Collaborative Optimization Design of Multi-train Operation Curve Based on Utilization of Regenerative Braking Energy in Urban Rail Transit

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Abstract. At present, with the rapid development of urban rail transit, the energy consumption of the urban rail transit system has become a hot spot for many scholars. In order to effectively reduce the traction energy consumption of the urban rail transit system and improve the utilization of regenerative braking energy, this paper proposes a collaborative optimization strategy for multi-train operation curve. Firstly, this paper builds the simulation model of multi-train operation for urban rail power supply, it uses the improved Rosenbrock algorithm to calculate and solve, and analyzes the energy flow and utilization of the system energy. On this basis, it establishes the optimization model, proposes a collaborative optimization strategy for multi-train operation curve under the different operational scenarios by using the particle swarm optimization for the optimization solution. Finally, based on the actual line and train data of Beijing Metro Batong Line, the effectiveness verification of the optimization strategy under multiple scenarios is realized.

Keywords: Urban Rail Transit, Regenerative Braking Energy, Multi-train Cooperative Optimization, Particle Swarm Optimization.

1 Introduction

In recent years, urban rail transit has developed rapidly. In order to enhance its competitiveness in the transportation industry, it is particularly important to reduce the energy consumption and operation cost of urban rail transit system. Generally, the energy consumption of urban rail transit system is mainly distributed in traction power supply system, escalator, ventilation and air conditioning, lighting, drainage and other subsystems [1-2]. The energy consumption of traction power supply system of urban rail transit accounts for about 40% of the total system energy consumption. Therefore, energy saving of the system can be achieved by reducing the energy consumption of the traction power supply system.

In order to reduce the energy consumption of the traction power supply system, some scholars conduct research on energy-saving train driving [3]. The main methods include the optimization control of train speed curve, the control variables mostly include the train operation condition transition point, coasting section, etc., and the optimization curve is obtained by analytical method or numerical calculation method [3].

At the same time, due to the frequent starting and braking of urban rail trains, considerable regenerative braking energy is generated [4]. The recycling of regenerative braking energy can greatly reduce the system energy consumption of trains in operation. At present, the methods to improve the utilization of regenerative braking energy include recycling through energy storage/energy feed device[5], optimizing train timetable or train operation curve. Among them, the methods of optimizing train timetable or operation curve can effectively increase the overlapping time of traction and braking working conditions between trains[6,7,8], that is, increase the energy interaction utilization between trains, which has advantages of low cost and high flexibility compared with other methods[9,10].

However, the current research mainly has the following two problems: Firstly, most of the studies did not model the traction power supply system of urban rail transit in detail, and the real-time energy flow of the system is ignored in the optimization process, it will affect the optimization effect. Secondly, for the regeneration system, the utilization of kinetic energy is mostly by optimizing the train timetable to increase the overlapping time between the traction train and the braking train. The optimization of the timetable will be limited by actual conditions, the optimization space is relatively small. Therefore, combined with the traction power supply system model, this paper proposes a multi-train collaborative optimization strategy, and finally verifies the effectiveness of the strategy by simulation.

2 Modeling and analysis of urban rail traction power supply system

In order to study the energy-saving optimization of the urban rail transit energy system, this chapter models and analyzes the urban rail multi-train traction power supply system.

2.1 Modeling of traction power supply system

Traction substation. Traction substations mainly use traction transformer and rectifier units to convert high-voltage AC to DC, and the essential is the rectifier unit. At present, the urban rail traction substation is mainly composed of two sets of 12 pulse rectification units in parallel to form 24 pulse rectification unit[11], thereby realizing unidirectional energy flow.

Traction network. Traction network is to transmit the electric energy to electric train through rail transit power supply system. It is composed of feeder, catenary, rail and return line [11]. In order to simplify the model of the traction power supply system, this paper only models the catenary and the rail, and uses the equivalent π-type circuit to represent it.

Train. Because the parameters of train position, speed and power are time-varying, the train is equivalent to the controlled current source. The input and output state of current is controlled by the value of train power. And in order to prevent the network voltage rising caused by the unused regenerative braking energy when the train is braking, which leads to the regenerative failure[4], the regenerative current limiter model is added to the circuit.

In summary, the construction of the urban rail traction power supply line model considering the up and down lines is shown in Fig.1. In order to realize the rapid solution of the system and considering its rigidity, this paper selects an improved Rosenbrock algorithm to solve the model [12].

