Research on Metro Power Supply System Based on New Green and Environmental Protection

Yaya Wang * and Junhui Liu
Xi’an Traffic Engineering Institute, Xi’an710300, China

*Corresponding author e-mail: WangYaya@xjgy.edu.cn

Abstract. Installing a ground-based super capacitor energy storage system in the subway will effectively recover the regenerative braking energy of the train, reduce the energy consumption of the system, and achieve the goal of green and environmental protection. Various substations, traction/braking trains and energy storage systems interact in real time through the traction network to form a complex multi-energy coupling system. Therefore, in order to improve the overall energy efficiency of the traction power supply system and reduce investment costs, this article proposes Comprehensive optimization method for power supply system parameters and energy storage system capacity configuration. Through research, it is found that compared to the optimization of a single energy storage system, comprehensive optimization effectively improves the energy-saving rate of the energy storage system when the investment cost is similar.

Keywords: Green environmental protection, low power consumption, subway power supply system, capacity configuration.

1. Introduction
The subway has become a major consumer of electricity in cities, and its energy saving and emission reduction problems are becoming increasingly prominent. There is an urgent need to improve the utilization rate of regenerative braking energy; in addition, the operation of subway vehicles has the characteristics of rapid start-stop operation and high short-term power impact. Reduce the current peak impact and control the voltage fluctuation of the catenary to ensure the power supply quality and operational safety of subway vehicles. Carrying out research on related technologies for dynamic energy flow control of subway car network systems based on ground energy storage to ensure the safety and quality of subway power supply is a current research focus. Because the subway traction network system is coupled with multiple power sources, the fluctuation of the traction network voltage is affected by many factors such as the starting density and the braking power of the vehicle. After the energy storage device is connected, can it accurately identify the network voltage fluctuation and storage caused by the regenerative braking energy? Whether the energy storage device can ensure that its SOC value is at an appropriate level during the entire working process to avoid long-term full or lack of electricity. Therefore, the control strategy after the energy storage device is connected to the subway traction network needs to be optimized to meet the requirements of the subway the requirements of operating conditions [1]. This paper comprehensively considers the output characteristics of the substation, the
braking resistance control curve and the capacity configuration of the energy storage system, and analyses the influence of each part of the parameters on the energy flow of the system through the equivalent circuit model, and proposes a multi-objective optimization of the power supply system parameters and the capacity configuration of the energy storage system method.

2. Metro traction power supply system modelling

2.1. Metro Traction Substation
The subway adopts the form of DC traction network power supply. Generally, in the traction substation, the 10kV/35kV medium voltage is transformed into 750VDC/1500VDC voltage by the traction rectifier unit to supply power to the train. The train is powered by the overhead traction network or the third rail [2]. Compared with the traction network, the train running on the line is a moving load. The non-synchronous braking operations of multiple trains on the same line will cause complex changes in the DC traction network voltage. Figure 1 shows the structure of the subway traction substation.

2.2. Train modelling
Trains are the main electrical equipment in the subway traction power supply system. In the modelling and simulation of the subway power supply system, a constant current source or a constant power source model can be used to equivalent trains. For the constant current source model, the current drawn at a certain position of the train at a certain time can be obtained through the actual measurement data or the calculation results of the train's single-car full-line traction. Its mathematical model is

$$I = f(T, p)$$

In the formula, T is the train running time; p is the train running position. After the above analysis, this article uses the constant current source model equivalent train. The train flow is related to the time and position of the train, and it is a moving load. Through actual measurement, the pantograph voltage and current of an actual engineering train of Shanghai Metro, and the voltage and current (average value) curve of a certain on-board braking resistor box are shown in Figure 2.
3. Analysis of the influence of power supply system parameters

In the subway traction power supply system with energy storage system, the energy of the substation, energy storage system, and train are transferred to each other through the traction network to form a multi-energy coupling system. The output characteristics of the substation, the braking characteristics of the train and the capacity configuration and control parameters of the energy storage system will interact to affect the energy flow efficiency of the system [3]. Therefore, this section establishes equivalent circuit models for different train operation scenarios, and analyses the effect of substation no-load voltage and braking resistor starting voltage on the relationship between substation-traction train, tractor-brake car, and brake-energy storage system the impact of energy transfer.

3.1. Substation-towing vehicle energy transfer

Based on the single-vehicle traction operation scenario, the influence of power supply system parameters on the energy transfer between the substation and the train is analysed. Among them, \( u_{s0}, r_s, \) is the no-load voltage of the substation, the equivalent internal resistance and output current of the substation; \( r \) is the unit resistance of the traction network; \( l_1, l_2 \) is the distance between the traction train and two adjacent substations; \( p_T, u_T \) is the traction Train power and pantograph voltage. The power supply system parameters used in the modelling analysis are shown in Table 1.

| Parameter                        | Value  |
|----------------------------------|--------|
| Equivalent internal resistance of substation \( r_s/\Omega \) | 0.0161 |
| Traction network unit impedance \( r/(\Omega/km) \)         | 0.016  |
| Distance between adjacent substations \( L/km \)         | 2      |

Among them, the node voltage equation is

\[
\frac{u_T - u_{s0}}{r_s + r_{l1}} + \frac{u_T - u_{s0}}{r_s + r_{l2}} = - \frac{P_T}{u_T}
\]

From equation (2), the relationship between train pantograph voltage \( u_T \) and substation no-load voltage \( u_{s0} \) can be obtained as
The energy transmission efficiency of the system is defined as the ratio of the traction power of the train to the output power of the substation 

\[ \eta(u_{s0}) = \frac{P_T}{P_{t1} + P_{t2}} \] (4)

When the train is located in the middle of two adjacent substations, that is, when the train power is 1MW, 2MW, 3MW, 4MW, the no-load voltage increases from 800V to 900V, and the system efficiency curve is shown in Figure 3. It can be seen from Fig. 3 that the energy transmission efficiency between the substation and the traction train increases with the increase of the no-load voltage; and the greater the train traction power, the more obvious the efficiency improvement. When the train traction power is 4MW, \( \eta \) increases It's 2.6% bigger.

