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The research of automatic speed control algorithm based on Green CBTC

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Abstract. Automatic speed control algorithm is one of the core technologies of train operation control system. It's a typical multi-objective optimization control algorithm, which achieve the train speed control for timing, comfort, energy-saving and precise parking. At present, the train speed automatic control technology is widely used in metro and inter-city railways. It has been found that the automatic speed control technology can effectively reduce the driver's intensity, and improve the operation quality. However, the current used algorithm is poor at energy-saving, even not as good as manual driving. In order to solve the problem of energy-saving, this paper proposes an automatic speed control algorithm based on Green CBTC system. Based on the Green CBTC system, the algorithm can adjust the operation status of the train to improve the efficient using rate of regenerative braking feedback energy while ensuring the timing, comfort and precise parking targets. Due to the reason, the energy-using of Green CBTC system is lower than traditional CBTC system. The simulation results show that the algorithm based on Green CBTC system can effectively reduce the energy-using due to the improvement of the using rate of regenerative braking feedback energy.

1 Introduction

Train speed automatic control algorithm is one of the core technologies of automatic train control system, and it adjusts the train's acceleration and deceleration by the actual operation conditions to ensure the train operating safety, timely, stability and energy-saving[1]. Due to the characteristics of the automatic train control process, such as nonlinear, large hysteresis and high real-time, the function of automatic speed control is the most core and complex module of the automatic train control system. And it reflects the intelligence and control level of the automatic train control technology.

The function of automatic speed control is usually achieved by two modules: the target speed calculation module and the speed control module[2][3][4]. According to the timing, energy-saving precise parking and comfort target, the target speed calculation module calculates the target speed. The speed control module controls the train by the target speed and the current status of train[5][6].

The target speed calculation module is the basis for realizing the automatic train speed control, also the basis for automatic speed control module. Therefore, the control and economic index, which the automatic train operation can reach, are highly dependent on the target speed. And the flexibility of calculating the target speed determines the adaptive capability of the vehicle ATO.

The target speed calculation mode can be divided into two: off-line calculation and online calculation. The off-line one is not part of the ATO software, and it calculates the operating curve by the line conditions, train performance, control objectives and past control experience. At present, the on-board ATO uses the off-line calculation method mostly[8][9][10][11][12][13][14]. The online calculation is part of the automatic speed control module. It calculates the target speed online according to the line conditions, real-time train performance, control targets and past control experience.

The online calculation mode can obtain factors online, such as train status, train performance, line conditions and so on. So the calculation result has smaller difference with the actual operation result, thus reduce the control degree of difficulty for the automatic speed control module. At the same time, it can respond to various changes when train is operating, and make favourable adjustment to improve the intelligent degree of the automatic train control system and the intelligent degree of rail transit and the transport organization efficiency.

2 Green CBTC system

The most difference between the Green CBTC system and the traditional CBTC system is the energy-saving for train operation. The traditional CBTC system focus on the energy-saving of single train operation, and scholars in different countries have done a lot of research in this area. However, Green CBTC system focus on the energy-saving of all trains in the system.

The basic principle of the Green CBTC system is to ensure that the traction and braking rates of multiple trains are almost the same in a power supply arm at the same time. In this way, the traction train will make the voltage of catenary reduction, and the regenerative braking energy of the braking train is used to supply the energy used by the traction train. Thus, the regenerative braking energy of the braking train would not be waste according to the resistor braking.

Green CBTC system can not only improve the utilization of renewable energy, but also can effectively protect the braking resistance of the train to increase its service life. It is the next generation of train control system which assembles transportation organization, power supply, vehicles, lines and signal specialty.

Based on the existing automatic speed control algorithm, the automatic speed control algorithm based on Green CBTC system adds the voltage acquisition interface of power supply arm, which is used to calculate the target speed. In this way, the energy-saving of the whole Green CBTC system is realized by decentralized and self-regulation way.

3 Train operation state machine model

The automatic speed control algorithm divides the train operation state into the following kinds: stationary state, start-up state, automatic operation state and parking state.

- Stationary state: The train speed is 0;
- Start-up state: The process of the train enters automatic operation state from stationary state. When the train speed is greater than the configuration, the train will be judged that it has entered the automatic state
- Automatic operation state: In this state, the automatic speed control algorithm automatically control the train based on current speed, stop point, lines data, vehicle data, and voltage of catenary.
- Parking state：When the distance between the train and stop point is less then configuration, the train enters into this state. According to the stop point and current speed, the automatic speed control algorithm outputs braking command to make the train stop at the stop point accurately

In the process that the train departs from station or interval to stop, the automatic speed control algorithm control the train according to the train state machine, and the train state transition diagram is shown in Figure 1.