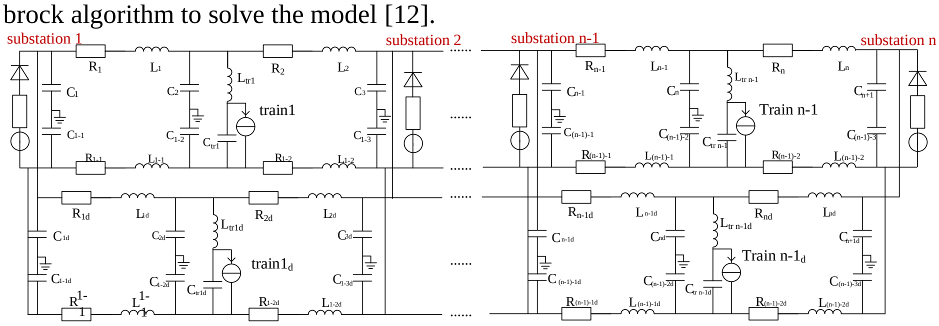


Fig. 1. Circuit model of multi-train traction power supply system

2.2 Energy flow analysis

By analyzing the energy flow and utilization of the system, the utilization mode of the system's regenerative energy can be determined. In the multi-train traction power supply system, taking the train as the reference object, according to the direction of energy flow[4], it can be divided into three parts: energy inflow, energy outflow and energy loss, as shown in Fig.2. And the main definition formula of each part of the energy is as follows.

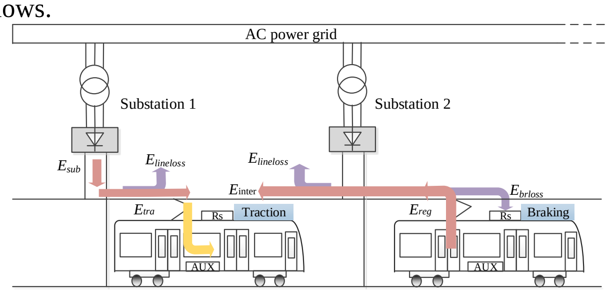


Fig. 2. Energy flow diagram of traction power supply system

$$E_{sub} = \int_0^T P_{sub} dt \qquad E_{tra} = \frac{1}{\eta_t} \cdot \int_0^T P_{tra} dt \qquad E_{br} = -\eta_b \cdot \int_0^T P_{br} dt \tag{1}$$

In formula (1), P_{sub} represents the output power of the substation, and E_{sub} represents the output energy of the substation. η_t represents the efficiency of traction energy transmission, P_{tra} represents the power required for train traction, and E_{tra} represents the traction energy required for train operation.

And η_b represents the transmission efficiency of braking energy, P_{br} represents the braking power of the train, E_{br} represents the braking energy of the train. T represents the total running time of the system.

According to the principle of energy conservation, the energy output part is equal to the sum of the energy inflow part and the energy loss part. In order to reduce the output energy of substation and improve the energy saving rate of regenerative energy, the main improvement method is to increase the interaction energy between trains. Therefore, this paper carries out research on the strategy of train operation curve adjustment.

3 The strategy of train operation curve adjustment based on the utilization of regenerative energy

The adjustment of train operation curve means that under the premise of ensuring the operation time and parking accuracy between stations[5], when the train generates regenerative braking energy, the regenerative energy can be effectively utilized by optimizing the operation curve of adjacent trains, so as to avoid regenerative failure and other problems.

3.1 Train operation optimization model

In order to realize the optimization of the train operation curve, the train operation optimization objective function is established firstly, and on this basis, the mathematical model of the train operation optimization is further constructed.

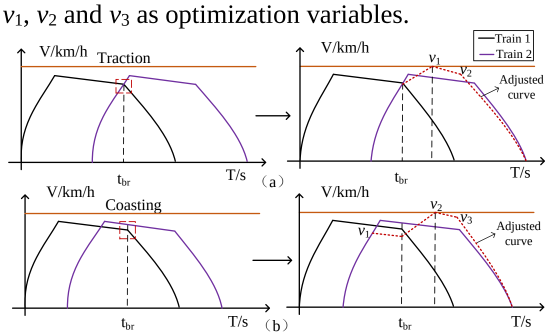
The optimization objectives are selected to consider the energy saving [3], the objective function and constraint conditions are shown in formula (2). Among them, J represent the system net traction energy consumption, E_{change} represents the interaction energy between trains, V_{limit} and $a_{\max}$ are speed limit and maximum acceleration of train respectively, n_1, n_2 represents the error requirements of the train stopping position and running time. s, v and t represent the position, speed and time of train operation. S represents the train's arrival position.

$$
\begin{aligned}
&\min J = E_{tra} - E_{change} \\
&s.t\ v(0)=0, v(\mathrm{T})=0 \\
&v(t) < V_{\lim it} \\
&a(t) < a_{\max} \\
&|s(t) - S| < n_1 \\
&|t - T| < n_2
\end{aligned}
\tag{2}
$$

3.2 Adjustment strategy of multi-train operation curve

When there are trains braking on the line, the adjacent trains may be in traction, coasting, braking and parking state. Considering the comfort of passengers, this paper selects the trains in traction and coasting state for adjustment.