3.2. Calculation of train regenerative braking energy utilization rate

Relevant studies have shown that regenerative braking energy utilization and traction energy consumption are important indicators to measure the energy-saving operation of trains. The utilization rate of regenerative braking energy represents the regenerative braking of the train, and the traction energy consumption of the substation reflects the overall energy consumption of the vehicle network system [4]. This paper defines the regenerative braking energy utilization rate \( \eta_{re-used} \) as the ratio of the total regenerative braking energy used by trains in the traction power supply system to the total regenerative braking energy generated by multiple trains, namely

\[ \eta_{re-used} = \frac{\Sigma E_{re} - \Sigma E_{re-\text{unuse}}}{\Sigma E_{re}} \] (5)

Where: \( E_{re} \) is the total energy of regenerative braking; \( E_{re-\text{unuse}} \) is the energy absorbed by the braking resistor, that is, the unused regenerative braking energy. The specific acquisition method is as follows: the product of the current provided by the power source module and the grid voltage is then integrated to obtain the total train regenerative braking energy [5]. The calculation method of braking resistor absorption energy consumption is the same as that of regenerative braking total energy acquisition, so I won't repeat it here. The energy consumption calculation formula of traction substation is as follows:

\[ E_{ss} = \int_0^T P_{ss} dt = \int_0^T U_s I_s dt \] (6)
In the formula: $E_{ss}$ is the energy consumption of the substation; $P_{ss}$ is the power of the substation; $U_s$ is the bus voltage of the substation; $I_s$ is the output current of the substation; $T$ is the running time of the train [6]. The specific acquisition method is as follows: In the established PSCAD simulation model, the voltage and current of the substation are measured in real time through the multi-meter module, and the product of the two is integrated to obtain the traction power of the substation. The current in the substation is positive. The value is the power integral when outputting energy to get the traction energy consumption of the substation during operation time.

4. Case analysis

4.1. Simulation conditions

Table 2 shows the parameters of subway vehicles used in the calculation examples. The number of energy storage systems in series is fixed at 14, and the number of parallel connections is optimized. The maximum operating speed of the train is 65km/h. It adopts four-stage traction and three-stage braking. The maximum traction power is 4MW and the maximum braking power is 2MW.

| Parameter                  | Value       |
|----------------------------|-------------|
| Train formation            | 3M3T        |
| Vehicle weight/t           | 279.6(AW2)  |
| Maximum acceleration/(m/s²)| 1           |
| Maximum deceleration/(m/s²)| 1           |

4.2. Optimization results

Figure 4 shows the Pareto optimal curve obtained by optimizing the capacity configuration of the energy storage system and comprehensively optimizing the system parameters under the 360s departure interval. It can be seen from Figure 4 that under the same energy storage system configuration cost, the total energy consumption of the system after comprehensive optimization of system parameters is effectively reduced compared to when only the energy storage capacity configuration is optimized. The energy saving effect is more significant [7]. Under the two optimization schemes, the Pareto curve has an inflection point: before this point, the total energy consumption of the system decreases significantly as the configuration cost increases; after this point, the total energy consumption of the system remains basically unchanged, so this paper selects this point as the best point of capacity allocation.

![Figure 4. Pareto optimal curve under 360s departure interval](image_url)
5. Conclusion
The subway has become a major consumer of electricity in cities, and its energy conservation and emission reduction problems have become increasingly prominent. There is an urgent need to improve the utilization rate of regenerative braking energy. The combination of DC traction power supply system and electric vehicle swap station can increase the economy of the system, while renewable energy supplies power to this system in the form of a DC microgrid, which improves the low carbon, flexibility and reliability of the system. On the one hand, the urban integrated transportation system provides a brand-new operation mode for the subway and the substation, and promotes the development of both.

References
[1] Qin, Q., Guo, T., Lin, F., & Yang, Z. Energy Transfer Strategy for Urban Rail Transit Battery Energy Storage System to Reduce Peak Power of Traction Substation. IEEE Transactions on Vehicular Technology, 68(12) (2019) 11714-11724.
[2] Lin, S., Huang, D., Wang, A., Huang, Y., Zhao, L., Luo, R., & Lu, G. Research on the regeneration braking energy feedback system of urban rail transit. IEEE Transactions on Vehicular Technology, 68(8) (2019) 7329-7339.
[3] Golightly, D., Gamble, C., Palacin, R., & Pierce, K. Multi-modelling for decarbonisation in urban rail systems. Urban Rail Transit, 5(4) (2019) 254-266.
[4] Zhang, G., Tian, Z., Tricoli, P., Hillmansen, S., Wang, Y., & Liu, Z. Inverter operating characteristics optimization for DC traction power supply systems. IEEE Transactions on Vehicular Technology, 68(4) (2019) 3400-3410.
[5] Sun, H., Wu, J., Ma, H., Yang, X., & Gao, Z. A bi-objective timetable optimization model for urban rail transit based on the time-dependent passenger volume. IEEE Transactions on Intelligent Transportation Systems, 20(2) (2018) 604-615.
[6] Hayashiya, H. Recent trend of regenerative energy utilization in traction power supply system in Japan. Urban Rail Transit, 3(4) (2017) 183-191.
[7] Ahmadi, S., Dastfan, A., & Assili, M. Energy saving in metro systems: Simultaneous optimization of stationary energy storage systems and speed profiles. Journal of rail transport planning & management, 8(1) (2018) 78-90.