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Feasibility Study on the Medium-Low-Speed Maglev Power Supply of DC 3-kV System Considering Train Acceleration

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Abstract

The DC (direct-current) 750V or DC 1500V power supply systems is currently adopted for the medium-low-speed (MLS) maglev, achieving a maximum train operational speed of 140 km/h. There are plans to increase this speed to between 160~200 km/h; however, it will result in higher energy consumption and higher positive rail (PR) voltage losses. To address these challenges, the increase of the power supply voltage to DC 3 kV is considered. This increase would enhance the power supply capacity, reduce the required PR current and decrease the number of necessary substations, allow for thinner PR rails and lower economic costs. Taking the Xinzhu Maglev Line in Chinese Chengdu, as a case study, this paper constructs a MLS maglev power supply system model. Considering different train running states of accelerating, coasting and braking, this paper conducts a comparative analysis of PR voltage losses and PR currents across DC 0.75 kV, DC 1.5 kV, and DC 3 kV systems when the train speed is increased to 160~200 km/h. Then, design distances between adjacent substations of three power supply voltage levels are compared; and train braking intensity is considered to analyze the influence patterns of power supply voltage levels on the braking over-voltages.

Keywords: DC 3 kV, medium-low-speed maglev, positive rail voltage loss, positive rail currents, substation, train speed, braking.

1 Introduction

Medium-low-speed (MLS) maglev technology is a promising solution for urban transportation due to its advantages of low noise, low vibration, low maintenance costs, low electromagnetic interference and so on. Currently, the maximum train operational speed of MLS maglev line is approximately 140 km/h. As urbanization continues to accelerate, there is a growing demand for higher-speed MLS maglev lines. Specifically in China, there is an ambition to enhance the speed of MLS maglev train to a range of 160~200 km/h. However, increasing the speed introduces several technical challenges: One is that the standard low-voltage of present maglev DC (direct-current) traction grid limits the train acceleration capability and induces the traction grid line voltage loss [1]. Adopting a DC 3 kV system instead of prior DC 750V or DC 1500V system has been identified as a potential solution to support the higher energy demands and mitigate line supply voltage loss.

Some scholars have studied the application of a DC 3 kV traction grid system [2-5]. The main focus has been on energy conservation and the regenerative inverter [2] or energy storage system [3] has been studied in detail to achieve this goal. Ref. [4] proposed two topology design schemes for DC 3 kV substations tailored to the traction power grids in Netherlands and it aims to improve traction power supply efficiency by recuperating braking energy that would otherwise be lost as heat. Additionally, some scholars moved beyond the current urban rail systems to theoretically study the combination of DC 3 kV systems and renewable energy from an energy-saving perspective [5]. Very few scholars have specifically analyzed and compared the differences of power supply capacity between the railway line before and after using DC 3 kV system [6]. Relevant research shown that higher voltage can effectively reduce energy loss and traction grid voltage loss, which helps shorten the distance between adjacent substations and consequently reduces substation construction costs. However, these findings are mostly derived from conventional railway scenarios. There is a lack of research about maglev system. The distinctive characteristics of maglev systems, such as their unique electromagnetic propulsion and levitation requirements, necessitate a tailored approach to evaluating the feasibility and benefits of adopting DC 3 kV system.

Establishing models for derivation or simulation has long been a common research approach for studying the power supply characteristics of rail transit systems. However, there are relatively few studies focused on the modeling of MLS maglev system. Existing analyses mainly concentrate on energy saving [7-8], including the application of braking resistance and super-capacitor energy storage devices, as well as the optimization of operational diagrams. In recent years, some scholars have attempted to establish detailed vehicle-grid models to study the electrical grounding of MLS maglev ower supply systems, but these studies did not consider the DC 3 kV system [9].

In summary, there are currently two gaps in the research on the application of DC 3 kV system in urban rail transit systems:

(1)Relevant research has not comprehensively considered the train's operating states during accelerating, coasting, and braking. When the train accelerates, the power supply voltage will drop significantly, and during braking, braking over-voltages may occur. If a DC 3 kV system is used to replace the traditional 0.75 kV and 1.5 kV DC systems, it is necessary to consider different train running scenarios.

