The Modeling and Simulation of DC Traction Power Supply Network for Urban Rail Transit Based on Simulink

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Abstract. In order to study the influence of the state of train on the power supply network of urban rail transit, it is necessary to model and analyse the DC traction power supply system and vehicles. Based on the analysis of the structure of power supply system for urban rail transit and according to the operating principle of train, the modeling method of traction power supply system is proposed. The model of DC traction power supply system and train are established in the Simulink environment. The speed, position and power of the train vary with time through simulation, so the electrical value of train operation such as voltage that changes over time can be obtained under the model. The simulation results and the measured data are consistent in the trend of change, but there is a certain difference in corresponding values (fluctuated in an acceptable range), which verifies the validity of the model. In addition, it compares the energy consumption of substations at different departure intervals.

1. Introduction

In recent years, China has entered the peak period of the development of urban rail transit, many cities have successively opened urban rail transit lines, and the total operating mileage is also increasing. With the rapidly development of the urban rail transit, it is necessary to carry out modeling and analysis of DC traction power supply system and trains in order to deeply study the impact of trains on the power supply network.

In the simulating research on traction power supply of urban rail transit, there are some methods used commonly, such as the average traffic method, train operation diagram method, numerical analysis method and modeling simulation method [1, 2]. The average traffic method which are based on probability theory with a certain amount of error. The train operation diagram method separates the integrity of the power supply of the entire traction network, and there will be a certain deviation from the actual situation. The numerical analysis method is more complex to solve the equations, which will encounter the situation that the numerical value does not converge. The modeling simulation method is based on the train traction calculation, which can obtain the voltage and other electrical quantities of substations and trains by simulation. Although the solution efficiency of this method is low, it is more convenient than tedious language programming and can directly observe the changes of electrical parameters, and the observability is better. The paper is based on this method to model and simulate the DC traction power supply network of urban rail transit in the simulink environment.
The rest of this paper is organized as follows. In section 2, we mainly introduce the modeling of DC traction power supply system for urban rail transit, and analyze the substations and the traction network respectively, and establish the corresponding equivalent model. In section 3, we introduce the modeling of the train. In section 4, we construct a simulation model of DC traction power supply for urban rail transit by combining the traction calculation of trains and the circuit model of DC traction power supply network, and we also give the calculation method of system energy consumption. Then we use the simulation result of a single train operation as an example to verify the effectiveness of the model, at the same time, the system energy consumption under different departure intervals is simulated in section 5. In section 6, conclusions are presented.

2. The modeling of DC traction power supply system

The DC traction power supply system of urban rail transit is composed of substation and the traction network, as shown in figure 1. Substation can provide power for train traction in certain areas of urban rail transit, and the traction network is power supply network which consists of feeders, catenary (third rails), track loops and return lines.

![Figure 1. Structure diagram of DC traction power supply system.](image1)

![Figure 2. Rectifier unit external characteristic curve.](image2)

2.1. Equivalent model of substation

In the traction power supply system of urban rail transit, substation is an important equipment that provides a stable DC750V or DC1500V voltage for the train after stepping down the main substation voltage by a 24 pulses rectifier transformer, and the output voltage of substation decreases with the increase of load current. Substation can be simplified by a constant ideal voltage source with internal resistance in the simulation of the DC traction power supply system [3].

In order to simplify the simulation analysis, this article limits the working area of the rectifier unit, so the external characteristics of the rectifier substation can be approximated as a straight line, as shown in figure 2. The rectifier unit of substation is a diode with uncontrollable rectification, the current flowing through substation has unidirectionality, so if the external voltage of the substation is greater than the rated terminal voltage, substation will not work. On the contrary, substation is put into use.

2.2. Equivalent model of traction network

Traction network is an important part of the DC traction power supply system. The traction network is mainly composed of catenary (third rails) and tracks. According to the uniform transmission theory, it can obtain the position of metro trains at each moment based on the operation diagram so that the establishment of catenary model can be represented by a variable resistor [4].

