High-Speed Maglev Train Battery Design Considering of the Position of Assist Stop Areas

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Abstract. With the increase of the operation speed in the high-speed maglev railway system, the distance between the assist stop areas can be increased. To ensure the safe operation between the two assist stop areas, the capacity of the onboard storage battery in maglev trains shall be redesigned. This paper derives the distance between the assist stop areas in different operation speed, which generate the speed curves for calculating the minimum battery capacity required for operation. We analysed the capacity requirements of the maglev battery at the different commercial operation and maintenance operation speed, as well as the impact of the battery capacity to the location design of the assist stop area, which can provide the guidance to the design of the onboard battery capacity in high-speed maglev train.

1. Introduction

With the application of the magnetic levitation technology, the high-speed maglev train can eliminate the wheel friction and operate at over 400 km/h, which becomes the direction of the future development in the railway transportation industry. The high-speed maglev system requires the assist stop areas (ASAs) to operate seamlessly, while the location design of ASA is the foundation of the stepping control in maglev operation [1-3]. By increasing the operation speed, the distance between the ASAs can be expanded [4]. During the operation of the maglev trains, the onboard storage battery is one of the critical components for providing energy to the levitation and guiding devices. The capacity of the onboard storage battery is critically vital in the maintenance operation between the assist stop areas, as the levitation failure accident may occur if the ASA distance is too large and cause the low battery level. Therefore, the location design of the ASA should consider the battery capacity of the high-speed maglev trains.

The capacity of the onboard battery is directly correlated with the placement of the ASA. Researches have been done on the location design of the ASA. [5] purposed a calculation method by establishing a kinetic model for the dynamic operation of the maglev trains. The ASA location was calculated at different operation speed, which derived the conclusion that the distance between the ASAs can be increased when a higher operation speed is applied. [6] proposed an algorithm for deriving the location of ASA based on the reference operation speed curve. The ASA placement study was carried out on the same maglev line with different operation speed.

So far, the existing research does not consider the impact of the capacity of onboard battery on the ASA distance. In this paper, the minimum battery capacity is calculated by deriving the maintenance operation speed curve at the different operation speed, which can provide the guidance for designing the capacity of the onboard storage battery in high-speed maglev trains.
2. Force and Operation Analysis

2.1. High-Speed Maglev Kinetic Model
The kinetic model of high-speed maglev train describes various external forces acting on the train along the running direction, including the traction force and braking force. The function of the kinetic model can be expressed as:

\[ F_p = F_e + F_s + F_m + F_i + F_f \]  \hspace{1cm} (1)

Where \( F_p \) is the traction force or braking force; \( F_e \) is the track induced eddy current resistance; \( F_s \) is the air resistance; \( F_m \) is the levitation resistance of the line induction motor; \( F_i \) is the resistance generated by slope; \( F_f \) is the friction force generated by the slide when applicable.

In the Shanghai Maglev system, the \( F_e, F_s, F_m, F_i \) and \( F_f \) are derived by the formulation below [5-11]:

\[ F_e = 2.8 \left( 0.53 \frac{N}{2} + 0.3 \left( \frac{v}{3.6} \right)^2 \right) \]  \hspace{1cm} (2)

\[ F_e = 1000N \left( 0.1v^2 + 0.02v^{0.7} \right) \]  \hspace{1cm} (3)

\[ F_m = \begin{cases} 
0 & (0 \leq v < 20) \\
7300N & (20 \leq v < 70) \\
N \left( 3.6 - \frac{146000}{v} - 200 \right) & (v \geq 70)
\end{cases} \]  \hspace{1cm} (4)

\[ F_i = \frac{MgL}{2} \]  \hspace{1cm} (5)

\[ F_f = 1000\mu Mg \sqrt{1 - \left( \frac{I}{1000} \right)^2} \]  \hspace{1cm} (6)

Where \( N \) is the number of carriages in a maglev train; \( v \) is the train speed in km/h; \( M \) is the mass of the train in kg; \( I \) is the track slope in \( 10^{-3} \); \( \mu \) is the friction coefficient between the train and track; \( g \) is the ratio of gravity to mass in N/kg.