(2)There has been no research on the application of DC 3 kV system in the MLS maglev line. The MLS maglev is different from traditional metros with a wheel-rail system, as it adopts a linear induction motor (LIM). The train body is suspended on the F rail and train is driven by electromagnetic force. This introduces differences, such as the motor air gap of the maglev being relatively larger. It leads to a decrease in the feedback braking electric power as motor air gap increases [10].

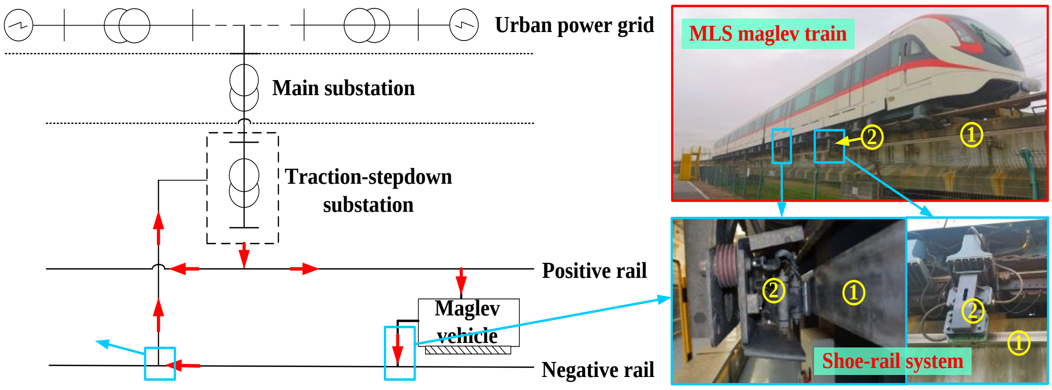

Figure 1: Diagram of MLS maglev electrical power grid system. ①: NR. ②: negative shoe.

This study aims to fill the above gaps in existing research by conducting a detailed analysis of the application of a DC 3kV system for MLS maglev lines. As shown in Figure 1, the MLS maglev train obtains electrical energy from the positive rail (PR) through the shoe-rail system, and the PR from the substation to the train position will carry voltage loss (i.e. traction grid voltage loss). Using the Chengdu Xinzhu Maglev Line in China as a prototype, this paper considers the situation where the speed of MLS maglev increases to 160~200 km/h. It compares and analyzes the DC 3 kV, DC 1.5 kV, and DC 0.75 kV systems from the perspectives of power supply capability, economic efficiency, and electrical safety, and further studies the reliability of the DC 3 kV system. Firstly, a detailed model of the maglev vehicle-grid traction power supply system is established. Then, focusing on different traction voltage levels, simulations are performed to compare the PR voltages and currents during train traction, coasting and braking. The advantages of DC 3 kV relative to DC 0.75 kV and DC 1.5 kV are evaluated based on safety standards. Subsequently, the permissible distance between adjacent substations is analyzed for different systems applied to the Xinzhu line. The impact of train speed on braking over-voltages under different systems is specifically analyzed.

2 Modeling scheme

The Xinzhu MLS maglev test line is an embedded maglev transportation system with a total length of 3.6 km. The line has two substations, but only one is in use. Due to the high leakage resistance of the negative rail (NR) to the ground and the absence of a drainage system, the line adopts a unilateral power supply system. Based on the traction power supply system of the Xinzhu line, a vehicle-grid model of the Xinzhu line is constructed using MATLAB. The leakage resistance of the NR to the ground per unit length is 10^7 Ω/m. Since the contact rail material is a steel-aluminum alloy with a rail area of about 82 cm^2, the unit-length resistance R_t is 0.1628 Ω/km.

In the running process of the MLS maglev train, frequent acceleration and deceleration are required, and the traction current often rapidly changes in a large range. In addition, the current direction of the reflex system also changes when the train position varies or state of braking starts. Above reality presents that DC rail transit system contains AC properties. To obtain simulation results to great precise, except for the resistance parameters, the contact rail inductance (L_0), contact rail capacitance-to-earth (C_0) and coupling conductance between PR and NR (C_{12}) are also considered in the modeling procedure. L_0 is considered equal to $\mu/8\pi$, where μ is the rail permeability and C_0, C_{12} are calculated by

$$\begin{cases} C_0 = \dfrac{2\pi\varepsilon_0}{\ln\left(2h_0/r_0\right)} \\ C_{12} = \dfrac{2\pi\varepsilon_0}{\ln\left(D_{12}/d_{12}\right)} \end{cases} \tag{1}$$

where $\mathcal{E}_0$ is the rail dielectric coefficient, h_0 is the rail height, r_0 is the rail radius, d_{12} is the distance between PR and NR, D_{12} is the distance between PR and image of NR.