When the train is running, the distance from substation is constantly changing, so the contact resistance between substation and train is also constantly changing. However, there is no module in simulink that can be used to represent a variable resistor, so it is built with a controlled voltage source based on the characteristics of the resistor. Using an ammeter to measure the current flowing through
the controlled voltage source and then multiply the resistance between train and substation, and the voltage value of the controlled voltage source can be obtained with the same physical characteristics as the variable resistor. In addition, in order to solve the algebraic loop problem, it is necessary to add a memory module behind the measured current value. The equivalent model of traction network is shown in figure 3.

\[ U_R = i_R \times R = i_R \times (\Delta r \times s) \]  

In the equation, \( U_R \) is the voltage value of the controlled voltage source, \( i_R \) is the measured contact network current value, \( \Delta r \) is the unit impedance of catenary, \( s \) is the distance from train to substation.

![Figure 3. The equivalent model of traction network.](image1)

![Figure 4. The equivalent model of the train.](image2)

### 3. The modeling of the train

When the network voltage fluctuates within the normal range, the energy absorbed by metro trains from the DC grid and the regenerative energy returning to the grid are less affected by the network voltage fluctuations. However, the current obtained by the train from catenary is directly affected by the actual network voltage. Therefore, the electrical output characteristics are mainly determined by the running status of the train. Based on the above analysis, the train can be equivalent to a power source, since there is no power source module in simulink, it is represented by a controlled current source.

However, it is worth noting when the train is braking, if there is not enough traction train or absorption device nearby to completely absorb the unused regeneration energy, the remaining regenerative braking energy will make the network voltage exceed the allowable fluctuation range. Therefore, over-voltage protection of the vehicle traction system is triggered and reduce the regenerative current of the train, which process is the failure of regenerative braking [5].

In order to reflect the train model during regenerative braking, a regenerative current limiter is added to limit the size of regenerative current. The equivalent model of the train is shown in figure 4. The power of train is divided by the voltage measured by the memory module, then the train's current can be obtained and passed to the controlled current source, which constitutes the equivalent model of the entire train. The memory module in the figure is also intended to solve the algebraic loop problem.

### 4. Traction power supply simulation system of urban rail transit

In the paper, the train traction calculation and DC traction power supply simulation are used to analyze the operation process of the train on traction power supply system, the changes of speed, power, position and voltage of the train over time are obtained [6]. The architecture diagram of traction power network simulation system for urban rail transit is shown in figure 5.

#### 4.1. Train traction calculation

Through the train traction calculation, the relationship between speed, distance and power of the train as a function of time is obtained. The simulation is performed on the basis of the train traction calculation to derive the position of the train and the change of the electric power at any time, which is taken as the input parameter of the DC traction power supply simulation module.

#### 4.2. Circuit model of DC traction power supply network
During the operation of metro trains, the load is changing constantly. Substations, catenary, trains, and tracks constitute a dynamic complex electrical network, and the topology of DC traction supply network is time-varying, and the location of running train is relevant. Therefore, the simplified circuit model of the DC traction power supply network needs to be analyzed firstly, taking the circuit model of a single train as an example. Substations adopt bilateral power supply, and the train runs from left to right, as shown in figure 6.

We can see that the train is equivalent to a power source model from figure 6, and its network voltage and current are $U_{dc}$ and $I_s$. Substation is equivalent to a constant ideal voltage source with internal resistance, which is irreversible [7]. The equivalent voltage of substation 1 and 2 is $U_{d0}$, and the equivalent resistance is $R_{s1}$ and $R_{s2}$, respectively. The resistance of traction network is evenly distributed, denoted by $R_1$ and $R_2$.

