Research on Non-catenary Power Supply Technology

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Abstract. The traction power supply mode of urban rail transit trains is mainly divided into two categories: contact power supply and contactless power supply. Among them, contactless power supply mode has advantages of cost saving, unrestricted operation area, energy conservation and environmental protection. Therefore, some domestic and foreign institutions have begun to carry out research in related fields and practical application. Based on the “Battery and super capacitor” train hybrid energy storage system, we study the contactless power supply technology in this paper, the description and conclusion can provide a reference for the further research of contactless power supply technology together.

1. Introduction
According to the operating conditions of rail transit, in order to give full play to the power and energy characteristics of different energy storage elements, lithium ion battery [1-5] and supercapacitor [6-8], which are suitable for the power system of rail transit, are used as energy storage elements in this study. The research is carried out from three aspects: the selection and modeling of energy storage components, the comparison and analysis of the topological structure and the energy management and control strategy of the energy storage system.

2. Energy Storage Components Selection and Modeling
2.1. Battery Selection and Modeling
As a new type of lithium ion battery, lithium titanate batteries have advantages of high safety, wide temperature range and long cycle life compared with other anode materials. Therefore, lithium titanate batteries are selected as the energy storage element in this paper [9]. The specific parameters are shown in table 1.
### Table 1. Parameters of lithium titanate single battery.

| Parameter                          | Unit    | Value |
|------------------------------------|---------|-------|
| Nominal voltage                    | V       | 2.3   |
| Nominal capacity                   | Ah      | 8.5   |
| Mass energy density                | Wh/kg   | 75    |
| Volume energy density              | Wh/L    | 100   |
| Charging cut-off voltage           | V       | 2.8   |
| End-off voltage                    | V       | 1.5   |
| Maximum charging current           | A       | 8C    |
| Maximum discharge current          | A       | 15C   |
| Operating temperature range        | ℃       | -20~+60 |

In order to characterize the internal characteristics of the single lithium ion battery, the first-order Davenport equivalent circuit model of a single battery was established based on the consideration of system simplicity, as shown in figure 1 [10].

![Figure 1. Single battery model.](image)

### Table 2. Ultracapacitors parameters

| Parameter                          | Unit    | Value |
|------------------------------------|---------|-------|
| Normal capacitance                 | F       | 83    |
| Internal resistance of DC          | mΩ      | 10    |
| Nominal voltage                    | V       | 48    |
| Maximum current                    | A       | 1900  |
| Maximum voltage                    | V       | 51    |
| Stored energy                       | Wh      | 53    |
| Operating temperature range        | ℃       | -40~65 |
| Maximum number of cycles           | w       | 100   |

2.2. Selection and Modeling of Ultracapacitors

At present, the research on supercapacitors in the world is getting deeper and deeper [11]. For example, companies like Panasonic, Maxwell and Econd have been leading the world in theoretical research, technological development and industrialization of supercapacitors. The application of ultracapacitors in the field of rail transit is also becoming mature. The parameters of ultracapacitors used in this study are shown in table 2.
Due to the low frequency characteristics of the load in the urban rail transit field, the RC simplified model is used in the supercapacitor modeling process in this paper [12]. The model has advantages of simple structure and easy parameter identification, as shown as figure 2.

![Figure 2. Supercapacitor monomer model.](image)

3. Comparative Analysis of Topological Structure of Energy Storage System

3.1. Passive Topology
The passive topology shown in figure 3 utilizes the simplest structure, with the advantages of easy implementation, low cost and high efficiency, but the disadvantage is that the ultracapacitor is only used as a low-pass filter and cannot play its role.

![Figure 3. Passive topology.](image)

3.2. Semi-active Topology
Figure 4 shows four semi-active topologies. In structure (a), the ultracapacitor has a wide operating range, and the voltage on the DC busbar side is stable, but the battery's mission life is impaired [13]. The structure (b) can reduce the rated capacity of the DC/DC converter. The battery has a flexible operating range, but the voltage on the DC busbar side varies greatly. The structure (c) can extend the battery life. Structure (d) the unidirectional DC/DC converter with smaller size is used to replace the bidirectional DC/DC converter to further reduce the size and control difficulty.
3.3. Active Topology

At present, three common active topological structures are shown in figure 5. Structure (a) is the most widely used in engineering applications, with strong controllability as its advantage and high cost and occupied volume as its disadvantage. (b) and (c) are cascade type and multi-input type respectively. The advantage of cascade type is that it can’t only give full play to the advantage of supercapacitor, but also avoid the voltage fluctuation of DC bus. The disadvantage is that the cost is increased and the efficiency is reduced. The advantage of multi-input is to reduce the cost and save the volume, but the disadvantage is to increase the difficulty of control.

