Optimization of Power Supply Section Planning in Medium-Speed Maglev System

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Abstract. The power supply planning of medium-speed maglev system (MSM) is related to line capacity greatly. To improving sectional through capacity , this paper takes the problem of dividing power supply zones of MSM as research object, i.e, the optimization of power supply planning. With the known number of zones, optimization object is maximum line capacity without consideration of generalized cost. Considering factors such as stator position in section, train speed profile characteristics, blocking time and blocking time overlap method, an optimization model of MSM stator combination is established. According to the given relative position of stators and target speed profile, a genetic algorithm is designed to obtain power supply plan that meets the target expectation. This method provides guidance for the future MSM power supply planning.

Keywords: Medium-speed maglev system; Power supply section; Headway time; Blocking time; Genetic Algorithm.

1. Introduction
As a form of city transportation, medium-speed maglev transportation has a great development prospect. MSM is different from wheel-rail system in motor form, traction power supply, etc. The ground power supply system uses long-stator linear synchronous motor, and each power supply zone is composed of stator segments as basic units. Since traction power supply engineering limitation, one power supply zone only allows one train occupying.

Wang\textsuperscript{4} analyzed the type of traffic organization with fixed block and mobile blocking signal system, then proposed a fixed line occlusion discrete model; Luan et al\textsuperscript{7} used the concepts of ‘blocking time’ to describe through capacity from a meso level; Tang\textsuperscript{5} proposed a tracking interval calculation method based on UIC406 principle; Liu et al\textsuperscript{2} proposed a method to calculate headway time based on moving block system. Wang\textsuperscript{1} employed virtual arc with the accumulated volume flow variables principles to describe the space-time tracks and designed a binary encoding way to achieve genetic operator, but rough variable size limited degree of optimization; With simulation line data from CRRC Tangshan Rolling Stock Co. Ltd, Lai\textsuperscript{15} considered factors like basic kinetic equation and double speed protection, and designed a dynamic programming method and a MILP method to optimize speed curve, the attribute values of speed curve ( time, velocity, position ) are key input data for stator division case in this paper. This paper aims to strengthen the through capacity of the medium-speed maglev section. Firstly, analyze the basic structure of the medium-speed maglev system. Secondly, develop the stator segment
combination optimization model under the condition of a given number of zones and design a genetic algorithm with specific operators. Finally, the applicability of the model is verified by case.

2. Problem Analysis
The concept of the MSM line structure, headway time, and blocking time are supplied for better description of stator planning problem.

2.1. Overview of MSM Line System Structure
The medium-speed maglev system includes: line system, operation control system, vehicle system, power supply system, safety guarantee system and communication system[^14]. Due to the fact that power supply system is a ground system, each section is divided into several power supply zones to provide kinetic energy for trains operation. Because of the limitation of traction power supply conditions, only one train can operate in one power supply zone. Therefore, when organize multi-train tracking, the quasi-mobile block system can greatly improve equipment and line capacity utilization. The stator segment is the part between feeder point and star ground point of the long stator[^8] It is the basic unit that constitutes the power supply zone. Each unit stator segment has designed length, so the power supply division problem is essentially a problem of permutation and combination of stator segments in the interval.

2.2. Blocking Time and Headway Time
The minimum tracking interval includes the station tracking interval (departure, arrival) and section tracking interval. According to Nikola Bešinović’s[^3] analysis of tracking interval, when organize multi-train tracking in sections, departure headway time is the theoretical minimum tracking interval in most cases, ie the optimization target variables. Employ blocking time to make quantitative description of temporal occupancy of train route traffic resources is efficient. Based on UIC406, which provides blocking time overlap method, we find limiting section for further calculation of the minimum hedway time. For details on the relationship of related variables, view the model building chapter.

3. Model
The division form of the power supply zone directly affects headway time, further affects the section through capacity. In the bi-rail and bi-directional maglev line system, train operation control unit is relatively independent. Based on this, under the condition that the number of power supply zones in section is known, a combination optimization model of stators is established.

3.1. Combination Optimization Model of MSM Stator
The following assumptions are made for the model: 1) The number of power supply divisions is the main factor of general cost, thus the generalized cost is relatively fixed. 2) The type of trains is the same and the target speed curve in the section is known, that is, attributes such as line slope, circular curve, auxiliary parking area location, train traction and suspension characteristics are not included in the model considerations. 3) Train operation control adopts tracking operation mode to organize train operation. 4) The length of each stator is known, the number of stators in each zone is integral.

