Chapter 32
Feasibility Study on the Power Supply of DC 3-kV System in Urban Railway

Xiaoyu Lei, Guofei Yang, Wei Liu, Cong Liu, Ying Wang, Ke Huang and Yunchuan Deng

Abstract The DC (direct current) traction power supply calculation is important for the design of urban railway power supply system. Aiming at the introduction of DC 3-kV traction supply system in domestic urban railway transport, this paper proposes calculation principle and procedures detailedly; then, based on the certain line of Shenzhen subway, the comparison in the design scheme of DC 1.5-kV system and DC 3-kV system is carried out through calculation, and the feasibility and superiority of DC 3-kV system are assessed in the aspects of power supply technical index, power supply quality and so on.

Keywords Urban railway transport · Traction power supply calculation · DC 3-kV traction supply system · Feasibility and superiority

32.1 Introduction

As one emerging public transport mode, urban railway transport has developed rapidly, and corresponding traction power supply system is one of important constituent parts. In recent years, due to technological progress, especially the acceleration of urbanization and growing increase of passenger flow, the volume of vehicle body in railway is larger increasingly, the marshaling of train is longer increasingly, and the train speed is improved increasingly, which put forward higher requirements for the overall dynamic performance of train. So, improving traction voltage and increasing systemic capacity is important direction in the development of urban railway transport.

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Traction substation transforms three-phase AC high-voltage into DC low-voltage; feeder line transforms the DC low-voltage into catenary, and electric vehicles receive electric energy through direct contact between their collectors and catenary [1, 2]. In the design of urban railway system, the calculation of traction power supply is extremely important and it is related with the critical design factors including traction systemic constitution, traction power supply mode, and substation settings. Besides, the traction power supply modes in urban railway mainly include current mode, voltage level, and collection mode. [3–5], where it is necessary to determine voltage level according to train, line structure, electrical equipment level, etc. In previous studies, [1] illustrated differences between DC 1.5-kV system and DC 3-kV system and drew the conclusion that the DC 1.5-kV system relates optimal way in urban railway transport system; similarly, [3] argued that the collection modes shall be unified for railway in one city and the DC 1.5-kV system shall be the first selection. [4] studied the optimization of urban railway train control and dynamic simulation of traction system; [6] proposed unified AC/DC power flow algorithm to realize the calculation of urban railway transport; based on the DC power supply model, [8] developed simulation system of solving train voltage and current, provided as economic and effective experimental method.

Although the DC 3-kV system has not been adopted in China urban railway system, the power supply calculation is necessary when the feasibility scheme is formulated and designed initially. Since existing references rarely studied feasibility of DC 3-kV system, this paper carried out power supply calculation and compared the design schemes of DC 3-kV system and DC 1.5-kV system; finally, in order to prove the feasibility and superiority of DC 3-kV system, the effect assessment is performed based on certain line of Shenzhen subway.

32.2 Selection for Traction Mode in Urban Railway Transport

The DC traction voltage modes adopted in urban railway transport are various and generally in the range of DC 0.6–3 kV, where the voltage modes at abroad include DC 0.6, DC 0.75, DC 0.825, DC 1, DC 1.2, and DC 1.5 kV, while domestic voltage modes adopt voltage standard of international electrotechnical commission (IEC), including DC 0.6, DC 0.75, and DC 1.5 kV [7, 8]. At present, domestic urban railway transport mainly adopts DC 0.75 kV mode and DC 1.5 kV mode. Considering that higher voltage will transfer higher power in equal conditions, compared with the DC 0.75-kV system, the DC 1.5-kV supply system is able to adapt to the electric vehicles with greater power and can reach higher speed levels, where the acceleration speed is improved accordingly under allowing adhesion; besides, the supplying current of DC 1.5 kV mode reduces by half, and the resistance consumption and the stray current from traction substation reduce

Table 32.1 Domestic and foreign DC traction power supply technology

Power supply mode	Direct current (DC)			Alternating current (AC)	
	0.75 kV	1.5 kV	3 kV	25 kV/50 Hz	15 kV/50/3 Hz
Abroad	1900–1915	1915–1930	1930–1950	1950-now	1915–1930
Domestic	1969-now	1969-now	–	1961-now	–

accordingly. Note that above comparisons can be also analogy to the comparison of DC 1.5-kV system and DC 3-kV system. In the selection of voltage mode, it is necessary to consider technical index, power supply quality, power supply distance, passenger-flow density comprehensively, and the selection should be determined based on comprehensive demonstration of economic development and comprehensive project in urban [7].