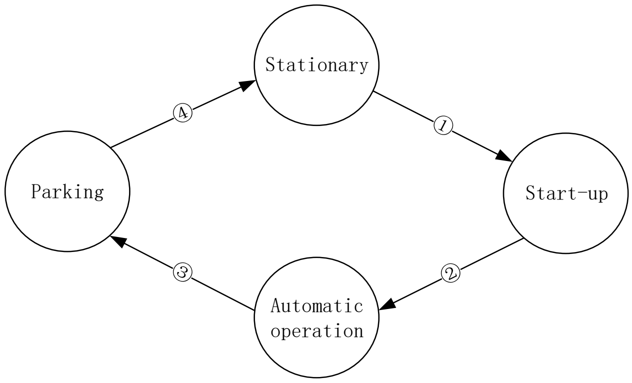

Figure 1: Train state transition diagram

The State transfer conditions are as follows:

① The train's speed is more than 0 km/h and less than the configuration speed;

② The train speed is more than configuration speed;

③ The distance between train position and stop point is less than configured distance.

④ The train's speed is 0 km/h.

During the operation process, the start-up state and park state take up a few time and distance, so the automatic speed control algorithm mainly through adjusting the braking and traction of automatic operation state to realize the energy-saving. So this paper will introduce the target speed calculation for automatic operation state.

4 Target speed calculation model

The target speed calculation model is the core of the automatic speed control algorithm and a typical multi-objective optimization control algorithm. According to the importance of different targets, the target speed calculation model is used to realize multi - objective optimization in a hierarchy computing model.

According to the requirement of railway operation organization, timing is level 1 control target which directly influence the operational efficiency under the premise of overspeed. The comfort target is realized by the traction and braking rate of the automatic speed control module. Therefore, the target of energy-saving is level 2 control target.

In conclusion, the target speed calculation module must first calculate the maximum permissible target speed, and then calculate the timing target speed, finally calculate the energy-saving target speed. After the calculation of target speed, using the speed control model controls the train traction and braking.

4.1 Maximum permissible target speed calculation model

The train operation process can be divided into three stages after braking command, as shown in Figure 2.

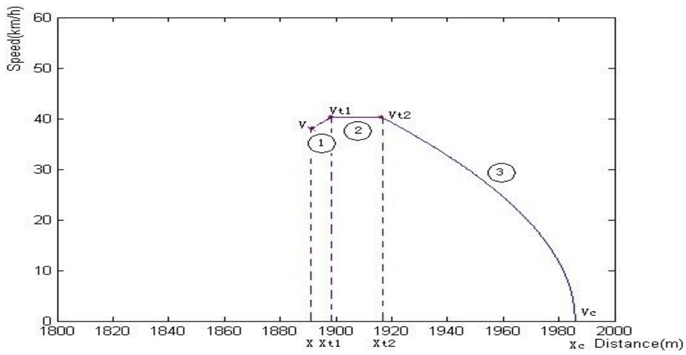

Figure 2: The braking curve of train

First stage（V → V_{t1}）: The braking command has been output, but the train is still keep the previous state in the range of response time, the time is described as t1;

Second stage（V_{t1} → V_{t2}）: Train traction has been cut off, the braking has not yet started, the time is described as t2;

Third stage（V_{t2} → V_c）: Braking supply before train stopped.

Among them, the time of the first and second stages depends on the current operation state of the train. If the train is currently in traction, it is necessary to consider the resection time of the traction and the response time of the braking command; If the train is currently in coast state and braking state, the response time of braking command only needs to be considered.

It is worth noting that not only braking force has worked, but also the basic resistance, tunnel resistance and curve resistance have worked in the train braking process. Since these are conducive to brake, they are not be considered in the calculation and used as safety margin.

Therefore, during the braking process, the considered external force is only traction and braking force. The energy conservation formula is as follows:

$$\begin{aligned} &E_k(X)+W_{traction}\left(X \rightarrow X_{t1}\right)= \\ &E_k(C)+W_q(X \rightarrow C)+W_{brake}\left(X_{t2} \rightarrow C\right) \end{aligned} \quad (1)$$

Where $E_k(X)$ is kinetic energy at braking trigger point; $E_k(C)$ is kinetic energy of speed limit point; $W_{traction}(X \rightarrow X_{t1})$ is the work by the traction force in the t_1 stage; $W_q(X \rightarrow C)$ is the difference of potential energy between the trigger point and the speed limit point; $W_{brake}(X_{t2} \rightarrow C)$ is the work by the braking force during third stage.