3.1.1 Symbol Definition

| Symbol | Description |
|--------|-------------|
| $s_i$  | Relative location of stator, $i \in \{1, 2, 3 \ldots I+1\}$, $I$ represents sum of sators in section: The distance range of stator $i$ is $[s_i, s_{i+1}]$, $i \in \{1, 2, 3\ldots I\}$ |
| $\Delta s_i$ | Length of stator, $\Delta s_i = |s_{i+1} - s_i|$ |
| $sta_i$ | Stator $i$ in section, $i \in \{1, 2\ldots I\}$ |
| $j$    | Index of power supply zone, $j \in \{1, 2, 3\ldots J\}$, $J$ is the sum number of zones |
| sec $j$ | Dividing power supply zone, $j \in \{1, 2\ldots J\}$ |
3.1.2 Objective function. The model takes the minimum departure tracking interval as objective function, and uses the number of stators in each power supply scheme as a decision variable to obtain the set of power supply plan. According to blocking time obtained from the division scheme and the speed curve, the objective function is the minimum headway time:

\[ z = \min_{j} t_{f,j}^{\text{min \_H}}, j \in [1,J] \] (1)

3.1.3 Constraints and variable relations. The relationship between constraint conditions and variables is described from the aspects of line condition and train tracks.

1. Line condition

1) Basic variable relations. The total length of the section is equal to the sum of power supply zone:

\[ L_{\text{all}} = \sum_{j=1}^{J} L_{j}^{\text{sec}} \] (2)

The total number of stators in section is the sum of the stators in each power supply zone:

\[ I = \sum_{j=1}^{J} n_{j} \] (3)

2) Length constraint of power supply zone. The number of stators in each zone can be described as: \( n_{j} = |m_{j+1} - m_{j}| \). Each power supply zone needs to meet the length range constraint. The MSM system adopts a long-stator linear synchronous motor, and the length of zone must be greater than the length of the unit stator segment and less than the maximum specification length of the partition length provided by the traction power supply system. By Ding[14], \( L_{\text{max}}^{\text{sec}} \) is set a default value 2500 m, and \( \Delta s_{i} \) is assumed 500 m. Therefore, the maximum number of stators in each section is \( \delta_{i} \), and \( \delta = 5 \).

\[ \Delta s_{i} \leq L_{j}^{\text{sec}} \leq L_{\text{max}}^{\text{sec}}, i \in \{1,2\ldots I\}, j \in \{1,2,3\ldots J\} \]

\[ L_{\text{max}} \leq \sum_{i=1}^{5} \Delta s_{i}, k \in [0,J - 5], k \in N \] (4)
3) Mapping relationship between power supply partition and stator segment. Inspired by Wang\cite{1}, we set logical variables $\lambda_i$ for the stator segment nodes to describe the relationship between stator and power supply zone. $\lambda_i = 1, \ i \in \{1, 2... I\}$, which means the node $i$ is the divided node of zones. The number of power supply nodes is fixed, which can be expressed as:

$$J=\sum_{i=1}^{I} \lambda_i - 1$$  

(5)

The number of stators in the power supply zone is determined according to the specific plan:

$$n_j = \sum_{i=m_j}^{n_j} \lambda_i - 1$$  

(6)

![Figure 1. The sketch of stator binary sequence.](image)

### 3.2. Train Operation Control

According to the train target speed curve, characteristics of blocking time of each train in each zone can be obtained. Based on this, the restricted section (bottleneck section) under tracking operation is available, and minimum tracking interval is determined. The block time block of the tracked train in the interval includes: establishment of the route, reaction time of the drivers and signal equipment, running time of approaching route, running time, clearing time and route release time. Blocking time of the train in zone can be expressed as:

$$t_{\text{block}} = t_{\text{end}} - t_{\text{start}} = t_{\text{setup}} + t_{\text{approach}} + t_{\text{running}} + t_{\text{clear}} + t_{\text{release}}$$  

(7)

Then, let $\Delta t = t_{\text{setup}} + t_{\text{light}} + t_{\text{release}}$ represent the set of blocking Time empirical coefficients. The train speed profile of different trains is same, according to UIC406 method, $t_{\text{min, } H}$ can be organized with blocking time elements:

$$t_{\text{min, } H} = t_{\text{approach}} + t_{\text{running}} + t_{\text{clear}} + \Delta t = \frac{L_{\text{sec}, j}}{V_{j, f}} + \frac{L_{f}}{V_{j, f}} + \Delta t$$  

(8)

By calculating and comparing each blocking time in sections, the limit section is determined and further employ the train speed profile to calculate departure headway time.