### 4.3. Energy consumption of substation

When the train runs in the power supply section, its operating state will affect the voltage and current of substation. When the train is accelerating, substations will supply power to metro trains to ensure its normal operation, and the train will not consume power when it is coasting, but when the train brakes and the external voltage exceeds the rated terminal voltage of substation, it will not supply power to train, so there is no energy consumption. Therefore, the energy consumption of substation can be calculated as the following formula.

$$E_{sub} = \int U_{d0}(I_{sub1} + I_{sub2})dt$$

In the formula, $U_{d0}$ is the equivalent voltage of substation, and $I_{sub1}$, $I_{sub2}$ are the output currents of substations 1 and 2, respectively.

### 5. Simulation analysis

#### 5.1. Model validation

Based on the above analysis, the paper combines the train traction calculation and the circuit structure of power supply network to build a simulation model of DC traction power supply system for urban rail transit in the simulink environment. In order to verify the validity of the model, the train operation data of a subway line was collected, and the simulation of a single train was performed on this basis, the simulation results and measured data were compared, as shown in figure 7.

This article selects a section of the line, the length of which is 2090m, and the train running time is 144s, and the rated network voltage is 835V, and the internal resistance of traction network is 0.016Ω/km. The simulation results and measured data have great similarities in the changing trend from figure 7, but there are certain differences in corresponding values. The difference between the two is mainly caused by various interferences in the actual circuit and the fluctuation of the network.
voltage. In the actual running process, the inertia of the train is relatively large, therefore, the change of the grid voltage is delayed accordingly. In the paper, the regenerative current limiter is set when the regenerative braking fails, so the simulated voltage of the train tends to be constant during braking stage. By analyzing and comparing the measured values, it is found that the deviation of the simulated values is within an acceptable range, which verifies the validity of the model.

5.2. Energy-saving effect analysis
After verifying the validity of the model, this section simulates the operation process of two trains in the same power supply area. It can be seen from figure 7, the train consumes electric energy when it is accelerating and the voltage of traction network is decreasing, and when regenerative energy is generated during braking, the voltage rises very high if it cannot be completely absorbed, so it is possible to use the regenerative energy to supply the accelerating train. On the one hand, it reduces the output energy consumption of substations. On the other hand, it reduces the network voltage of traction network, and the impact on the relevant electrical equipment and the contact network can also be reduced.

In order to achieve a higher energy-saving effect, the operation of two vehicles using the same control strategy at different departure intervals within a certain station has been simulated, the energy consumption at different departure intervals is shown in figure 8. We can see that when the departure interval is 60 seconds, the energy-saving effect is the best, which is exactly the very time for the forward train starts to brake and the following train starts to accelerate. Therefore, the very time should be matched as much as possible in the design of the schedule, so as to achieve better energy-saving effect.

![Figure 7. The simulation results of a single train.](image)
6. Conclusions
The paper combines the train traction calculation and the circuit structure of traction network to build a simulation model of DC traction power supply for urban rail transit. The process of a single train running in the interval is simulated, and the result is successfully obtained that the simulated value and the actual measured data have similar trends, which verifies the validity of the simulation model. At the same time, the energy consumption of the system at different departure intervals is analyzed, and it is concluded that adjusting the departure interval between metro trains can achieve energy saving. The model which is set up in the paper as the most basic simulation model is of great significance for the follow-up study of DC traction power supply system for urban rail transit. The modular design of the model provides great convenience for the subsequent addition of substation modules, traction network sub-modules, and train sub-modules. It can simulate the actual operation of multiple trains in more power supply ranges or even the entire subway line, which lays the foundation for further research. The electrical parameters obtained from simulation can also be used to estimate the impact of train operating conditions on the urban AC grid and so on.

Acknowledgments
This work is supported by the Beijing Laboratory of Urban Rail Transit, the Beijing Key Laboratory of Urban Rail Transit Automation and Control, the Fundamental Research Funds for the Central Universities(2018JBZ006), and the State Key Laboratory of Rail Traffic Control and Safety (Beijing Jiaotong University) (No. RCS2018ZT012).

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