Firstly, taking the operation adjustment of two trains as an example, it is assumed that the first train (train 1) will brake at time *t*, and the state of adjacent trains (train 2) needs to be detected at this time. If train 2 is in traction state, as shown in Fig.3(a), the kinetic energy of train 2 after time *t* will be provided by train 1 under the restriction of speed limit and other conditions, and the running acceleration changes with the regenerative energy of train 1 in real time. Among them, turning speed v_1 and v_2 are optimization variables; If train 2 is in coasting state, as shown in Fig.3(b), set turning speeds v_1, v_2 and v_3 as optimization variables.



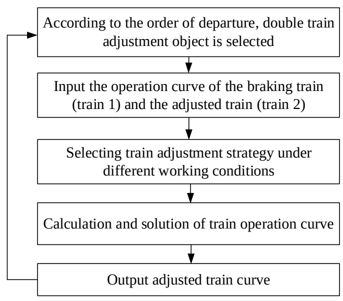


Fig. 3. Train operating curve adjustment strategy

Fig. 4. Flow chart of operating curve adjustment

In summary, when there are multi-train running, the adjustment strategy of train operation curve is shown in Fig.4. In order to ensure the effective utilization of renewable energy, the object of two-train adjustment is set in the same power supply section or adjacent power supply section. To ensure that the global optimal value can be found in a short time, this paper proposes a method for solving train operation curve based on particle swarm optimization. The advantages of particle swarm optimization are simple rules, easy convergence and high accuracy[14].

4 Simulation analysis

Based on the multi-train operation curve adjustment strategy, this chapter verifies the train operation curve adjustment strategy for multiple operation scenarios.

4.1 Simulation conditions

First of all, this paper conducts simulation verification based on actual vehicles and line data of the Beijing Metro Batong Line. The train runs from Guoyuan Station to Tuqiao Station. The simulation parameters are shown in Table 1, including traction power supply system and train parameters. The two-train operation curve is shown in Fig.5.

Table 1. Main parameter and value

Parameter	value	Parameter	value
Train rotation quality	210.15t	Maximum train deceleration and acceleration	-0.85m/s^2,0.8m/s^2
No-load voltage of substation	860V	Catenary/rail resistance	0.02/0.019Ω/km
Catenary/rail inductance	1.07/0.65mH/km	Catenary/rail-to-ground capacitance	6.02/26.5nF/km
Simulation time	200s	Braking resistance range	900-970V
n_1	0.25m	n_2	5s

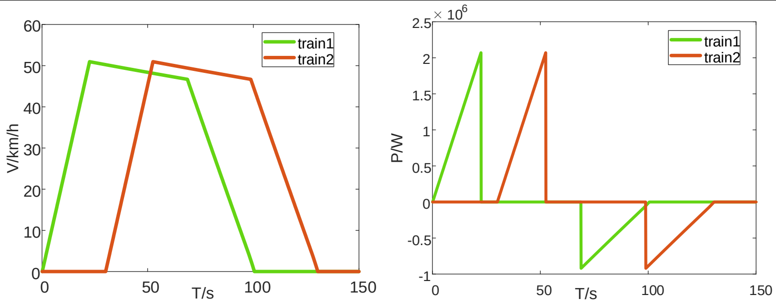


Fig. 5. The speed and power curves of the two vehicles not adjusted

4.2 Simulation verification in multiple scenarios

Scenario 1. When train 1 is braking, train 2 is in the coasting state. According to the dual train adjustment strategy, the optimal variables are traction-coasting, secondary traction-coasting and coasting-braking transition point speed. The optimized running curve of the train is shown in Fig.6(a), including the speed and position curves of before and after adjustment. It can be seen that, through optimizing the speed of the transfer point, when train 1 is braking, train 2 can effectively absorb the regenerative braking energy.

At the same time, the optimization objectives before and after the adjustment and the output energy of the substation are compared, as shown in Table 2. The punctuality and parking accuracy of the adjusted train can be up to 99.9%. Compared with before adjustment, interactive energy utilization is increased to 3.49kWh, output energy of substation is reduced by 1.92 kWh. It also further stabilizes the fluctuation of traction network voltage and reduces the time of regeneration failure, as shown in Fig.6(b).

