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A Regenerative Braking Energy Recovering Scheme for High-Speed Maglev

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Abstract

This paper addresses the inefficient utilization of regenerative braking energy (RBE) in high-speed maglev traction power supply systems, where conventional methods either waste energy via braking resistors or face economic penalties when feeding power back to the grid due to poor power quality. To overcome these limitations, a flexible high-speed maglev traction power supply system integrated with a supercapacitor-based Energy Storage System (ESS) and a corresponding energy management strategy is proposed. The strategy leverages the ESS's load-shifting capability to store RBE during train braking and release it to assist in train traction or shave grid peaks, thereby achieving RBE recovery, peak-shaving and valley-filling.
An optimal scheduling model aiming at minimizing the daily operational cost of the system is established. The objective function comprehensively considers grid-side costs. A case study based on the operational data of the Shanghai Maglev Line demonstrates the strategy's effectiveness. The results show a significant reduction in the total daily cost by 8,594.18 CNY. Furthermore, the maximum demand power is reduced from 3.52 MW to 3.14 MW, validating the system's peak-shaving capability. The study concludes that the proposed approach not only enhances energy efficiency but also provides a cost-effective solution for the sustainable development of high-speed maglev transportation.

Keywords: high-speed maglev, regenerative braking energy, energy management, traction power system, energy recovery strategies, energy-efficient train operation, energy storage integration.

1 Introduction

High-speed maglev trains break through the adhesion limitations of traditional rail transit, representing the highest-speed ground transportation mode. They offer advantages such as high operational speed, absence of friction, no direct emissions, and low noise, making them a strong candidate for constructing the next generation of green and intelligent transportation corridors [1,2]. The single regenerative braking energy of a high-speed maglev train can reach up to 21% of its traction energy consumption [3], indicating significant potential for the utilization and recovery of regenerative braking energy. Currently, regenerative braking energy is fed back directly to the DC link, causing a voltage rise. Once the DC link voltage exceeds its threshold, the braking resistor activates to dissipate the regenerative braking energy. However, this method poses certain safety risks to the normal operation of the high-speed maglev railway traction power supply system and results in energy waste. Although a four-quadrant converter system [4] can feed the regenerative braking energy back to the grid, its low power quality means the grid not only will not pay for it but may also impose additional penalties due to its high harmonic content, which is not conducive to exploiting the economic benefits of regenerative braking energy. To address this issue, reference [5] introduced an energy storage system (ESS) into the high-speed maglev traction power supply system and proposed a braking energy recovery scheme. However, this approach overlooks the economic benefits of the ESS in grid energy interaction and fails to fully utilize its peak-shaving capability.

Aiming at the underutilization of regenerative braking energy in high-speed maglev traction power supply systems, this paper proposes a regenerative braking energy recovery strategy for high-speed maglev. The strategy aims to leverage the load-shifting characteristics of the ESS to achieve peak shaving and valley filling in the high-speed maglev traction power supply system, thereby recovering regenerative braking energy, improving energy utilization efficiency, and unlocking its economic benefits.

2 Flexible High-Speed Maglev Traction Power Supply System and its management scheme

2.1 Topology of Flexible High-Speed Maglev Traction Power Supply System

The electrical power for the high-speed maglev traction power supply system is sourced from a 110 kV high-voltage grid. It is stepped down to 20 kV via a 110/20 kV main substation and fed into a 20 kV high-voltage feeder network. The power is then converted into a 5 kV DC voltage by rectifiers and connected to the DC bus. Under traction (driving) conditions, the braking resistor is inactive. Electrical power is supplied from the DC bus through inverters to the long-stator linear motors to drive the train. When the system enters the braking condition, the regenerative braking energy is fed back to the inverter side through the feeder lines. After being regulated by the braking chopper, this energy is directly dissipated by the braking resistor or the overvoltage protection circuit within the rectifier. To achieve comprehensive utilization of the regenerative braking energy, this paper integrates an Energy Storage System (ESS) into the high-speed maglev traction power supply system by leveraging its load-shifting characteristic, thereby constructing a Flexible High-Speed Maglev Traction Power Supply System. Its structure is illustrated in the Fig.1.

