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Multi-objective operation optimization for electric multiple unit-based on speed restriction mutation

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ABSTRACT

The electric multiple unit (EMU) is a complex system running in dynamic environments. Satisfaction on real-time manual operation strategy of the EMU with respect to the multi-objective operation demands, including security, punctuality, accurate train parking, energy saving and ride comfort, depends on the drivers' experience and a given V–S curve (velocity versus position curve). To improve the operation strategy, a multi-objective optimization model of EMU operation is developed on the basis of dynamic analysis and speed restriction mutation. Using a modified particle swarm optimization algorithm, a Pareto optimal solution set is obtained by the online optimization of the EMU's operation strategy. Finally, according to the preference order ranking, an optimal operation strategy is sorted out from the Pareto set which satisfies the multi-objective requirements in real time. Experimental results on the field data of CRH380AL (China's railway high-speed EMU type-380AL) demonstrate the effectiveness of the proposed approach.

1. Introduction

The Electric Multiple Unit (EMU) provides passenger transport services in a complex and dynamic running environment. Since the services should simultaneously satisfy the multi-objective requirements of security, punctuality, accurate train parking, energy saving and ride comfort, how to optimize the EMU operation strategy is a multi-objective optimization problem (MOP). The objective of the MOP is to obtain satisfying operation strategies which can meet the multi-objective requirements from numerous operational approaches [1,2]. On the other hand, stochastic and paroxysmal changes in the environment, such as natural hazards or equipment failure of the railroads, lead to speed restriction mutation (SRM). Obviously, SRM causes many difficulties in solving the MOP of the EMU operation [3,4]. Moreover, the intense interaction effects among the EMUs caused by their high-density tracking arouse a higher requirement for the real-time performance of EMU operation. Further, as the automatic EMU operation has been a development tendency, it is critical that the operation strategies are totally reliable [5,6]. Consequently, the operation strategies of EMU not only should meet the multi-objective requirements, but also have real-time effectiveness.

In previous optimization research on EMU operation, energy consumption and punctuality were primarily considered as the optimization indexes. However, the requirements of accurate train parking and ride comfort, which are closely related with the security and quality of the transport services, were largely ignored. Furthermore, most of the previous studies were carried out offline. Aiming to address the optimization problem of EMU operation, an optimization model based on the optimization index of energy consumption was built in [7,15], while the other indexes are handled as constraints. However, they ignored the multi-objective requirements of the problem. A multi-objective model was established in [1], which considered the optimization indexes of energy saving, punctuality and accurate train parking after which a hybrid particle swarm optimization algorithm (PSO) was employed to optimize the operation strategies. Unfortunately, they adopted the weighted sum method to aggregate these optimization indexes into a single index, which sacrifices the balance and flexibility of optimization results. A multi-objective optimization model based on the indexes of punctuality, accurate train parking, energy saving and ride comfort was established in [8]. A modified differential evolution algorithm was adopted to solve the MOP of EMU operation in an off-line optimal way, so as to obtain the Pareto optimal solutions. However, there was no guarantee of the validity of their results in a dynamic environment.

It is well know that the multi-objective PSO (MOPSO) can efficiently obtain a Pareto solution set of the MOP, as well as be suitable for solving the MOP of EMU operation [9]. Considering the challenge of multi-objective planning of urban land-use, the MOPSO

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algorithm was adopted to optimize the arrangement of urban land uses in [10], and a Pareto set of land-use arrangements were obtained. Although their experimental results met the multi-objective requirements well, the efficiency of the MOPSO algorithm was lower as a result of the growing population. Fortunately, this problem can usually be solved by using reference points or preference information to guide the particles to a certain region of the Pareto Front [11,12]. For instance, the important relationship between objectives was used as preference information about the MOPSO algorithm in [12], and the effectiveness of the method was improved greatly.

In this paper, a multi-objective online optimization model is established, which based on the indexes of security, punctuality, accurate train parking, energy saving and ride comfort. Subsequently, the multi-objective online optimization of the EMU operation is realized by a modified MOPSO algorithm, which based on real-time data on the running process of EMU. Finally, based on the principle of balance and the preference order ranking, the optimal strategy is sorted out from the Pareto set.

