Hybrid tram energy management based on PMP

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Abstract. Dynamic programming is often used to solve the global optimization problem of hybrid energy storage tram. However, the amount of calculation is too large, resulting in the calculation time is too long. To solve this problem, an energy management strategy (EMS) based on Pontriagin minimum principle (PMP) is proposed. Through the analysis of Hamilton function, the optimal control path is obtained by solving the minimum value each time. The global optimization problem is changed into instantaneous, and the calculation speed is fast. The simulation results show that the energy management strategy based on PMP can ensure the normal operation of tram. Keep the bus voltage of hybrid energy storage tram within a reasonable range. Compared with the energy management method based on rule control, the power consumption is reduced by 9%.

1. Introduction

In recent years, with the development of urban industrialization and the rapid growth of urban population, in order to effectively solve the problem of ground traffic congestion. Major cities all over the world pay more and more attention to the development of public transport [1]. Compared with buses, rail transit has the advantage of large capacity, which is conducive to large numbers of people in large and medium-sized cities commuting in concentrated time. Subway can be used as the vehicle of urban underground rail transit, but the infrastructure construction of subway is relatively complex, the engineering quantity is large, and the construction cost of some cities is relatively high. In this context, the ground rail transit such as urban light rail and tram has outstanding economic advantages. The tram has a short infrastructure construction cycle, so it does not need to build too many underground projects like subway. The construction of supporting facilities is relatively economical, so it is adopted by some cities at home and abroad to increase ground public transport and improve urban congestion [13-16].

Hybrid energy storage trams have the advantages of traditional trams, and do not need grid, which can further reduce the construction cost of ground infrastructure and shorten the construction period of the project. Moreover, the energy utilization efficiency can be improved through the energy management (EMS) optimization strategy of the hybrid energy storage system [2]. At the same time, in the design stage of the train, the EMS strategy can be carried out by establishing the train simulation model. It can effectively verify the correctness of the strategy and reduce the development cost [3]. In recent years, many scholars have carried out corresponding research on EMS applied to hybrid energy storage vehicles. The first type of EMS is energy management strategy based on rule control, which has the advantages of strong practicability, such as rule-based control method based on threshold and fuzzy control proposed in reference [4-6]. The threshold method has the characteristics of easy engineering implementation, but the selection of threshold range and strategy. The realization needs to
be based on engineering experience, and the actual adaptability is poor, and the energy utilization efficiency is not high. In addition, scholars in literature [7-10] have studied the energy management strategy of global optimization based on intelligent algorithm, such as: dynamic programming [7]. Its advantage is that it can solve the global optimal control, and its control path is the global theoretical optimal solution. Therefore, its energy management efficiency is high, but due to the large amount of calculation and slow calculation speed, it is difficult to realize the vehicle online.

Based on the above, (1) this paper proposes a hybrid energy storage tram energy management (EMS) strategy based on Pontryagin minimum principle (PMP). The energy consumption of trams is taken as the objective function for global optimization, and the Hamiltonian function is used to transform the global optimization solution into solving the instantaneous minimum value to obtain the optimal control path. The strategy has the calculation speed in order to verify the effectiveness of EMS strategy based on PMP, this paper builds a tram dynamic simulation model based on MATLAB / Simulink platform to verify the feasibility of the control strategy, and compares the model with the energy management of rule control strategy.

2. Tram model

2.1. Topology of hybrid energy storage system (Hess)

As shown in Figure 1, the basic structure topology of the tram system with battery and super capacitor hybrid energy storage is shown. The super capacitor is directly connected with the bus, and the battery is connected with the bus through the DC / DC converter. The advantage of the semi-active hybrid energy storage topology is that the output power of the battery and the super capacitor can be controlled, and the high energy density characteristics of the battery can be brought into play. High power density characteristics. The topology structure can make the number of cells and supercapacitors more reasonable, and make the energy management efficiency of hybrid energy storage system of tram higher.

2.2. Simulation model of tram

The power system structure of hybrid energy storage tram in this paper is shown in Figure 1. The whole vehicle is composed of on-board energy storage system and traction transmission system, which provides traction and auxiliary power supply energy.