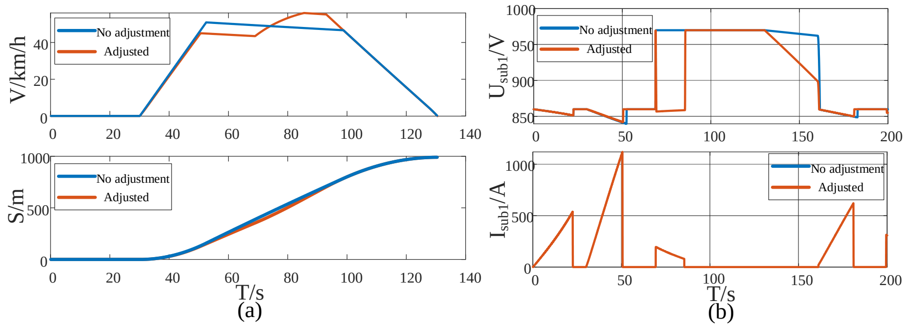


Fig. 6. Comparison before and after adjustment

Table 2. Simulation comparison in scenario 1

	No adjustment	Adjusted	Comparison
Operation time	130.3s	130.3s	100.0%
Parking position	991m	991.11m	99.9%
Interaction energy	0.43kWh	3.49 kWh	3.06kWh
Output energy of sub-station	20.12 kWh	18.2 kWh	1.92 kWh

Scenario 2. When train 1 is braking, train 2 is in the traction state. The optimal variable is traction-coasting and coasting-braking transition point speed. The optimized train 2 operation curve is shown in Fig.7(a). Similarly, the optimization objectives before and after adjustment and the output energy of the substation are compared as shown in Table 3. Compared with the adjustment, the punctuality and parking accuracy of the adjusted train can be up to 97%, and the utilization rate of interactive energy was increased to 3.57kWh, and the output energy of substation was also 0.64kwh lower than before. Meanwhile, the comparison of the fluctuation of traction network voltage is shown in Fig.7(b).

Table 3. Simulation comparison in scenario 2

	No adjustment	Adjusted	Comparison
Operation time	150.3s	146.4s	97.4%
Parking position	990m	990.12m	99.9%
Interaction energy	0.43 kWh	3.57 kWh	3.14kWh
Output energy of sub-station	12.55 kWh	11.91 kWh	0.64kWh

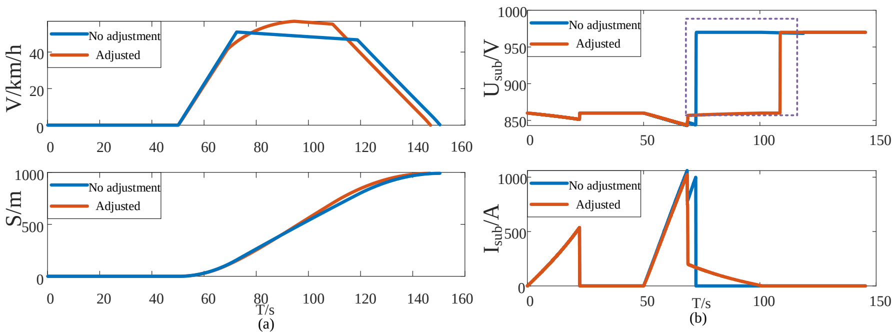


Fig. 7. Comparison before and after adjustment

In order to further analyze the system's energy saving effect, the definitions are respectively made as formula (3). it represents the utilization rate of system regenerative braking energy, where E_{change} represents the interaction energy between trains. Therefore, the comparison results of energy efficiency are shown in the Table 4. The system regenerative braking energy utilization rate have been significantly improved.

$$\eta_{E_{reg}} = \frac{E_{change}}{E_{br}} \times 100\% \tag{3}$$

Table 4. The comparison of regenerative energy utilization

	No adjustment	Adjustment
Scenario 1	5.20%	25.36%
Scenario 2	4.17%	34.34%

5 Conclusion

In order to reduce the energy consumption of the urban rail traction power supply system, the utilization rate of the regenerative braking energy of the system is improved. This paper proposes the multi-train collaborative optimization strategy based on particle swarm algorithm, combined with multi-train traction power supply system for simulation analysis, and uses particle swarm algorithm to optimize the curves of train speed and displacement under different operation scenarios. Finally, based on the actual conditions of the Beijing Metro Batong Line, it is proved that this strategy can effectively increase the interaction energy between trains. Finally, the energy utilization rate of regenerative braking increased by 25% on average. Therefore, the strategy proposed in this paper has certain significance for energy saving of urban rail transit system.

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