In this paper, the active topological structure in figure 5 (a) is selected to study the energy management problem.
4. Energy Management Control Strategy

In this paper, the model predictive control algorithm is used to study the energy management problem, and the optimization goal is to reduce the energy loss of battery pack and ultracapacitors. In the traction (positive energy flow) phase of each station interval, the model predictive control is realized by setting the predicted step size, and the constraint conditions are set to limit the supercapacitor SOC. The energy allocation strategy for braking stage is formulated as follows:

\[
\begin{align*}
P_{dc}(k) &= \begin{cases} 
P_{dmd}(k), & P_{dmd}(k) \leq P_{dc\text{max}}^{\text{dmd}}(k) \\
P_{dc\text{max}}^{\text{dmd}}(k), & P_{dmd}(k) > P_{dc\text{max}}^{\text{dmd}}(k) 
\end{cases} \\
P_{batt}(k) &= \begin{cases} 
0, & P_{dmd}(k) \leq P_{dc\text{max}}^{\text{dmd}}(k) \\
P_{dmd}(k) - P_{dc\text{max}}^{\text{dmd}}(k), & P_{dmd}(k) > P_{dc\text{max}}^{\text{dmd}}(k) 
\end{cases}
\end{align*}
\]

(1)

where, \(P_{dmd}\) is the power of the vehicle braking recovery stage at moment \(k\), and \(P_{dc\text{max}}^{\text{dmd}}\) is the maximum power limit of the DC/DC converter.

The evaluation equation and constraint conditions of the model predictive control in traction stage are as follows:

\[
J(k) = E_{loss}(k) = \left(\frac{P_{dmd}(k)(1-\alpha(k))}{V_{batt}(k)}\right)R_{\text{batt},k}T_s + \left(\frac{P_{dmd}(k)\alpha(k)}{V_{SC}(k)}\right)R_{\text{SC},k}T_s
\]

\[
\text{s.t.} \quad \begin{align*}
SOC_{\text{batt},\text{min}} &\leq SOC_{\text{batt}, \text{dmd}}(k) \leq SOC_{\text{batt},\text{max}} \\
SOC_{\text{SC},\text{min}} &\leq SOC_{\text{SC}, \text{dmd}}(k) \leq SOC_{\text{SC},\text{max}} \\
I_{\text{batt}, \text{dmd}}(k) &\leq I_{\text{batt, max}} \\
\alpha &\in [0,1]
\end{align*}
\]

(2)

where, \(P_{dmd}\) is the required power on the DC side, and \(\alpha\) is the power distribution coefficient of the traction system; \(SOC_{\text{batt, min}}\) and \(SOC_{\text{batt, max}}\) are the upper and lower SOC of the battery, respectively; \(SOC_{\text{SC, min}}\) and \(SOC_{\text{SC, max}}\) are the upper and lower SOC of the supercapacitor, respectively. \(I_{\text{batt, max}}\) is the maximum output current multiplier of the battery.

5. Simulation and Verification

The catenary power supply system consists of a lithium battery pack, a supercapacitor, a DC/DC converter and a load. See the figure 6.

![Figure 6. Structural block diagram of catenary power supply system.](image)

Simulation results are as figure 7:
It can be seen from the simulation results that the battery and the ultracapacitor can cooperate well to maintain their respective performance while meeting the power demand of the train operation, and at the same time reduce the energy loss of the system as much as possible.

6. Conclusion
This paper takes urban rail transit train as the research object, and carries out research on power supply technology for "battery + supercapacitor" vehicle-mounted hybrid energy storage system. The battery and supercapacitor are selected and modeled respectively, and the topological structure of various energy storage systems is summarized and compared. Finally, an energy management control strategy based on model predictive control algorithm is proposed. The simulation model was built in the MATLAB simulation software, and the effectiveness of the proposed strategy was verified by the simulation results.

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