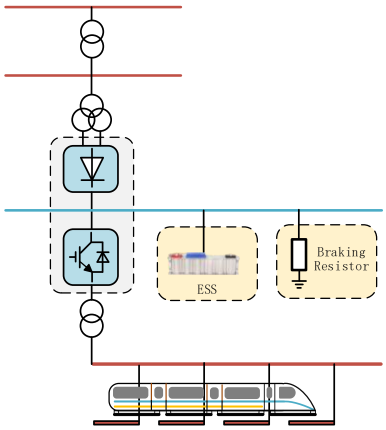


Fig.1 Topology of Flexible High-Speed Maglev Traction Power Supply System

Due to the characteristics of the high-speed maglev traction power supply system, such as high load power, high harmonic content, and fast dynamic response requirements, an energy storage device with rapid dynamic response and strong instantaneous power support capability is necessary for regulation. This paper selects supercapacitors as the Energy Storage System (ESS), primarily based on their excellent rapid charge-discharge characteristics and high power density. Leveraging the supercapacitor's fast response and power buffering capabilities, when a high-speed maglev train is in regenerative braking mode, the system can store the feedback braking energy in real-time. When a subsequent train on the line enters traction mode, the stored energy is then released to provide traction power. This mechanism can not only achieve "peak shaving and valley filling" of power, smoothing the power fluctuations of the traction network, but also reduce the power impact on the upstream grid. It enhances system operational stability while significantly improving comprehensive energy utilization efficiency.

2.2 Flexible High-Speed Maglev Traction Power Supply System Energy Management Strategy

Based on the energy flow mechanism, this paper manages and controls the energy of the high-speed maglev traction system. When the Energy Storage System (ESS) is inactive, the energy flow mode of the Flexible High-Speed Maglev Traction Power Supply System is identical to that of the conventional system. The traction power demand is entirely supplied by the grid, and the recovered braking energy is fed back to the DC bus and dissipated by the braking resistor, as expressed in Equation (1).

$$\begin{cases} P_{load} = P_{grid} \\ P_{RBE} = P_{brake} \end{cases}, P_{load} > 0, P_{RBE} < 0 \tag{1}$$

in which P_{load} represents the traction demand, P_{RBE} means the power of regenerative braking energy, P_{grid} and P_{brake} represent the power of grid and braking resistor.

When the Energy Storage System (ESS) is operational, the energy flow mode of the Flexible High-Speed Maglev Traction Power Supply System changes according to the traction condition. When the train is in traction mode, the ESS and the grid jointly supply the traction power demand, as shown in Equation(2).

$$P_{load} = P_{grid} + P_{ESS}, P_{ESS} > 0 \tag{2}$$

in the equation P_{ESS} means the power of energy storage system.

When the train is in the braking condition, the kinetic energy of the train is converted into electrical energy, which is then fed back to the DC link through the feeder cables. The regenerative braking energy is first absorbed by the Energy Storage System (ESS). When the power limit or the state of charge (SOC) upper limit is reached, the excess regenerative braking energy is dissipated by the braking resistor, as shown in Equation(3).

$$\begin{cases} P_{RBE} = P_{ESS} + P_{brake}(SoC < SoC_{\min}) \\ P_{RBE} = P_{brake}(SoC > SoC_{\min}) \end{cases}, P_{ESS} < 0 \tag{3}$$

2.3 Establishment of the Optimal Model for the Flexible High-Speed Maglev Traction Power Supply System

A. Cost Function

The high-speed maglev energy management system aims to achieve global optimal daily operational economy for the high-speed maglev traction power supply system. The objective function is formulated as follows:

$$\min\ f_0 = c_{CP} + c_{EP} + c_{ESS} + \ c_{SOC,penalty} \tag{4}$$

In the equation, c_{CP} represents the capacity price (Capacity Price), c_{EP} denotes the energy price, $c_{ESS,c}$ is the usage cost of the Energy Storage System (ESS), and $c_{SOC,penalty}$ signifies the electricity cost incurred when the ESS's state of charge does not return to its initial value after operation.

