Fuzzy Energy Management for a Catenary-Battery-Ultracapacitor based Hybrid Tramway

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Abstract. In this paper, an energy management strategy (EMS) based on fuzzy logic control for a catenary-battery-ultracapacitor powered hybrid modern tramway was presented. The fuzzy logic controller for the catenary zone and catenary-less zone was respectively designed by analyzing the structure and working mode of the hybrid system, then an energy management strategy based on double fuzzy logic control was proposed to enhance the fuel economy. The hybrid modern tramway simulation model was developed based on MATLAB/Simulink environment. The simulation results show that the proposed EMS can satisfy the demand of dynamic performance of the tramway and achieve the power distribution reasonably between the each power source.

1. Introduction
With the rapid development of world economy and the advancement of urbanization, traffic congestion, air pollution, noise pollution and other urban problems become increasingly serious. Giving priority to the development of public transport become the first target to solve the problem of urban traffic[1-2]. In recent years, modern trams have been studied and applied rapidly in domestic and foreign cities[2-3], because it adopts new technology, such as its low floor, the capacity of moderate, low noise, and a new type of power supply technology. Hybrid modern tramway has equipped with energy storage devices as a new power supply devices, which reducing the cost of catenary or third rail, and recycling the regenerative braking energy[2,4-5].

Multiple energy sources expand power supply capacity of tramway, while they increase the complexity of the system, in order to realize the switching between different working modes, and improve the overall efficiency of power supply system, etc., the energy management strategies are needed to complete all the objectives[2,4-8]. In recent years for the research and application of energy management strategy of hybrid system mainly divided into the rules-based control and optimization – based control algorithms. The control strategy based on rules was presented for the catenary-battery-ultracapacitor based tramway in [5]. However, the rules-based strategy can't optimize the use of energy. Herrera et al.[2] presented a fuzzy logic control for the catenary-battery-ultracapacitor based tramway, which estimated the traction energy consumption according to a particular operation condition, then the estimated energy consumption was used as the input of fuzzy logic control. Li et al.
[7] optimized the energy management strategy of fuel cell hybrid tramway by combining the wavelet analysis and fuzzy logic control. Fuzzy logic control method does not depend on the accurate mathematical model of the system. It shows the advantages of good robustness and high control performance for the control of nonlinear and complex objects. In this work, firstly the hybrid system structure of the catenary-battery-ultracapacitor based tramway is introduced. Secondly, a system simulation model is presented according to the modeling approach of ADVISOR[6,9]. Finally the fuzzy energy management strategy is presented and simulated.

2. System modeling
The hybrid system of catenary-battery-ultracapacitor powered hybrid modern tramway is composed of the following parts: (i) catenary, (ii) battery module, (iii) ultracapacitor module (UC), (iv) dc/dc unidirectional (UC convertor), (v) dc/dc unidirectional (battery convertor), (vi) tramway loads, (vii) EMS. Figure 1 shows the configuration of the catenary-battery-UC powered hybrid system for the tramway.

![Figure 1. Configuration of the catenary-battery-ultracapacitor hybrid system for the tramway](image)

The traditional tramway is powered by overhead catenary or third rail, and the energy of braking is also dissipated by resistance braking or mechanical braking. The battery and UC are being used as energy storage system(ESS) of the hybrid tramway. In the catenary-less zone, the hybrid tramway is powered by battery and UC (Energy storage system, ESS), in the station or in the catenary zone the hybrid tramway can be powered by catenary, meanwhile the battery and UC are charged through the catenary, and when the tramway braking, the battery and UC can recycled braking energy. Figure 2 shows the operation process of the hybrid tramway. Next hybrid tramway model is introduced.

2.1. The longitudinal dynamic model of tramway
To simplify the calculation, the longitudinal dynamic model of the tramway is simplified multi particle model which is rigid connection. The model is expressed as

$$\sum_{j=1}^{n} F_{j,m} = \sum_{j=1}^{n} m_{j,D} g w_{j,D} - \sum_{j=1}^{n} F_{j,b} - \frac{\sum_{j=1}^{n} m_{j,D}}{3.6} \frac{dv}{dr} = 0 \tag{1}$$

where, $j$ is the number of particle, $n$ is quantity of particle, in this paper, the every power bogie is used as a particle. $v$ is the tramway speed, $F_{j,m}$ is traction force of particle, $m_{j,D}$ is the mass of particle which includes the rotating mass coefficient, $F_{j,b}$ is the braking force of particle which included Regenerative braking and mechanical braking, $w_{j,D}$ is the sum of unit of resistance which included basic resistance and the attachment resistance.
2.2. Transmission system and motor model

The mechanical transmission system of the hybrid tramway is mainly the gear box, and the gear ratio is fixed, so the transmission system model is expressed as

\[
\begin{align*}
T_{\text{gear,in}}^* &= \frac{T_{\text{gear,out}}^*}{i_0} + T_{\text{inertia}} + T_{\text{loss}} \\
\omega_{\text{gear,in}}^* &= \omega_{\text{gear,out}}^* \cdot i_0
\end{align*}
\]

where, \( T_{\text{gear,in}}^* \) is the input torque demand of the gear box, \( \omega_{\text{gear,in}}^* \) is the input rotate speed demand of the gear box, \( T_{\text{gear,out}}^* \) is the output torque demand of the gear box, \( \omega_{\text{gear,out}}^* \) is the output rotate speed demand of the gear box, \( i_0 \) is the gear ratio. \( T_{\text{inertia}} \) and \( T_{\text{loss}} \) are respectively gearbox inertia and mechanical torque loss.