Based on the train kinetic model, we can derive the following speed curves:
- Traction acceleration curve, which is the curve of speed changing with displacement when the train is in traction mode.
- Eddy current braking curve, which is the curve of speed changing with displacement when the train is in eddy current braking mode.
- Sliding braking curve, which is the curve of speed changing with displacement when the train is in sliding braking mode. [12]

2.2. Stepping Control
There are several ASAs on the high-speed maglev line; each has the corresponding safety braking curve and coasting curve. The operation control system of the high-speed maglev adopts the stepping control mode, which enables the train continuously move from one ASA to the next. Figure 1 is an illustration of the stepping control principle in the maglev system.
3. Onboard Storage Battery Consumption Analysis

3.1. Calculation of the Location of ASA

According to the principle of stepping control of the stop point, the speed of the train is always above the safety coasting curve of the next ASA, and below the safety braking curve of the current ASA. In Figure 1, the minimum stepping-control speed range can be derived by joining the safety braking speed curve, safety coasting speed curve and the train operation speed curve into one point. In this case, the spacing between two ASAs is the largest, and the number of ASAs between two stations is the least. The flow chart of setting the position of ASAs between two stations is shown in Figure 2.

Figure 1. Stepping Control in Maglev System [6]
Calculate ending point of the current ASA
Reverse calculation for the safety braking speed curve
Calculate the connection point of the safety braking speed curve and the train operation speed curve
Based on the connection point and the safety coasting speed curve, calculate the beginning point of the next ASA

If the end has reached?

NO

YES

Output locations of all the ASAs and the maximum gap distance

**Figure 2.** Flow chart for calculating the location of ASA

### 3.2. Calculation of the Maintenance Operation Speed Curve

After the emergency stop is triggered by a malfunction or protection of the maglev train, the train will stop in the current ASA. In order to ensure the safety, the train can apply the maintenance operation after the recovery, in which the maintenance operation speed is relatively low. The speed curve during the maintenance operation includes the following three stages:

1) Accelerate from standby to the maintenance operation speed;
2) Apply the maintenance operation speed for uniform running;
3) Apply the brake to reach the next ASA.

Based on the method illustrated in Figure 2, the maximum ASA distance, traction acceleration curve, eddy current braking curve and maintenance operation speed can be derived. Therefore, the maximum maintenance operation speed curve between the two ASAs can be obtained, which is calculated in Figure 3.
Input train maintenance operation speed, distance between two ASAs

Based on the maintenance operation speed, calculate the acceleration distance and the eddy current braking distance, the sum of the two distances is derived as the minimum distance

If the minimum distance is shorter than the ASA distance

YES

NO

Output the maintenance operation speed curve

Output the maximum operation speed

Figure 3. Flow chart for calculating the maintenance operation speed curve

3.3. Calculation of the Onboard Battery Consumption

During the commercial operation and the maintenance operation of a high-speed maglev train, the energy consumption of its levitation, guidance and on-board electrical equipment, including air conditioning and boiling equipment, is mainly provided by onboard linear generator and onboard storage battery. The energy balance equation is as follows:

\[ \text{Energy Balance Equation} \]

\[ W_{\text{lig}} + W_{\text{bat}} = W_{\text{xf}} + W_{\text{dx}} + W_{\text{sb}} \]  \hspace{1cm} (7)

Where \( W_{\text{lig}} \) is the output energy from the onboard linear generator; \( W_{\text{bat}} \) is the energy consumed from the onboard storage battery; \( W_{\text{xf}} \) is the energy consumption of the levitation devices; \( W_{\text{dx}} \) is the energy consumption of the guidance devices; \( W_{\text{sb}} \) is the energy consumed by onboard electrical equipment.

The output power of the onboard linear generator is related to the operating speed of the train. The simplified formula for calculating the output energy is:

\[ W_{\text{lig}} = \int_{t_0}^{t_{\text{wh}}} (av^2 + bv + c) dt \]  \hspace{1cm} (8)

Where \( a, b \) and \( c \) are constant coefficients; \( t_{\text{wh}} \) is the train maintenance time duration in hours.

The formula for deriving the energy consumption of the onboard storage battery is:

\[ Q_{\text{bat}} = \frac{(P_{\text{xf}} + P_{\text{dx}} + P_{\text{sh}}) \cdot t_{\text{wh}} - W_{\text{lig}}}{U_{\text{bat}}} \]  \hspace{1cm} (9)

Where \( Q_{\text{bat}} \) is the energy consumed from the onboard battery in Ah; \( P_{\text{xf}} \) is the consuming power of the levitation devices in kW; \( P_{\text{dx}} \) is the power consumption of the guidance devices in kW; \( P_{\text{sh}} \) is the power of the onboard electrical devices in kW; \( U_{\text{bat}} \) is the voltage of the onboard storage battery in V.