### 4. Algorithm Design

Power supply planning is actually the result of permutation and combination of stator segments. Thus, the problem is reconstructed by introducing logical variables $\lambda_i$, and the node number adopts binary cascade coding, which makes the employment of genetic algorithm to realize the selection and arbitration process of feasible partitioning schemes have certain advantage. In the sectional through capacity optimization problem, the fitness is the minimum tracking interval time, which is the objective function of the model.

#### 4.1. Algorithm Process

The crossover process uses a single point crossover. While traversing population, if individual $a$ meets the crossover probability, it will randomly match another individual $b$ and random cross node band, then judge whether it meets the constraints: 1) Individual $a$ and $b$ have different sequence segments before
and after the cross node; 2) The number of stator segment nodes logical value equals 0 in the adjacent power supply partition nodes divided into 1 is less than four. The length of node band is set a default value and general view of cross process as follows:

![Figure 2. The sketch of cross process.](image)

The mutation process firstly traverses and selects individuals in the population, if the mutation probability is satisfied, 4 random mutation points are assigned, which consist of two pairs of the 0-1 and two pairs of the 1-0. The sum of logical variables of stator nodes that equals 0 in the adjacent power supply partition nodes divided into 1 is limited to be less than four.

5. Case Study

5.1. Data Preparation

Based on the medium-speed maglev simulation line data and train speed curve discrete data provided by Lai and CRRC Tangshan Rolling Stock Co., Ltd, a genetic algorithm is designed using the MatLab 2019 mathematical solver for verification. Total length of the section is 26154.0 meters containing 53 stator section. With unit distance step 100m, the speed profile based on given distance changes attribute values of time, speed, distance among per unit. The target speed curve is shown as follows:

![Figure 3. 3-D target speed curve.](image)

5.2. Results Analysis

In this case, some input parameters are given. The number of dividing zone in this case is 25, crossover operator equals to 0.8 and mutation operator value is 0.1. There are 25 individuals that iterate 1000 times in the process. And the corresponding plan of dividing stator serial nodes are shown:

\[
\text{div_index_best} = [1 \ 5 \ 7 \ 8 \ 9 \ 12 \ 13 \ 14 \ 15 \ 16 \ 17 \ 18 \ 22 \ 25 \ 29 \ 30 \ 32 \ 36 \ 38 \ 41 \ 43 \ 45 \ 48 \ 49 \ 50 \ 54];
\]

The fitness value of change point is shown in the following table:

| Iteration | 1     | 4     | 7     | 37    | 171   | 325   | 327   | 435   | 1000  |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Fitness(s)| 103.27| 98.89 | 98.47 | 96.55 | 95.01 | 94.47 | 94.35 | 93.04 | 93.04 |

![Figure 4. Fitness with 1000 iterations.](image)

With finite iteration, the minimum value of the headway time gradually decreases from 103.27 to 93.04, the optimized result is able to meet the target expectation. Therefore, using the stator segment sequence number to reconstruct the problem in the power supply planning optimization problem of the medium-speed maglev system can effectively realize the search for the optimization scheme and the iterative process of genetic algorithm.

6. Conclusion

To find a better way to describe the objective, it is traversed from maximum capacity to minimum
headway time and a binary sequence coding method is developed to describe the section with 53 stators and 25 power supply sections. A genetic algorithm is employed with 1000 iterations and get the relatively minimum headway time(93s). The result meets target expectation after certain times iteration. This method could provide a theoretical basis for the division of the power supply of the medium-speed maglev line in the future.

In particular cases, there will be situations where the number of power supply districts is uncertain, so it is necessary to consider the equilibrium game relationship between the generalized cost and the throughput capacity, which is also the content further to be studied.

Acknowledgements
The authors gratefully acknowledge financial support from the National Key R & D Program of China (Grant No. 2016YFB1200601).

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