicles or at the track side. On-board Energy storage system (ESS) permit trains to temporarily store their own braking energy and reuse it in the next acceleration stages [10]. On the other hand, stationary ESS absorb the braking energy of any train in the system and deliver it when required for other vehicles' acceleration. The structure of ESS is shown as Fig. 2.

3.1 Onboard Energy Storage

In onboard ESS, the storage medium is placed on the vehicle. The onboard ESS can greatly promote the energy saving of the urban transportation system, because the energy recovered and stored during the braking process can be used to provide energy for the vehicle in the next acceleration process, as shown in Fig. 3. The energy stored by the regenerative braking during the deceleration of the train can be used for the next process of accelerating itself. Compared with the wayside storage device, since onboard energy storage device has no line losses, it has higher energy transmission efficiency.

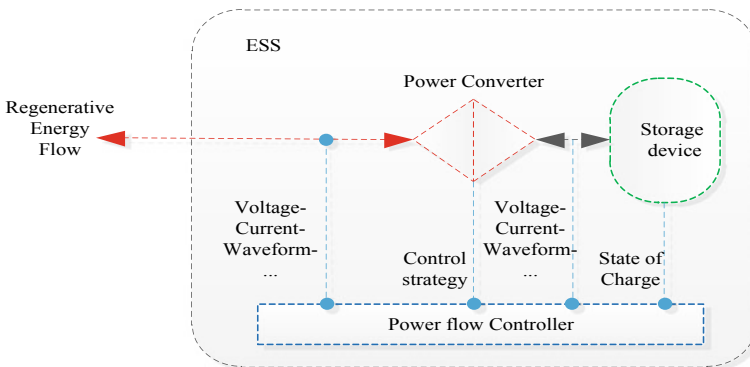


Fig. 2 Components of an ESS for railway applications

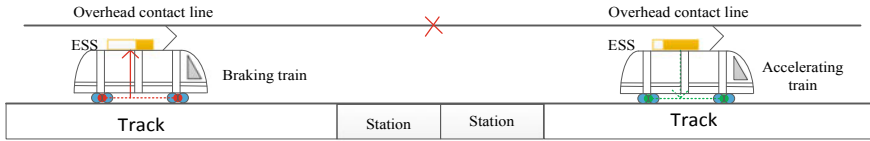


Fig. 3 Schematic of on-board ESS operation in urban rail

The main advantage of the onboard energy storage system is to reduce the maximum power required during the acceleration of locomotives, which saves energy costs and transmission line resistance losses. At the same time, due to the presence of on-board energy storage devices, the voltage drop of the overhead line is restricted, the power supply voltage is stabilized, and a greater driving density is allowed on the original infrastructure [11]. Have a certain power autonomy, for example, you can drive a distance in the area catenary free operation and tourist attraction. Onboard energy storage systems also have major shortcomings. Compared with wayside storage devices, on-board energy storage requires the installation of energy storage devices in each car, so it requires additional space and increases the overall weight of the train. Studies have shown that the use of on-board storage equipment has increased the energy consumption of train traction by 1–2% [12]. On the other hand, the cost of implementation, maintenance, and safety concern, are high, because onboard energy storage need to be installed at each train. In real life, there are many cases where on-board energy storage is implemented, for instance, Brussel metro and tram lines and Madrid Metro line in Europe, values of energy savings up to 27.3–36.3% [13, 14].

3.2 Wayside Energy Storage

In the case of a wayside storage device, the accumulated braking energy comes from any nearby train, and it is released when power demand is detected, a schematic overview of wayside ESS is shown in Fig. 4.

Compared with on-board ESS, it has sufficient installation space and weight, however, the line transmission losses is higher. Therefore, attention must be paid to the location of the storage equipment next to the rail. One of the benefits of wayside ESS is to minimize the problems related to voltage sag [5, 15]. Since the fixed ESS

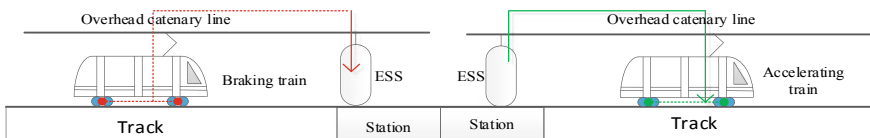


Fig. 4 Schematic of wayside ESS operation in urban rail

has larger weight and volume than mobile energy storage systems, in this case, the storage technology suitable for wayside ESS applications is wider. Super capacitors have excellent characteristics and can be used in scenarios that reduce maximum power requirements and stabilize voltage, but for on-board storage, the use of super capacitors may be limited due to the maximum volume requirements, depending on the specific requirements of each system. As the wayside ESS has less restrictions on the storage device volume, the flywheel energy storage technology has become a reality. For safety reasons, flywheel energy storage devices are generally used in special containers or underground [14, 15].