First of all, the traction system of tram is modeled. In this paper, the inconsistency of each traction system is ignored in the process of modeling of traction system, and a single traction system is modeled. Then formula (1) can be obtained, where $F_{w, all}$ is the total traction force, $F_w$ is the traction force of a single traction system.

$$F_{w, all} = 4F_w$$  \hspace{1cm} (1)
The inertia formula of the train is expressed as:

\[ a_{\text{tram}} = \frac{dv}{dt} = \frac{F_{\text{ab}} - F_f}{M_{\text{tram}}} \]  

Where, \( a_{\text{tram}} \) is the acceleration of the train, \( v \) is the speed of the train, \( t \) is the time, \( m_{\text{tram}} \) is the equivalent mass of the train, the equivalent mass of the train generally includes the rotating mass of the rotating subsystem, \( F_f \) is the total resistance of the train, and the total resistance consists of three parts: unit basic resistance \( f_0 \), unit curve resistance \( f_r \) and unit additional resistance \( f_i \) of the train. The calculation formula is as follows:

\[
\begin{align*}
  f_0 &= k_1 + k_2 v + k_3 v^2 \\
  f_i &= i \\
  f_r &= 600/R \\
  F_f &= \frac{(f_0 + f_i + f_r) M_{\text{tram}} g}{1000}
\end{align*}
\]  

In the above formula, \( k_1, k_2 \) and \( k_3 \) are the calculation parameters, \( R \) is the curve radius of the current position of the train (unit: m), \( i \) is the slope size (‰), and \( g \) is the gravity acceleration (m/s²).

2.3. Energy storage system model

The topology of battery capacitor hybrid energy storage system is shown in Figure 2. The semi-active topology can control the output power of the battery, ensure that the state of charge of the super capacitor is kept in a certain range, and the bus voltage is kept in a certain reasonable range.

As shown in Figure 3, the single cell model of power battery [5] is shown. In order to make the calculation faster and more accurate, the battery single model with power supply series internal resistance is adopted in this study, and the change of battery internal resistance is ignored.

According to the model, formula (4) can be derived, in which \( SOC_{\text{bat}} \) is the initial state of charge, \( SOC_{\text{bat}} \) is the state of charge. \( I_{\text{bat}_\text{cell}} \) is the current. \( Q_{\text{bat}_\text{cell}} \) is the capacity. \( R_{\text{o}_\text{cell}} \) is the internal resistance value. \( U_{\text{bat}_\text{cell}} \) is the terminal voltage. \( U_{\text{o}_\text{c}_\text{cell}} \) is the open circuit voltage. \( P_{\text{bat}_\text{cell}} \) and \( P_{\text{batcell} \text{out}} \) are the battery power consumption and output power respectively.

\[
\begin{align*}
  U_{\text{bat}_\text{cell}} &= U_{\text{o}_\text{c}_\text{cell}} - I_{\text{bat}_\text{cell}} R_{\text{o}_\text{cell}} \\
  SOC_{\text{bat}} &= SOC_{\text{bat}} - \int I_{\text{bat}_\text{cell}} dt / 3600Q_{\text{bat}_\text{cell}} \\
  P_{\text{bat}_\text{cell}} &= I_{\text{bat}_\text{cell}}^2 R_{\text{o}_\text{cell}} + P_{\text{batcell} \text{out}}
\end{align*}
\]  

As shown in Figure 4 is the monomer model of supercapacitor [6]. In this paper, the supercapacitor unit is modeled by ideal capacitor series resistance. According to the model, formula (5) can be derived. In formula (5), \( U_{c0} \) is the initial open circuit voltage of the monomer supercapacitor, and \( U_{c\_cell} \) is the open circuit voltage. \( U_{\text{uc}_\text{cell}} \) is the terminal voltage. \( I_{\text{uc}_\text{cell}} \) is the current flowing through
the super capacitor. \( C_{uc\_cell} \) is the maximum capacity value of super capacitor. \( P_{uc\_cell} \) and \( P_{uccell\_out} \) are the consumed power and output power of supercapacitor respectively.

\[
\begin{align*}
U_{uc\_cell} &= U_{C_{cell}} - I_{uc\_cell} R_{uc\_cell} \\
U_{C_{cell}} &= U_{C_{cell}} = \int \frac{I_{uc\_cell} dt}{C_{uc\_cell}} \\
P_{uc\_cell} &= I_{uc\_cell}^2 R_{uc\_cell} + P_{uccell\_out}
\end{align*}
\] (5)