The formula (1) is a state of energy balance, which indicates that the current speed can be decreased below the limiting speed at the speed limit point by braking supply at trigger point. Therefore, the formula (1) is deformed, as shown below:

$$\begin{aligned} &W=E_k(X)+W_{traction}\left(X \rightarrow X_{t1}\right) \\ &-E_k(C)-W_q(X \rightarrow C)-W_{brake}\left(X_{t2} \rightarrow C\right) \end{aligned} \quad (2)$$

According to formula (2), if $W \geq 0$, it indicates that the current energy of the train exceeds the energy point, the braking need be supplied, and the maximum permissible target speed V_{top} should be the speed of speed limit point; if $W < 0$, it indicates that the current energy of the train is lower than the energy point, the braking is not necessary, and the maximum permissible target speed V_{top} should be the maximum operation speed.

4.2 Timing target speed calculation model

Timing target speed is calculated under the maximum permissible target speed. If the maximum permissible target speed is a limit speed of speed limit area, considering the first target is not overspeed, it need not to calculate timing target speed, and use the maximum permissible target speed as the target speed. If the maximum permissible target speed is the maximum operation speed, it needs to calculate the timing target speed.

The algorithm calculates the timing target speed by the remaining operation time, whether the final stop point is known, the position of the final stop point, the known speed limit area within the movement authorization and so on.

(1) Calculating the time of park state t_{park}:

$$t_{park}=\sqrt{\frac{2 \times S_{park}}{\overline{a_{park}}}} \quad (3)$$

Where S_{park} is the distance between stop point and braking supplied point; $\overline{a_{park}}$ is the average braking deceleration in park state.

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(2) Considering the train goes through the speed limit area at the limit speed, it can calculate the time which train goes through the ith speed limit area t_{sl_i} :

$$t_{sl\_i} = \frac{S_{sl\_i}}{V_{sl\_i}} \tag{4}$$

Where S_{sl_i} is the length of the ith speed limit area; V_{sl_i} –is the limit speed of the ith speed limit area.

(3) According to the current remaining operation distance and operation time, and the result of step(1)(2), it can calculate the actual and adjustable operation distance S_{left} and operation time t_{left}

$$S_{left} = S_{sp} - S_{train} - S_{park} - \sum_{i=0}^{n} S_{sl\_i} \tag{5}$$

$$t_{left} = t_{plan} - t_{used} - t_{park} - \sum_{i=0}^{n} t_{sl\_i} \tag{6}$$

Where S_{sp} is the position of stop point; S_{train} is the current position of the train; t_{plan} is planning operation time; t_{used} is the time has been used。

(4) Calculate the timing target speed

If actually adjustable operation distance S_{left} is less than 0, or operation time t_{left} is less than 0, it indicates that there has no adjust margin, then the timing target speed is the same as maximum permissible target speed.

If actually adjustable running distance S_{left} and running time t_{left} are both more than 0, the timing target speed V_{time} can be calculated:

$$V_{time} = \frac{S_{left}}{t_{left}} \tag{7}$$

If $V_{time} \geq V_{top}$, using V_{top} as the timing target speed, otherwise using V_{time} as the timing target speed.

4.3 Energy-saving target speed calculation model

Energy-saving target speed is calculated by two factors: the current voltage and the standard voltage of catenary. The algorithm calculates the energy change according to the difference between the current voltage and the standard voltage, and then calculates the energy-saving target speed through the train speed, line conditions, vehicle performance and so on.

Set the standard voltage is U_s , the standard current is I_s , the current voltage is U_k , according to the difference of voltages, it can calculate the current I_k :

$$I_k = \frac{(U_s - U_k) \times p}{L \times r \times \left(1 + \frac{1}{m^q}\right)} \tag{8}$$

Where p is the first parameter of feed method，unilateral feed method takes 2, bilateral feed method takes 4; L is length of power supply arm; r is the resistance value of the feed line and loop current line per kilometre; m is the number of trains in the power supply arm; q is the second parameter of feed method，unilateral feed method takes 2, bilateral feed method takes 1;

According to the standard voltage, standard current and the current voltage and current, it can calculate the energy difference change ΔW :

$$\Delta W = U_s \cdot I_s - U_k \cdot I_k \tag{9}$$

Considering the speed control cycle used for calculating the target speed is small(less than 200 ms), it can be assumed that the change of gradient is 0 during one speed control cycle. Then using the energy conservation model (1) to calculate the energy-saving target speed V_{energy} :

$$E_k(X) + \Delta W = E_k(C)$$

$$\frac{1}{2}\cdot m\cdot V_k^2+\Delta W=\frac{1}{2}\cdot m\cdot V_{energy}^2$$

$$V_{energy}=\sqrt{\frac{m\cdot V_k^2+2\cdot\Delta W}{m}} \qquad (10)$$

Taking formula (8) and (9)into formula (10), it can calculate the energy-saving target speed V_{energy} :

$$V_{energy}=\sqrt{\frac{m\cdot V_k^2+2\cdot\left(U_s\cdot I_s-U_k\cdot\frac{(U_s-U_k)\times p}{L\times r\times\left(1+\frac{1}{m^q}\right)}\right)}{m}} \qquad (11)$$