The comparison for application ages of all the traction supply technology in domestic and abroad is shown in Table 32.1. Obviously, the DC 3-kV system has not been applied at domestic, while DC 3 kV mode has been adopted at abroad. In Belgium, the national operating mileage of electrified railway has reached 3536 km, where the DC 3 kV mode is adopted in the 83.4 % of total mileage. Besides, the coverage of current electrification railway has reached 100 % in Georgia, and DC 3 kV mode has been adopted with the rapid development of urban railway transport. The construction of Tbilisi section was carried out through the project cooperation regarding DC 3 kV between Georgia and China Railway Eryuan Engineering Group CO in 2010.

32.3 Modeling for DC 3-kV Power Supply System

32.3.1 Traction Substation Model

In the traction power supply system of DC 3 kV, traction substation adopts parallel operation of two 12-pulse rectifier units to constitute the 24-pulse output, where the connection form of 12-pulse rectifier unit is shown in Fig. 32.1.

As the interphase reactor without bridge operates, the interaction between two electrical bridges of rectifier unit will appear [9], and the expressions of voltage and current at DC side and fundamental power at AC side under normal operation mode are, respectively, depicted in (1)–(5).

$$E_d = \frac{6U}{\pi}\left\{\begin{array}{l}\frac{\sqrt{2}(3+2\sqrt{3})}{7}\left[\sin(\alpha_1+\mu)-\sin\alpha_1\right]+\\ \frac{1+\sqrt{3}}{2}\left[\sin\left(\alpha_1+\frac{\pi}{12}\right)-\sin\left(\alpha_1+\mu-\frac{\pi}{12}\right)\right]\end{array}\right\} \tag{1}$$

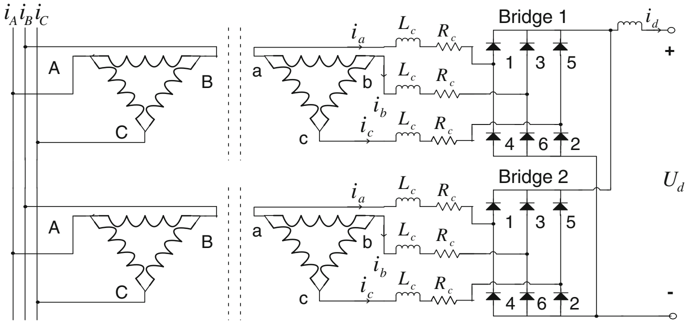

Fig. 32.1 12-pluse rectifier connection mode

$$I_d = \frac{\sqrt{2}U}{X_c}\left\{-\sqrt{3}[\sin(\alpha_1+\mu) - \sin\alpha_1] + 2\left[\sin\left(\alpha_1+\mu-\frac{\pi}{6}\right) - \sin\left(\alpha_1-\frac{\pi}{6}\right)\right]\right.$$
$$\left. + \frac{\sqrt{3}-1}{4\sqrt{2}}\left[\sin\left(\alpha_1-\frac{5\pi}{12}\right) - \sin\left(\alpha_1+\mu-\frac{7\pi}{12}\right)\right]\right\} \tag{2}$$

$$P_1 + jQ_1 = 2\sqrt{3}U\left(I_{a2,r1} + jI_{a2,i1}\right) \tag{3}$$

$$P_1 = \frac{4\sqrt{3}U^2}{\pi X_C}\left\{\sin\mu\phi_{31}(\mu) + \sin\left(\frac{\pi}{6}-\mu\right)\phi_{32}(\mu) + \sin\left(\mu+\alpha_1-\frac{\pi}{3}\right)\phi_{33}(\mu)\right.$$
$$\left. + \sin\left(\mu+\alpha_1+\frac{\pi}{3}\right)\phi_{34}(\mu) + \sin(\mu+\alpha_1)\phi_{35}(\mu) + 0.7588\right\} \tag{4}$$

$$Q_1 = \frac{4\sqrt{3}U^2}{\pi X_C}\left\{-\sin\mu\psi_{31}(\mu) - \sin\left(\frac{\pi}{6}-\mu\right)\psi_{32}(\mu) - \cos\left(\mu+\alpha_1-\frac{\pi}{3}\right)\psi_{33}(\mu)\right.$$
$$\left. - \cos\left(\mu+\alpha_1+\frac{\pi}{3}\right)\psi_{34}(\mu) - \sin(\mu+\alpha_1)\phi_{35}(\mu) + 0.4375\mu + 0.058\left(\frac{\pi}{6}-\mu\right)\right\} \tag{5}$$