3.3 Energy Storage Technology

Choosing the most suitable storage technology as ESS for urban rail transit need to consider many factors, such as energy capacity and specific energy, rate of charge and discharge, durability and life cycle. The common energy storage technologies that have been utilized in rail transit systems are batteries, super capacitors and flywheels.

Battery. Battery technology is the oldest energy storage technology and is widely used in various scenarios. The battery system is composed of multiple different electrochemical cells, which form a unit in series–parallel connection [16]. The batteries used in rail transit systems include Lead–acid (PbSO_4), Lithium-ion (Li-ion), Nickel-metal hydride (Ni-MH) and sodium sulfur (Na-S). Other types of batteries like flow battery may have the potential to be used in rail transit systems. Battery energy storage technologies are relatively easy to achieve large-capacity energy storage, and have the characteristics of wide range of capacity and power scale. However, the charge and discharge speed and the number of charge and discharge of battery energy storage will be limited and cannot be used for rapid dynamic power compensation, such as stabilizing voltage fluctuations, suppressing dynamic oscillations, smoothing rapid changes in power generation output, etc. [17].

Flywheel. The flywheel energy storage (FES) system based on modern power electronics has two modes of energy storage and energy release. When the external system needs energy, the flywheel acts as the prime mover to drive the flywheel motor to generate electricity, and the flywheel kinetic energy is transmitted to the load in the form of electrical energy through a bidirectional energy converter. The flywheel energy storage system is a device that stores and releases kinetic energy. The flywheel is driven by a motor and can reach very high speeds [18]. FES has some favorable characteristics, including high cycle efficiency (up to ~95% at rated power), relatively high power density, no depth-of-discharge effects and easy maintenance [19]. However, the shortcomings of the flywheel storage system are also very serious, such as risk of explosion in case of failure, high weight and cost [20].

Supercapacitor. A super capacitor is an electrochemical double-layer capacitor composed of two porous electrodes soaked in an electrolyte solution. A super capacitor is an electrochemical element, but no chemical reaction occurs during its energy storage. The electric double layer capacitor is essentially an electrostatic energy storage unit. Its capacitance value is related to the electrode potential and the specific surface area. Because the solvent in the electrolyte may decompose when the voltage is too high, and the thickness of the ionization layer is generally only 1 nm, it can not withstand too high voltage, so the charging voltage of the electric double layer capacitor can only reach 1–4 V, mainly by increasing The specific surface area of the double-layer capacitor increases the capacitance. Now the capacitance value of the double-layer capacitor has reached 1500 F or higher, but the voltage is only 1–3 V.

4 Reversible Substation

In the DC network, current can only flow in one direction, and the regenerative braking energy generated in the system cannot be injected into the distribution network, because the diode rectifiers only are allowed unidirectional power flow. Reversible substation technology (also called bidirectional substation or converter substation) can achieve bidirectional energy flow in both directions, as shown in Fig. 5. This means that excess renewable energy may be used in the operator’s network (lighting, escalators, offices) or eventually sold back to the energy supplier.

Compared with ESS, the recovery of braking energy through reversible substations may be considered as a more effective option because their conversion loss is smaller. However, if fine-tuning analysis of the most appropriate position is not performed, the resistance loss may be relatively high. Compared with ESS, other important advantages of reversible substations are as follows: they require reduced space, have lower safety constraints and do not require detailed maintenance. In addition, implementation, maintenance and repair do not affect the operation in the rail system. However, reversible substations do not allow vehicles to operate without contact networks, and cannot be used for voltage stabilization or peak reduction purposes.

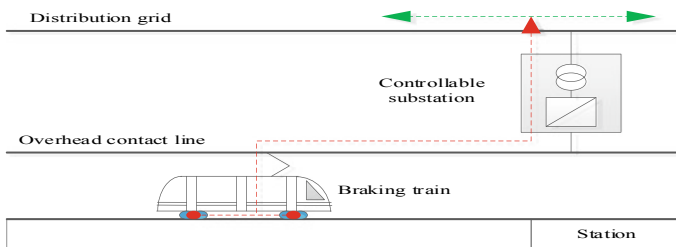


Fig. 5 Schematic of reversible substations in urban rail

5 Conclusion

In this paper, different methods and technology that can be used for regenerative braking energy storage and utilization has been analyzed. According to application scenarios, different technologies is selected. Three main technologies are used at home and board, including train timetable optimization, energy storage solution, and reversible substations.

Timetable optimization is a solution with low cost to improve the utilization rate of regenerative energy, which require no new installations in general. However, its application might be limited by some service requirements, such as passenger and railway company, meanwhile, the realization of technology demand to real-time monitor operation of the train.

In terms of energy storage solution, for the beauty of the city and space saving, onboard ESS is most used when catenary free operation of the vehicle is needed. Wayside ESS must not only consider the line loss and voltage drop during energy transmission, but also the site setting of ESS. With the development of energy storage technology, ESS will be applied more widely.