The maglev train consists of three TBs, while each TB carries two pairs of collector shoes, as depicted in Figure 2. The latter presents the electrical structure and equipment layout of the maglev train. The train is suspended by a combination of multiple electromagnet coils, while the electromagnetic force is generated by a short stator LIM [11]. The LIM rotor distributed on the running track corresponds to the expanded secondary side of the rotating motor. A traction drive system is considered in the modeling. In the Xinzhu line, the inverter uses constant slip frequency control mode, and each TB carries five suspension frames. One LIM stator and two inverters are equipped on each suspension frame. The output rated power and output frequency range of LIM are 68.3kVA and 4kHz, respectively. For the LIM, the air gap length is larger which brings about larger excitation consumption and the additional end-effects exist, compared to the rotating motor. They result in a lower power factor and efficiency [12-13]. The power factor and efficiency are respectively 0.65 and 0.6, for the Xinzhu line. In the modeling, motor is equivalent approximately by rotating motor module, on the premise of ensuring that its input and output characteristics are consistent with the on-site actuality of LIM. In addition, the resistance of wire connection between adjacent TBs is considered. Note that a copper wire having an area of 120 mm^2 is considered. Figure 3 illustrates the developed vehicle-grid model, which considers the NR grounding pattern of the Xinzhu line.

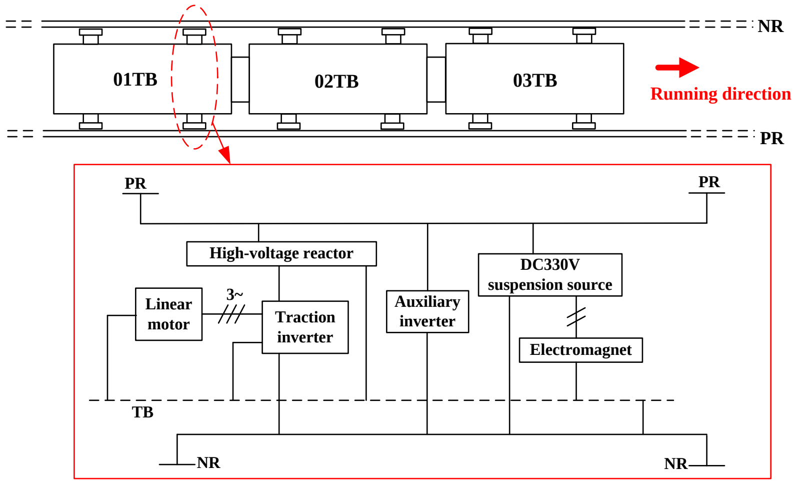

Figure 2: Electrical structure and equipment layout of MLS maglev train.