In (1)–(5), U, P_1, and Q_1 are, respectively, voltage effective value, fundamental active power, and fundamental reactive power at the AC sidetrack of 12-pulse rectifier unit; E_d and I_d are, respectively, voltage and current at the DC side of 12-pulse rectifier unit; X_C is commutating reactance of rectifier unit; α_1 is delay conduction angle, and $\alpha_1 = \tan^{-1}\left(\frac{2-\sqrt{3}}{7}\right) \approx 2.192^{\circ}$; μ is commutation overlap angle, which satisfies (6).

$$\frac{X_C I_d}{\sqrt{2}U} + \cos(\alpha_1 + \mu) - \cos\alpha_1 - \frac{\sqrt{3}-1}{4\sqrt{2}}\left[\sin\left(\alpha_1 - \frac{5\pi}{12}\right) - \sin\left(\alpha_1 + \mu - \frac{7\pi}{12}\right)\right] = 0 \quad (6)$$

32.3.2 Multi-conductor Traction Catenary Model

Multi-conductor catenary model is generally adopted in the simulation and calculation of power supply, and it is constituted by five conductors, including upstream catenary, downstream catenary, upstream rail, downstream rail, and stray current collecting network (current-discharge network) as seen in Fig. 32.2.

For the upstream and downstream catenary in urban railway, the traction current comes from all the traction substations at the same feeding section. However, in the traditional traction calculation method and section calculation method of operation chart, only two substations are related; besides, the train only collects currents from two adjacent substations under normal bilateral power supply. So, it is feasible to install a few parallel lines at different catenary positions for the catenary parallel operation except that the catenaries at upstream direction and downstream direction supply currents to trains.

For upstream and downstream rail, rail acts as return circuit of traction current, and the difference of operation currents under different states is obvious, where most of currents are able to return to the negative pole of source, while a small portion of currents are always leaked to ballast bed and surrounding soil medium at the poor insulated position between rail and ground, namely formatting stray current. Generally, current-equalized line is installed at each station to parallel with return wires as many as possible to reduce rail return resistance.

For collection network of stray current, the structural concrete irons at each feeding section, which includes ballast bed, bridge, and tunnel, are connected together and connected with the negative bus terminal of traction substation to form the pathway of stray currents.

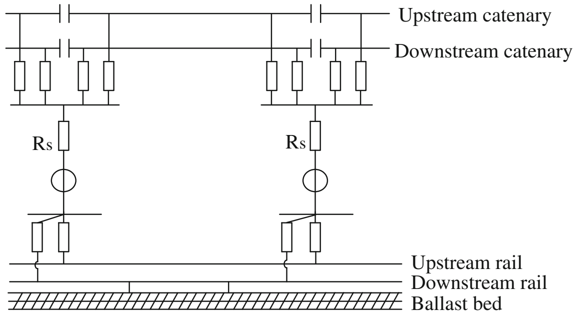

Fig. 32.2 System model of multi-conductor catenary

32.4 Procedures of Traction Supply Calculation

In theory, compared with DC 1.5 kV mode, catenary voltage level is improved by one time, average and effective catenary currents are reduced, catenary consumption is reduced, distance between traction substations is longer, rail current flowing towards traction substation is reduced and rail potential is improved in DC 3-kV system.

According to the train operation diagram, the traction calculation of DC system when multi-trains are running in line is carried out to obtain installment capacity of rectifier unit and catenary voltage, and the rectifier unit can be expressed as the model of voltage source series with resistance. The DC voltage adjustment rate is the relative reference value of the difference between rated no-load DC voltage and rated DC voltage on ideal no-load DC voltage. As the no-load of rectifier unit has reached the rated load with 300 %, the external characteristic of rectifier unit presents straight line. Besides, catenary resistance is equivalent to the constitution of catenary and rail, and the train is equivalent to current source model.

In the traction calculation, the lowest catenary voltage consumption can be checked to confirm that it is in the range of standard requirement under operation abscission and load with peak hour (the departure density of train is 30 per hour); in addition, the capacity of traction substation is calculated under operation abscission, load with peak hour, and overload coefficient of rectifier unit (considered with the overload of 150 % and two operation hours).