In this paper, we do not consider the inconsistency between the power battery and the supercapacitor. It is considered that all cell and supercapacitor have the same characteristics respectively. Based on this, the formula of power battery pack and super capacitor bank can be deduced as follows:

\[
\begin{align*}
U_{bat} &= m_{bat} U_{bat\_cell} \\
I_{bat} &= I_{bat\_cell} n_{bat} \\
U_{uc} &= m_{uc} U_{uc\_cell} \\
I_{uc} &= I_{uc\_cell} n_{uc}
\end{align*}
\] (6) (7)

In the above formula, \( U_{bat} \), \( U_{uc} \), \( I_{bat} \) and \( I_{uc} \) represent the terminal voltage and current flow of the power battery pack and super capacitor bank respectively. \( m_{bat} \), \( m_{uc} \), \( n_{bat} \) and \( n_{uc} \) represent the number of series and parallel connection of power battery pack and super capacitor bank respectively.

3. Energy management strategy based on PMP principle

According to the characteristics of hybrid energy storage, an energy management strategy based on PMP algorithm is designed. The strategy can solve the global optimal control path of the train under the power and capacity constraints of power battery pack and super capacitor

3.1. Energy management strategy based on PMP

In order to reduce the overall energy consumption of trams, this paper proposes an energy management strategy based on PMP, which is verified on the platform of MATLAB / Simulink. Its performance index is the total energy consumption of the train:

\[
J = \int_{t_0}^{t_f} \frac{P_{bat}(t) + P_{uc}(t)}{3600} dt
\] (8)

The equation of state is as follows:

\[
\begin{align*}
S\text{OC}_{bat}(t) &= -(U_{bat\_ocv} - \sqrt{U_{bat\_ocv}^2 - 4R_{bat} P_{bat\_output}}) / (2R_{bat}Q_{bat}) \\
U_{uc\_ocv}(t) &= -(U_{uc\_ocv} - \sqrt{U_{uc\_ocv}^2 - 4R_{uc} P_{uc\_output}}) / (2R_{uc}C_{uc})
\end{align*}
\] (9)

Set boundary conditions, and the constraints of the hybrid energy storage system are set (where the variable superscripts min and max represent their minimum and maximum thresholds respectively):

\[
\begin{align*}
SOC_{bat}(t_0) &= SOC_{bat0} \\
U_{uc\_ocv}(t_0) &= U_{uc\_ocv0} \\
U_{uc\_ocv}(t_f) &= U_{uc\_ocv\_end}
\end{align*}
\] (10)
\[
0.2 \leq \text{SOC}_{\text{bat}} \leq 0.8 \\
500 \leq U_{\text{uc}, \text{ocv}} \leq 900 \\
\text{P}_{\text{bat, output}}^\text{min} \leq \text{P}_{\text{bat, output}} \leq \text{P}_{\text{bat, output}}^\text{max} \\
\text{P}_{\text{uc, output}}^\text{min} \leq \text{P}_{\text{uc, output}} \leq \text{P}_{\text{uc, output}}^\text{max} \\
\text{P}_{\text{demand}} = \text{P}_{\text{bat, output}} + \text{P}_{\text{uc, output}} 
\] 

Among them, \( P_{\text{demand}} \) is the demand power of tram.

The Hamiltonian function is constructed:

\[
H(\text{SOC}_{\text{bat}}, U_{\text{uc}, \text{ocv}}, u(t), \lambda_{\text{bat}}, \lambda_{\text{uc}}, t) = \frac{\text{P}_{\text{bat}}(t) + \text{P}_{\text{uc}}(t)}{3600} + \dot{\lambda}_{\text{bat}} \text{SOC}_{\text{bat}}(t) + \dot{\lambda}_{\text{uc}} U_{\text{uc}, \text{ocv}}(t) 
\]

Where \( \lambda_{\text{bat}} \) and \( \lambda_{\text{uc}} \) is the coordination factor, and its co state equation is as follows:

\[
\begin{align*}
\dot{\lambda}_{\text{bat}} &= -\partial H(\text{SOC}_{\text{bat}}, U_{\text{uc}, \text{ocv}}, u(t), \lambda_{\text{bat}}, \lambda_{\text{uc}}, t) / \partial \text{SOC}_{\text{bat}} \\
\dot{\lambda}_{\text{uc}} &= -\partial H(\text{SOC}_{\text{bat}}, U_{\text{uc}, \text{ocv}}, u(t), \lambda_{\text{bat}}, \lambda_{\text{uc}}, t) / \partial U_{\text{uc}, \text{ocv}}
\end{align*}
\] 

In this paper, the terminal state quantity of the battery pack is not fixed. Therefore, according to the minimum principle, the terminal value of \( \lambda_{\text{bat}} \) is 0. Because the internal resistance of the battery model in this paper is ignored, \( \dot{\lambda}_{\text{bat}} \) is 0. According to this, it can be deduced that the constant 0 of \( \lambda_{\text{bat}} \) in the system model can meet the calculation conditions.