Another solution to increase the mount of energy saved during braking is reversible substation, which can permit bidirectional energy flow. However, regenerative energy generally contains harmonic waves, which must be eliminated before being allowed to flow into the main power network.

Acknowledgements The authors would like to thank the editors and the anonymous referees for their constructive comments and careful proof, which were helpful in the improvement of the manuscript. This work was supported by the National Natural Science Foundation of China under Project 51767015, the Gansu Provincial Natural Science Foundation of China (Gansu Provincial Science and Technology Plan) under Project 18JR3RA117 and Lanzhou Jiaotong University-Tianjin University Joint Innovation Fund Project 2019051.

References

1. Wu, Y., and F. Li. 2014. Development and current status of new power supply mode for modern tram. *Electric Locomotives and Mass Transit Vehicles* 37 (5): 5–9 (in Chinese).
2. Yang, X., X. Li, Z. Gao, et al. 2012. A cooperative scheduling model for timetable optimization in subway systems. *IEEE Transactions on Intelligent Transportation Systems* 14 (1): 438–447.
3. Bai, Y., Y. Cao, Z. Yu, et al. 2019. Cooperative control of metro trains to minimize net energy consumption. *IEEE Transactions on Intelligent Transportation Systems* 21 (5): 2063–2077.
4. Yang, X., X. Li, B. Ning, et al. 2015. A survey on energy-efficient train operation for urban rail transit. *IEEE Transactions on Intelligent Transportation Systems* 17 (1): 2–13.
5. Khodaparastan, M., A.A. Mohamed, and W. Brandauer. 2019. Recuperation of regenerative braking energy in electric rail transit systems. *IEEE Transactions on Intelligent Transportation Systems* 20 (8): 2831–2847.
6. Chen, J.F., R.L. Lin, and Y.C. Liu. 2005. Optimization of an MRT train schedule: Reducing maximum traction power by using genetic algorithms. *IEEE Transactions on Power Systems* 20 (3): 1366–1372.

7. Gordon, S.P., and D.G. Lehrer. 1998. Coordinated train control and energy management control strategies. In Proceedings of the 1998 ASME/IEEE Joint Railroad Conference, 165–176. IEEE.
8. Yang, X., X. Li, B. Ning, et al. 2015. An optimisation method for train scheduling with minimum energy consumption and travel time in metro rail systems. *Transportmetrica B: Transport Dynamics* 3 (2): 79–98.
9. Li, X., and H.K. Lo. 2014. An energy-efficient scheduling and speed control approach for metro rail operations. *Transportation Research Part B: Methodological* 64: 73–89.
10. González-Gil, A., R. Palacin, and P. Batty. 2013. Sustainable urban rail systems: Strategies and technologies for optimal management of regenerative braking energy. *Energy Conversion and Management* 75: 374–388.
11. Arboleya, P., P. Bidaguren, and U. Armendariz. 2016. Energy is on board: Energy storage and other alternatives in modern light railways. *IEEE Electrification Magazine* 4 (3): 30–41.
12. Domínguez, M., A.P. Cucala, and A. Fernández, et al. 2011. Energy efficiency on train control: design of metro ATO driving and impact of energy accumulation devices. In *9th World Congress of Railway Research*, 22–26.
13. Barrero, R., X. Tackoen, and J. Van Mierlo. 2010. Stationary or onboard energy storage systems for energy consumption reduction in a metro network. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 224 (3): 207–225.
14. Barrero, R., J. Van Mierlo, and X. Tackoen. 2008. Energy savings in public transport. *IEEE Vehicular Technology Magazine* 3 (3): 26–36.
15. Iannuzzi, D., E. Pagano, and P. Tricoli. 2013. The use of energy storage systems for supporting the voltage needs of urban and suburban railway contact lines. *Energies* 6 (4): 1802–1820.
16. Luo, X., J. Wang, M. Dooner, et al. 2015. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy* 137: 511–536.
17. Fengbing, Li. 2015. *Control and Optimization of Hybrid Energy Storage Systems Containing Lithium-ion Batteries and Super-Capacitors*. Chongqing: Chongqing University (in Chinese).
18. Faraji, F., A. Majazi, and K. Al-Haddad. 2017. A comprehensive review of flywheel energy storage system technology. *Renewable and Sustainable Energy Reviews* 67: 477–490.
19. Hadjipaschalis, I., A. Poullikkas, and V. Efthimiou. 2009. Overview of current and future energy storage technologies for electric power applications. *Renewable and Sustainable Energy Reviews* 13 (6–7): 1513–1522.
20. Sebastián, R., and R.P. Alzola. 2012. Flywheel energy storage systems: Review and simulation for an isolated wind power system. *Renewable and Sustainable Energy Reviews* 16 (9): 6803–6813.