As depicted in Fig. 32.3, the power supply calculation on DC system mainly includes traction calculation module and power calculation module. The major

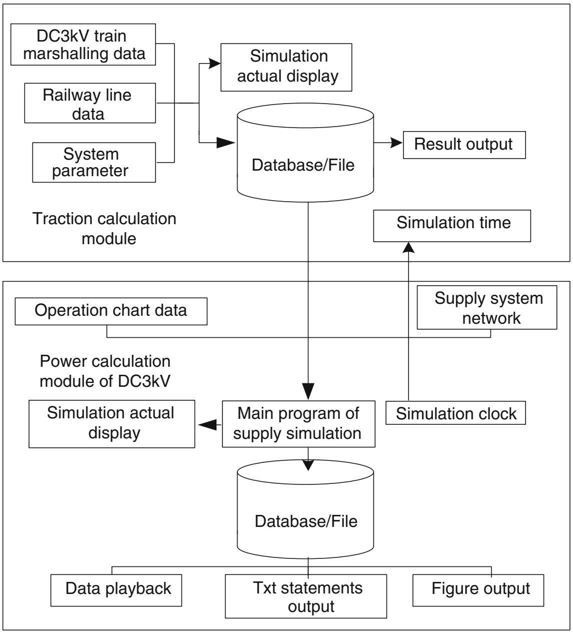

Fig. 32.3 Structure on DC 3-kV power supply calculation system

functions in traction calculation module include vehicle parameter editor, line editor, train operation simulation, energy consumption calculation, output of result report; the major functions of power calculation module include train diagram editor, operation simulation of train group, structure module of DC 3-kV system, power supply simulation module, and result output module.

32.5 Calculation for Power Supply System in Urban Railway

Take certain line of Shenzhen subway, for example, where the overall line length is 27.7 km and the amount of stations is 16, and the vehicle marshaling of Shenzhen metro line 5 is adopted to carry out power supply calculation. In the calculation section, considering that many rampway intervals exist and distances between a few adjacent stations are too large, the amount of substations is selected as 13 and it includes 2 interval substations, where the power supply calculation module is seen in Fig. 32.4. To study the performance of DC 3-kV urban railway traction system, the comparison calculation between DC 3- and DC 1.5-kV systems is carried out under the same line condition.

In the DC 1.5-kV system, the distances between a few adjacent stations are long, and it is necessary to set interval substation. Considering the factors regarding rail potential, it is feasible to adopt 13 substations in DC 1.5-kV system (including two interval substations). As the DC 3 kV mode is adopted, the scheme of 8 substations is selected through comparison. Compared with DC 1.5-kV system, the distance between average substations is around 4 km, improving by 1.8 times, and the substation installation capacity is reduced from 43.05 MVA into 38 MVA. Through traction calculation, the distribution curves of catenary voltages and rail potentials at

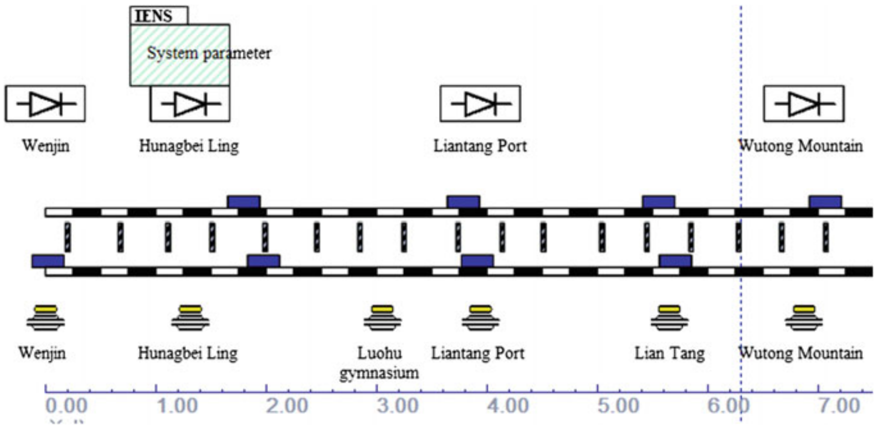

Fig. 32.4 Interface of power supply calculation module

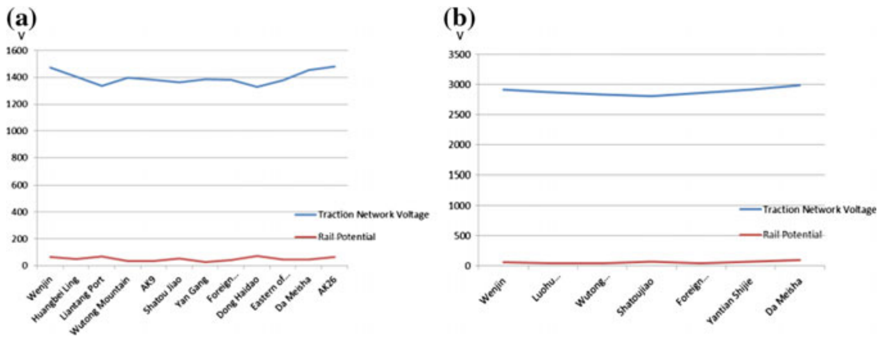

Fig. 32.5 Catenary voltage and rail potential under different power supply modes. **a** DC 1.5-kV system. **b** DC 3-kV system