1) Electricity Cost

The high-speed maglev traction power supply system employs a two-part tariff for electricity pricing, with a voltage level of 110 kV. The tariff calculation consists of a capacity (demand) charge and an energy charge [6].

Among these, the capacity price is calculated based on the maximum demand, and the energy price is calculated according to the energy tariff provided in [6]. The calculation formulas are as follows.

$$c_{CP} = p_{\max P} \max(P_{Grid,\,15avg}) \tag{5}$$

in which the $p_{\max P}$ represents the demand price, $P_{Grid,\,15avg}$ means the demand power of grid and the $\max(\cdot)$ means the maximum value.

On the other hand, the energy price is calculated based on the electricity drawn from the grid and the corresponding tariff, as shown in the following equation.

$$c_{EP} = \sum_{t=0}^{T} p_{ep} P_{grid}(t) \tag{6}$$

in which p_{ep} means the electricity price.

2) Usage Cost of Energy Storage System Cost

The usage cost of the Energy Storage System (ESS) is composed of the investment cost and the maintenance cost. The investment cost consists of the power cost and the capacity cost. The calculation method is shown in Equation (7).

$$c_{ESS,invest} = (1+\eta_{main})\left(p_{power}P_{ESS}^{\max} + p_{capacity}E_{ESS}^{\max}\right) \tag{7}$$

in which η_{main} is the maintenance cost ratio of ESS, p_{power} and $p_{capacity}$ represents ESS unit power cost and ESS unit capacity cost.

To facilitate the calculation of the ESS's daily operational usage cost, this paper quantifies it as the cost per kilowatt-hour of electricity used. Specifically, it is calculated based on the ESS's full lifecycle cycle count and its maximum energy storage capacity to determine the usage cost per kilowatt-hour of electricity discharged. The calculation method is shown in Equation (8).

$$c_{ESS,use} = \frac{c_{ESS,invest}}{nE_{ESS}^{\max}} \tag{8}$$

where n represents the full lifecycle cycle count of the Energy Storage System.

Therefore, the daily operational cost of the ESS can be calculated by Equation(9).

$$c_{ESS,c} = \sum_{t=0}^{T} c_{ESS,use}\,\mathrm{abs}\left(P_{ESS}(t)\right)dt \tag{9}$$

3 Case Study

3.1 Experiment Setup

To verify the superiority of the proposed energy management system, a case study analysis is conducted in this paper based on the traction power supply system power data from the Shanghai High-Speed Maglev Commercial Operation Demonstration Line. The optimization algorithm employed is the Particle Swarm Optimization (PSO) algorithm. As the algorithm is not the main focus of this paper, it will not be introduced separately. The key experimental parameters are listed in Table 1.

Economical Indexes	Value	Unit
ESS unit capacity cost	300	$/kW
ESS unit power cost	100	$/kW·h
Unit capacity price	38.4	CNY/kW·month
Electricity price	0.6790	CNY/kW·h
Transfer efficiency	95	%
Cycle index	50000	times
Maintenance cost ratio	7	%
real-time exchange rate	7.11	CNY/$
$P_{ESS,max}$	5	MW
$E_{ESS,max}$	1	MW·h
SOC_{min}	0.1	/
SOC_{max}	0.9	/
Population	40	/
Maximum iteration times	2000	times