If $V_{energy}\geq V_{top}$， then set V_{top} as the energy-saving target speed; otherwise set the V_{energy} as the energy-saving target speed。

4.4 Target speed calculation model

According to the maximum permissible target speed, timing target speed and energy-saving target speed, it can calculate the target speed V_{target} :

$$\begin{cases} V_{target}=V_{top} & V_{time}\geq V_{top}\,||\,V_{energy}\geq V_{top} \\ V_{target}=\alpha\cdot V_{time}+\beta\cdot V_{energy} & V_{time}<V_{top}\,\&V_{energy}<V_{top} \\ \alpha+\beta=1 \end{cases} \qquad (12)$$

Where α is weight of timing target, β is weight of energy-saving target, they can be adjust by operational requirements.

5 Simulation and Analysis

In order to verify the automatic speed control algorithm based on greed CBTC system, this paper uses the type B metro vehicle and a part of Beijing Chang Ping metro line as basic data to simulate this algorithm. Part of the relevant data is shown in table1、table2、table3.

Table 1 Vehicle type and marshalling method

Vehicle type	Marshalling Method		Length of Train
B type	4 unit	2 motors and 2 trailer	81.2 m

Table 2 Relevant data of traction and braking

Main parameters	B type	
Acceleration	(0～40 km/h): ≥0.83 m/s^2 (0～120 km/h) ≥0.45 m/s^2	
Deceleration	Service Brake	Emergency brake
	1.0 m/s^2	1.2 m/s^2
Basic resistance	F = 0.000792 * V^2 + 0.025 * V + 3.74 F - N/KN; V - km/h	

Table 3 Other technical parameters

Parameter	Index
Tracking interval	180 s
Travel speed	≧ 30km/h
Numbers of vehicle on mainline	7
Dwell time	20 s – 40 s
Power feed method	Bilateral feed method
Voltage of power supply	750 VDC

Simulating the 7 vehicles circularly operating a route in order to compare the timing, precise parking and energy-saving of the traditional CBTC system and the Green CBTC system. The simulation process is shown in figure3 and the result is shown in table 4.

Figure 3(a) simulation process

Figure 3(b) simulation process

Table 4(a) Simulation result

Technical index	Traditional CBTC system	Green CBTC system $\alpha = 1$ $\beta = 0$
Timing rate	100%	100%
Precise parking rate	99.99%	99.99%
Overall energy consumption	2056.01 KW•h	1967.46 KW•h
Actual energy consumption	1607.49 KW•h	1529.45 KW•h
Regeneration braking energy utilization rate	27.40%	27.27%
Comfort	Good	Good

Table 4(b) Simulation result

Technical index	Green CBTC system	
	$\alpha = 0.786$ $\beta = 0.214$	$\alpha = 0.5$ $\beta = 0.5$
Timing rate	100%	95%
Precise parking rate	99.99%	99.99%
Overall energy consumption	1988.82 KW•h	1966.8 KW•h
Actual energy consumption	1462.15 KW•h	1412.72 KW•h
Regeneration braking energy utilization rate	31.72%	33.50%
Comfort	Good	Good

Through the simulation results in table 3, it can obtains the following conclusions:

Under the same technical index, the Green CBTC system can reduce energy consumption significantly, and improve the utilization rate of regenerative braking energy.

Different timing and energy-saving weight will affect the timing rate and energy-saving effect.

The greater the weight of energy-saving, the worst the timing rate, but the energy-saving effect will be better.

The Green CBTC system has no effect on precise parking and comfort.

According to the simulation results, setting the average price of industrial electricity in Beijing is 0.8 RMB, the operation time is 15 hours for one day, 7 vehicles for 3 minutes tracking operation. Compared to the traditional CBTC system, the Green CBTC system can save 2273532 KW•h, 1818800 RMB which is 9.94% of the total electricity fee.

6 Conclusion

Resource is increasing tense in nowadays society, energy-saving and emission reduction is the focus of attention by all the countries. As the energy-saving target of railway transportation, this paper proposes an automatic speed control algorithm, which is based on Green CBTC system. The algorithm uses decentralized and self-discipline, achieves the energy-saving for the whole system, breaking through the individual energy-saving research direction. Through the simulation analysis, the algorithm can greatly reduce the energy consumption for the whole system, and improve the utilization rate of regenerative braking energy. It has practical application value. However, the algorithm has not been put into practical application yet. Because of the actual factors, such as line conditions and train performance, there are some differences between the simulation results and the actual results. Therefore, the algorithm still needs to be tracked and adjusted, and further improved by practical application.

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