The \( P_{\text{xf}}, P_{\text{dx}} \) and \( P_{\text{sh}} \) can be obtained from the site measurement on maglev trains.

4. Calculation Result and Analysis

In this paper, a straight line with a length of 50km is used to calculate the location of the ASAs. By setting the commercial operation speed as 200 k/h and the length of the ASA is 200 m, the location of the ASAs can be calculated.
As shown in Figure 4, when a 50km high-speed maglev line is operating at a commercial speed of 200km/h, the number of ASAs to be set should be at least 6, and the maximum spacing between ASAs is 9.658km.

According to the maximum ASA spacing of 9.658km, the maintenance operation curve is calculated by using different maintenance operation speeds, which is used for deriving the energy consumption of onboard battery, shown in Figure 5.

Based on Figure 5, we can get the following conclusions:

- Considering the safety of maintenance operation, the maintenance speed should not be too high. When the commercial operation speed is 200km/h and the maintenance operation speed is 100km/h, the design capacity of the onboard battery should be at least 9.17 Ah. When the maintenance speed is 110km/h, the design capacity of the on-board battery should be at least 8.32 Ah.

- The higher the maintenance speed, the lower the battery consumption. This is because the output power of the onboard linear generator is directly related to the operation speed. The higher the maintenance running speed, the greater the output power of the on-board linear generator. When the output power of the on-board linear generator exceeds the consumption power of the levitation, guide and onboard electrical devices, the onboard battery can be charged. Therefore, the battery consumption becomes smaller during the maintenance operation.
• When a high-speed maglev train stops in the current ASA due to fault or protection, to ensure the safety, the maintenance speed selected for recovery operation must consider the remaining power of the current onboard. If the less onboard battery level is indicated, the train maintenance speed must be set to a higher value.

Another study case was carried out on the same test network with the commercial operation speed at 400km/h. By applying the same analysis, a 50km high-speed maglev line needs to have least 4 ASAs, and the maximum spacing between ASAs is 19.619 km. Table 1 is the comparison of the onboard battery power consumption at different maintenance speed in 200 km/h and 400 km/h maglev system.

| Maintenance operation speed (km/h) | Commercial operation at 200km/h (Ah) | Commercial operation at 400km/h (Ah) |
|-----------------------------------|--------------------------------------|--------------------------------------|
| 80                                | 17.43                                | 30.58                                |
| 90                                | 12.45                                | 19.30                                |
| 100                               | 9.17                                 | 10.98                                |
| 110                               | 8.32                                 | 7.65                                 |
| 120                               | 7.57                                 | 4.83                                 |

In Table 1, when the commercial speed is 200 km/h, if the maintenance operation speed is 100 km/h, the design capacity of the onboard battery should be at least 9.17 Ah. If the maintenance speed is 110km/h, the design capacity should be at least 8.32 Ah. When the commercial speed 400km/h and the maintenance operation speed is 100km/h, the design capacity should be at least 10.98 Ah. If the maintenance speed is 110 km/h, the capacity should be at least 7.65 Ah.

This is because as the speed of high-speed maglev trains increases, the maximum spacing between ASAs will gradually increase. When the output power of the onboard linear generator is less than the sum of the consumed power of the overall onboard devices, the power consumed by the onboard battery will increase with the increase of the maximum ASA distance.

5. Conclusion
Based on the calculation and the analysis illustrated in this paper, we can get the following outcomes:

• The commercial operation speed and maintenance operation speed of the train must be considered when designing the capacity of the onboard battery of the high-speed maglev system.

• As the speed of commercial operation increases, the maximum distance between ASAs will gradually increase. When the output power of the onboard linear generator is less than the sum of the consumed power of the suspension device, guidance device and onboard electrical equipment, the design capacity of the onboard battery should be larger.

• When increasing the maintenance operation speed, the energy consumption of the onboard battery becomes lower. Therefore, before entering the maintenance operation mode, it is mandatory to validate the battery level of the onboard storage battery. When the onboard battery level is low, the maintenance operation speed should be increased to ensure safe operation.

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7. References
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