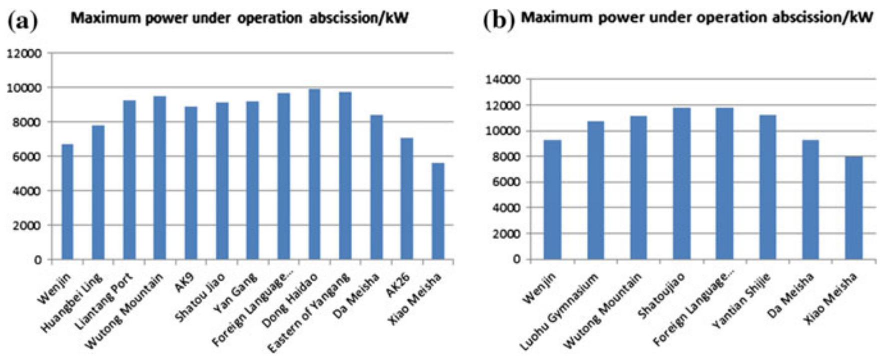

Fig. 32.6 Comparison on maximum power under different power supply modes. **a** DC 1.5-kV system. **b** DC 3-kV system

all stations under DC 1.5-kV system and DC 3-kV system are, respectively, obtained as depicted in Fig. 32.5a, b. In the scheme of DC 1.5-kV system, the minimum catenary voltage is 1329 V and rail potential is below 60 V basically; in the scheme of DC 3-kV system, the minimum catenary voltage is 2804 V, rail potential is around 60 V, and the maximum rail potential is only 100 V. Considering that the restriction standard of rail potential is 120 V, the design requirements are satisfied in both DC 1.5-kV system and DC 3-kV system.

In addition, maximum powers of DC 1.5-kV system and DC 3-kV system under operation abscission are, respectively, obtained through calculation, which are described in Fig. 32.6a, b. Obviously, the maximum power are, respectively, close to 10,000 and 12,000 kW. Combining with appropriate overload coefficient, the recommended design capacities of single unit in DC 1.5-kV system and DC 3-kV system are, respectively, depicted in Tables 32.2 and 32.3.

Table 32.2 Power supply design project of DC 1.5-kV system

Substation	Wen Jin	Huangbei Ling	Liantang Port	Wutong Mountain	AK9	Shatou Jiao	Yan Gang
Recommended capacity (kW)	2500	3300	3300	4000	3300	3300	3300
Substation	Foreign language institute		Dong Haidao	Eastern of Yangang	Da Meisha	AK26	Xiao Meisha
Recommended capacity (kW)	4000		4000	4000	3300	2750	2000

Table 32.3 Power supply design project of DC 3-kV system

Substation	Wen Jin	Luohu Gymnasium	Wutong Mountain	Shatou Jiao
Recommended capacity (kW)	4000	5000	5000	5500
Substation	Foreign language institute	Yantian Shijie	Da Meisha	Xiao Meisha
Recommended capacity (kW)	5500	5000	4000	4000

32.6 Conclusion

The calculation of DC traction power supply system has great significance in the design of urban railway power supply system. Aiming at the introduction of DC 3-kV power supply system in domestic urban railway, by combining with certain line of Shenzhen subway, this paper carries out corresponding feasibility calculation and analysis elaborately, and the following conclusions are obtained: Compared with the DC 1.5-kV system, the distance between average substations is improved by around 1.8 times, the amount of substations is reduced from 13 substations into 8 substations, and the length of each feeding arm is longer in the DC 3-kV system; besides, the maximum rail potential is only 100 V in the DC 3-kV system, which is lower than the restriction standard of rail potential. Combining with the substation maximum powers under operation abscission of DC 1.5-kV system and DC 3-kV system, corresponding recommended design capacities of single unit under operation abscission are, respectively, obtained. Based on the calculation result and economy, the feasibility and superiority of DC 3-kV system are proved.

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