The remainder of this paper is organized as follows: Section 2 briefly describes the dynamic analysis of the EMU. The multi-objective online optimization model and method of EMU operation are given in Sections 3 and 4, respectively. The experimental results and discussions are provided in Section 5. Finally, conclusions and future work are given in Section 6.

2. Dynamic model of the EMU running process

Fig. 1 describes the force acting on EMUs during the running process.

Based on the force analysis in Fig. 1, the dynamic model of the EMU's running process is established, as shown in the following equation [13]:

$$\begin{cases} C = u - w \\ w = w_0 + w_j \\ w_0 = a + by + cy^2 \\ w_j = w_i + w_r + w_s \end{cases} \tag{1}$$

where C is the resultant force, u is the controlling force, and $u > 0$ refers to traction (F_t) while $u < 0$ refers to braking force (F_b); w is the running resistance, which is composed of the basic resistance w_0 and the additional resistance w_j. Moreover, w_j mainly includes ramp resistance w_i, curve resistance w_r and tunnel resistance w_s; a, b, c are the drag coefficients [14].

Based on Eq. (1), the dynamics of EMU can be defined as follows:

$$\begin{cases} \dfrac{dt}{dl} = \dfrac{1}{v} \\ v\dfrac{dv}{dl} = u(c, v) - w(l, v) \end{cases} \tag{2}$$

where $l \in [0, L_0]$ is the location of EMU, L_0 is the station spacing, t is the running time of EMU; $v \in [0, V(l))$ is the running speed of EMU, $V(l)$ is the automatic train protection speed restriction (SR) at the location l. $c \in \{1, 0, -1\}$ is the operation state of EMU, and "1, 0, −1" refers to the operation state of traction, coasting and braking, respectively; $u(c, v)$ and $w(l, v)$ are the same as Eq. (1).

Fig. 1. Force analysis of the EMU's running process.

3. Multi-objective online optimization model for EMU operation

As mentioned above, the optimization of the EMU operation is a MOP, which should simultaneously meet the multi-objective requirements in a dynamic running environment. Therefore, a multiple-objective online optimization model (MOOM) is built to provide a quantitative basis for the study.

3.1. Optimization indexes of EMU operation

Accordingly, the optimization indexes for the MOP of the EMU operation, which include safety allowance, punctuality, energy consumption, accurate train parking and ride comfort, are detailed in Sections 3.1.1–3.1.5.

3.1.1. Safety allowance index

The safety allowance of the EMU running process is usually evaluated by the difference between the speed of the EMU and the SR [7,15]. Since the SR changes with changes in the running environment, the SR data are obtained from the driver machine interface (DMI) of the EMU in each sampling period dt. In this way, the calculation model of the safety allowance is established in real time, which is defined as follows:

$$f_v = \frac{1}{V(l) - v} \tag{3}$$

where $V(l)$ and v are the same as Eq. (2), f_v is the safety allowance index for the operation strategy. Obviously, the smaller the f_v is, the safer the running process of EMU becomes.

3.1.2. Punctuality index

The services provided by the EMU are strictly limited by the train timetable [7,15]. Accordingly, the difference between T (the actual inter-station running times of the EMU) and T_0 (the given time in the timetable) is taken as the punctuality index, which is defined as follows:

$$T = \sum_{1}^{N} dt, \quad N = 1, 2, \ldots, K \tag{4}$$

$$f_t = T - T_0 \tag{5}$$

where dt is the sampling period and k is iterations during the optimization process. The smaller the f_t is, the more punctual the services be.

3.1.3. Energy consumption index

The calculation of the energy consumed in traction is a basis for the optimization of the operation strategy. The energy consumption is closely related to the conditions of railway line, the EMU's traction characteristics and operation strategies and so on. Thus, in the case that the traction characteristics and line conditions are fixed, the objective of energy saving could be realized by optimizing the operation strategy. However, since the running EMU is a complex nonlinear system, it is difficult to directly calculate the energy consumed in traction of its running process. Consequently, the running process of the EMU is divided into numerous linear intervals. The traction energy of each interval and the whole section is shown in the following equations, respectively [16,17,22]:

$$E_i = F(v)\, dS(v, dt) \tag{6}$$