In the process of solving the problem, \( P_{\text{bat}} \) and \( P_{\text{uc}} \) which can make Hamilton function \( H \) reach the minimum value, are taken at each time to obtain the global optimal control path.

\[
\begin{align*}
P_{\text{bat, output}}^*(t) &= \arg\min[H(\text{SOC}_{\text{bat}}, U_{\text{uc}, \text{ocv}}, u(t), \lambda_{\text{bat}}, \lambda_{\text{uc}}, t)] \\
P_{\text{uc, output}}^*(t) &= \arg\min[H(\text{SOC}_{\text{bat}}, U_{\text{uc}, \text{ocv}}, u(t), \lambda_{\text{bat}}, \lambda_{\text{uc}}, t)]
\end{align*}
\] 

In the actual strategy optimization process, the initial value of \( \lambda_{\text{uc}} \) should be selected for operation. If the operation results meet the boundary conditions, the initial value meets the optimization conditions; otherwise, the \( \lambda_{\text{uc}} \) value is adjusted according to the operation results, and then the operation is carried out again. The flow chart of simulation algorithm is shown in Figure 5.

![Figure 5. algorithm flow chart](image-url)
4. Test verification results

Based on MATLAB / Simulink software, the tram dynamic model is established by using the basic parameters of tram as shown in Table 1 and the parameters of energy storage system as shown in Table 2. The energy management strategy based on PMP is established and compared with the rule control method based on threshold method. The speed curve is shown in Figure 6 and the train demand power curve is shown in Figure 7.

The energy consumption comparison between PMP based energy management strategy and rule control method based on threshold method is obtained by simulation. The rule control rule based on threshold method: the battery discharge is the main method, and the super capacitor bank is used to supplement the required power. When the super capacitor capacity is low, the open circuit voltage is low. In order to keep the bus voltage within a reasonable range, the battery pack outputs more power. The EMS strategy based on PMP is based on the global optimization results of the algorithm. The open circuit voltage curve of the global super capacitor is more reasonable, so that the super capacitor can work reasonably under the maximum power limit and the minimum open circuit voltage limit. Moreover, under the condition of meeting the normal power demand of the train, the high power impact of the battery is greatly reduced, and the battery life is optimized. The simulation results show that the total power consumption of the PMP based energy management strategy is reduced by about 9% compared with the rule control method. The output power of the battery pack and capacitor bank based on the PMP energy management strategy is shown in Figure 8. The open circuit voltage variation of battery SOC and super capacitor bank based on PMP is shown in figure 9.

| Technical indicators       | parameters | Technical indicators       | Parameters |
|----------------------------|------------|----------------------------|------------|
| Vehicle weight             | 53t        | bus voltage                | 500–900V   |
| DC/DC efficiency           | 0.98       | axle radius                | 0.54m      |
| transmission system efficiency | 0.95    | motor rated power          | 4×230kW    |

Table 2. Parameters of energy storage system.

| Parameters                         | Battery | Supercapacitor |
|------------------------------------|---------|----------------|
| The monomer capacity               | 20A·h   | 5600F          |
| Rated voltage (V)                  | 2.3     | 2.7            |
| The number of series connection    | 136     | 336            |
| The number of parallel connection  | 12      | 5              |
5. Conclusion

In this paper, the dynamics model and energy storage system model of hybrid energy storage tram are established, and according to the characteristics of hybrid energy storage system. The energy management strategy based on PMP is proposed, which is verified by experiments on the software platform. Compared with the traditional threshold control strategy based on rule control, the power consumption is reduced by 9%, and the power allocation is more reasonable. At the same time, the calculation speed of the control algorithm is also improved. It is convenient for the online realization of vehicle control strategy, and has the prospect of engineering application.

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