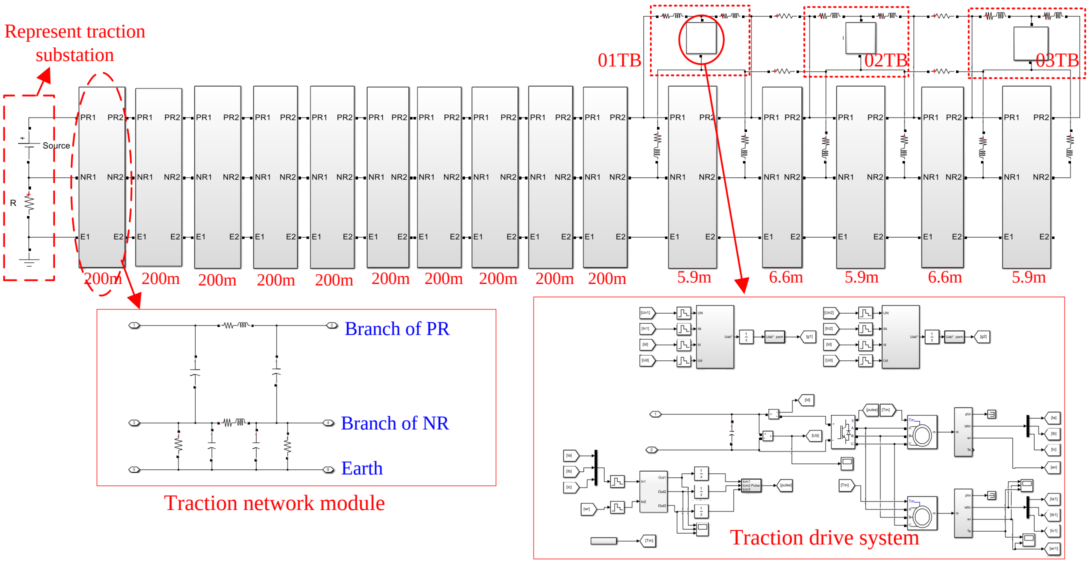

Figure 3: Grid-vehicle model of MLS maglev.

3 Results

3.1 Simulation and comparison of unilateral power supply modes

Based on the built model of Xinzhu maglev line, we analyze the PR voltage losses (denoted as ΔU) and PR currents (denoted as I) corresponding to the single-sided power supply modes of 0.75 V DC, 1.5 kV DC, and 3 kV DC. The analysis considers acceleration, where the train speeds up from 180 km/h to 200 km/h; coasting, where the train travels at a constant speed of 180 km/h; and braking, where the train decelerates from 200 km/h to 180 km/h. Table 1 presents the comparative results. Here, the lower percentage under acceleration indicates the maximum percentage decrease in PR voltage relative to the substation voltage at the train location; the lower percentage under coasting indicates the stable decrease percentage in PR voltage relative to the substation voltage at the train location; and the rise percentage under braking indicates the percentage increase in the highest voltage relative to the substation voltage during the braking process.

			DC 0.75 kV	DC 1.5 kV	DC 3 kV
ΔU	Accelerating	Amplitude [V]	274.7	328.4	510.4
		Lower percentage [%]	36.62	21.89	17.01
	Coasting	Amplitude [V]	70.9	121.3	231.3
		Lower percentage [%]	9.45	8.09	7.71
	Braking	Amplitude [V]	90	148	190.4
		Rise percentage [%]	12	9.87	6.35
I	Accelerating	Amplitude [V]	2202.4	1567.2	696.4
	Coasting	Amplitude [V]	151.8	90.4	46.9
	Braking	Amplitude [V]	367.8	274.9	146.2

Table 1: Traction grid voltage losses and PR currents under different running scenarios and different supply voltage levels.

According to Table 1, regardless of acceleration or coasting states, the higher the supply voltage results in the lower PR voltage loss (the maximum percentage of voltage loss for 0.75 kV, 1.5 kV and 3 kV DC system under acceleration are 36.62%, 21.89%, and 17.01%, respectively, and under coasting conditions in order are 9.45%, 8.09%, and 7.71%); under braking conditions, the higher the supply voltage causes lower maximum traction grid voltage rise (the maximum percentage of voltage rise for DC 0.75 kV, DC 1.5 kV, and DC 3 kV in order are 12%, 9.87%, and 6.35%). When the train runs 3.6 km from the substation and the speed increases from 180 km/h to 200 km/h, if the DC 0.75 kV supply system is still used, the lowest PR voltage at the train location is only 475.3 V, below the GB50157-2003 [14] and IEC 60850 [15] standards. Additionally, according to Table 1, the higher supply voltage level leads to the lower maximum PR current, stable PR current, and floor PR current corresponding to acceleration, coasting, and braking, respectively.

3.2 Comparison of distances between adjacent traction substations

Considering the limitations on PR voltage loss specified in GB50157-2003 and IEC standards, we analyze the permissible distances between adjacent traction substations for different maximum train target speeds. Simulation analysis is based on the vehicle-grid electrical parameters provided in Chapter 2 for the Xinzhu Maglev Line, and the results are presented in Table 2. It can be observed that, after the maximum target speed reaches 200 km/h, the DC 3 kV system allows for a distance of up to 5.6km between adjacent substations, significantly exceeding the distances corresponding to the other two systems, which can greatly reduce the construction cost of substations. As the supply voltage level increases, the impact of the target speed on the permissible distance between adjacent substations decreases.