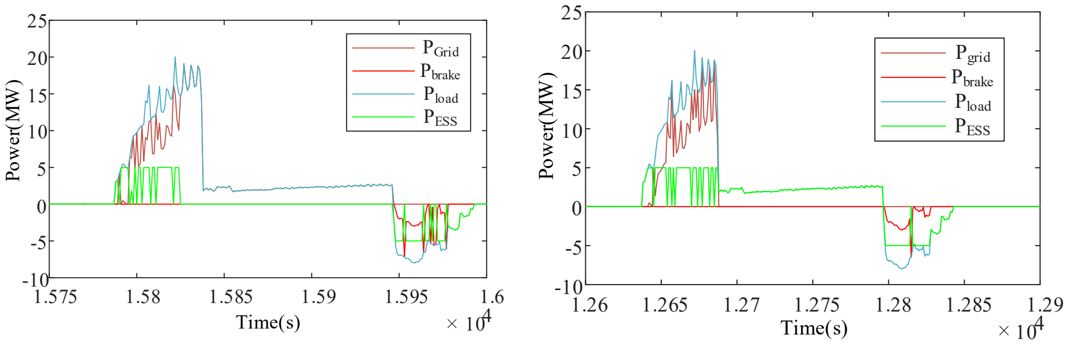
Table 1: Referential parameters for the case study [6][7].

The daily operational costs after optimization are shown in the table below.

Index(CNY)	Before Optimization	Optimized result
Capacity Charge	4386.16	3897.77
Electricity Charge	29845.03	19359.30
ESS Usage Cost	0	2415.94
Total Cost	34231.19	25637.01

Table 2: Daily Operational Cost of High-Speed Maglev Traction Power Supply System.

As can be concluded from the table, the optimized capacity price (demand charge) decreased by 488.39 CNY, and the energy price decreased by 10,485.73 CNY. In contrast, the ESS usage cost increased by only 2,415.94 CNY, which is significantly lower than the savings from the capacity and energy prices. Consequently, the total cost was reduced by 8,594.18 CNY. This indicates that the proposed method not only reduces the energy price by recovering regenerative braking energy but also leverages the peak-shaving effect of the ESS. The representative power response scenario are illustrated in Fig.2.



a) 300km/h b) 430km/h

Fig.2 Representative Power Response under Different Velocity

As can be seen from the figure, at both 300 km/h and 430 km/h speeds, the Energy Storage System (ESS) supplies power to the train together with the grid when the train is in the traction condition, and stores the Regenerative Braking Energy (RBE) when the train is in the braking condition.

Fig.3 presents the demand power curve of the high-speed maglev traction power supply system. As can be seen from the figure, the demand charge for the flexible high-speed maglev system decreased from 3.52 MW to 3.14 MW, further demonstrating the peak shaving capability of the flexible high-speed maglev traction power supply system.

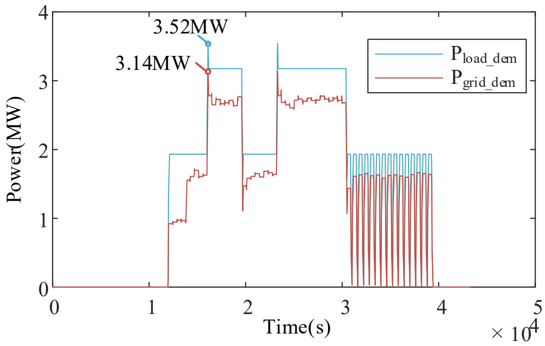


Fig.3 the demand power curve

4 Conclusions and Contributions

This paper addresses the issue of low utilization and poor economic return of regenerative braking energy (RBE) in high-speed maglev traction power supply systems. To overcome the limitations of conventional methods a flexible high-speed maglev traction power supply system incorporating an energy storage system and a corresponding energy management strategy are proposed. A comprehensive daily operational economic optimization model was established, and a case study based on the power data from the Shanghai Maglev Line was conducted. The results demonstrate that the total daily operational cost was reduced by 8,594.18 CNY. The savings in energy charges (10,485.73 CNY) and capacity charges (488.39 CNY) far outweighed the added ESS usage cost (2,415.94 CNY) and the maximum demand power was lowered from 3.52 MW to 3.14 MW, directly reducing capacity charges and validating the system's load-shifting capability.

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