		160 km/h	170 km/h	180 km/h	190 km/h	200 km/h
Supply voltage level	0.75 kV	3.7 km	3.1 km	2.6 km	2.2 km	1.9 km
	1.5 kV	5.0 km	4.6 km	4.2 km	3.9 km	3.7 km
	3 kV	6.3 km	6.1 km	5.9 km	5.7 km	5.6 km

Table 2: Traction grid voltage losses and PR currents under different running scenarios and different supply voltage levels.

3.3 Comparison of traction grid voltage rises under braking scenarios

During the operation of MLS maglev trains, frequent braking is often necessary. During braking, the PR voltage rises easily result in vehicle-grid over-voltages, insulation failure and deterioration of power quality. Thus, the braking of train must be further considered based on the prior application analyses. Here, the braking states are considered when the train abruptly decelerates from speeds of 140, 150, 160, 170, 180, 190, and 200 km/h to 100 km/h. A comparative analysis is conducted to evaluate the voltage rise during these braking processes under the three supply voltages. Table 3 provides the maximum voltage rise values corresponding to different braking intensities for 0.75 kV, 1.5 kV and 3 kV systems, while Figure 5 illustrates the corresponding percentage of voltage rise (i.e., the percentage increase in the highest grid voltage relative to the substation voltage). According to the results, the impact of braking intensity on the voltage rise is related to the supply voltages, with higher voltage levels experiencing less pronounced effects.

	DC 0.75 kV	DC 1.5 kV	DC 3 kV
140 km/h to 100 km/h	1.4 V	3.9 V	2.9 V
150 km/h to 100 km/h	8.2 V	12.2 V	7.4 V
160 km/h to 100 km/h	23.4 V	28.0 V	14.9 V
170 km/h to 100 km/h	46.4 V	48.6 V	30.8 V
180 km/h to 100 km/h	74.7 V	86.5 V	67.9 V
190 km/h to 100 km/h	108.8 V	138.6 V	115.8 V
200 km/h to 100 km/h	152.5 V	202.7 V	202.2 V

Table 3: Maximum PR voltage rise when maglev train brake from different speeds to 100 km/h under different traction supply voltage modes.

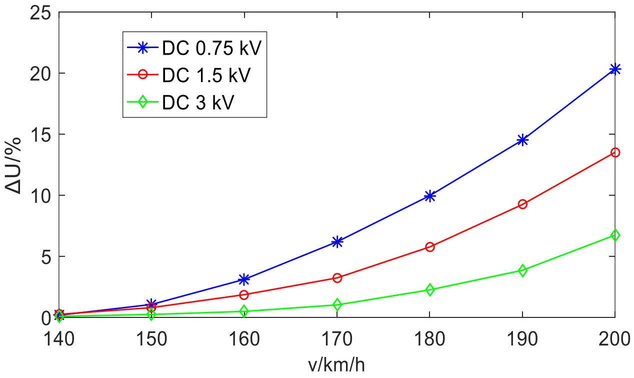

Figure 5: Percentages of exceeding standard voltage of different supply voltage levels under braking state.

4 Conclusions and Contributions

This paper addresses the application prospects of increasing the speed of MLS maglev trains to 160~200 km/h. Considering that the current DC 0.75 kV and DC 1.5 kV power supply systems used by MLS maglev lines may not meet the speed-up requirements, a study on the adaptability of the DC 3 kV system for train speed-up is carried out. Taking the typical MLS maglev line (Chengdu Xinzhu Maglev Line) as a prototype, a detailed traction power supply system model was built, taking into account the impact of different train operating states (acceleration, deceleration and coasting). A comparative analysis of the power supply capacity, construction economics and electrical safety under different supply voltage levels after speed-up was conducted. Compared to DC 0.75 kV and DC 1.5 kV system, the conclusions regarding the DC 3 kV system are as follows.

(1) Under the conditions of train traction operation or coasting operation, if the cross-sectional area of the contact rail is kept unchanged, the use of the DC 3 kV system significantly reduces the PR voltage loss and PR current, indicating that the DC 3 kV system has stronger electric power supply capacity. Transforming the existing maglev line system to DC 3 kV can reduce the number of substations, saving costs. Additionally, the contact rail cross-sectional area can be designed smaller according to the contact rail current-carrying capacity, further saving costs.

(2) In the case of train braking, the impact of braking intensity on the PR voltage rise is related to the power supply voltage level; the higher the voltage level results in the smaller impact. Considering the suppression of braking over-voltages, the DC 3 kV system also has advantages over the other two power supply modes.

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