The tractive characteristic and braking characteristic need to be prepended in the motor model, which is showed as

\[
T_{\text{m,in}}^* = \begin{cases} 
\max(T_{\text{m,out}}^*, T_{\text{m,\max}}^*(\omega)) & T_{\text{m,out}}^* \geq 0 \\
\min(T_{\text{m,out}}^*, T_{\text{m,\max}}^*(\omega)) & T_{\text{m,out}}^* < 0 
\end{cases}
\]

where, \( \omega_{\text{m}} \) is rotate speed of motor, \( T_{\text{m,in}}^* \) is input torque demand of motor, \( T_{\text{m,out}}^*(\omega_{\text{m}}) \) is output torque demand of motor, \( T_{\text{m,\max}}(\omega_{\text{m}}) \) are respectively the maximum traction torque and the maximum braking torque of motor, which is obtained by motor characteristic curve. Figure 3 shows the single motor characteristic curve of the hybrid tramway.
3. EMS
Because the hybrid system has a variety of power source, there are many working modes of the hybrid system, and the power distribution will be more complex. To simplify the design of the controller, meanwhile to implement the precise control of power distribution between the each power source, in guarantee tramway dynamic performance, under the premise of improving fuel economy, the EMS based on double fuzzy logic controller is designed, the first is the catenary-less zone fuzzy logic controller (FLC 1), the second is catenary zone fuzzy logic controller (FLC 2). Figure 4 shows the EMS controller of the hybrid tramway.

To facilitate the analysis, the variables are defined as follow: \( P_{\text{bus},d} \) is the power demand of dc bus, \( P_{\text{cat}} \) is the output power of catenary, \( P_{\text{batt}} \) is the input or output power of battery, the positive value is defined as discharge mode, and the negative value is defined as charge mode, \( P_{\text{uc}} \) is input or output power of UC, the positive value is defined as discharge mode, and the negative value is defined as charge mode, \( \eta_{dd} \) is efficiency of dc/dc convertor, \( SOC \) is the capacity of battery, \( SOE \) is the capacity of UC.

There are three input variables and one output variable for the FLC 1, the fuzzy domain scope of \( P_{\text{bus},d} \) is defined as \([-1,1]\), the fuzzy domain scope of \( SOC \) and \( SOE \) is defined as \([0,1]\), the fuzzy domain scope of \( P_{\text{batt},d} \) is defined as \([-1,1]\). The fuzzy subset of \( P_{\text{bus},d} \) is \{HB, MB, LB, M, LT, MT, HT\}, The fuzzy subset of \( SOC \) and \( SOE \) is \{L,M, H\}, The fuzzy subset of \( P_{\text{batt},d} \) is \{HC, LC, M, LD, HD\}[2]. Figure 5 shows the membership functions, table 1 shows the fuzzy reasoning rules.
Figure 5. The membership functions of FLC 1

Table 1. The membership functions of $P_{\text{batt},d}$ for FLC 1

| SOE = L | $P_{\text{bus},d}$ | HB | MB | LB | M | LT | MT | HT |
|---------|------------------|----|----|----|---|----|----|----|
| SO      | L                |    |    |    |   |     |     |    |
| C       | M                | HC | HC | LC | M | LD | LD | LD |

| SOE = M | $P_{\text{bus},d}$ | HB | MB | LB | M | LT | MT | HT |
|---------|------------------|----|----|----|---|----|----|----|
| SO      | L                |    |    |    |   |     |     |    |
| C       | M                | HC | HC | LC | M | LD | LD | LD |

| SOE = H | $P_{\text{bus},d}$ | HB | MB | LB | M | LT | MT | HT |
|---------|------------------|----|----|----|---|----|----|----|
| SO      | L                |    |    |    |   |     |     |    |
| C       | M                | HC | HC | LC | M | M  | M  | M  |

Table 2. The fuzzy reasoning rules of $P_{\text{batt},d}$ for FLC 2

| SOE = L | $P_{\text{bus},d}$ | HB | LB | M | LT | HT |
|---------|------------------|----|----|---|----|----|
| SOC     | L                | HC | HC | HC | LC | M  |
| M       | HC | HC | HC | LC | LD |
| H       | HC | HC | HC | LC | LD |

| SOE = M | $P_{\text{bus},d}$ | HB | LB | M | LT | HT |
|---------|------------------|----|----|---|----|----|
| SOC     | L                | HC | HC | HC | LC | M  |
| M       | HC | HC | HC | LC | LD |
| H       | HC | HC | HC | LC | LD |

| SOE = H | $P_{\text{bus},d}$ | HB | LB | M | LT | HT |
|---------|------------------|----|----|---|----|----|
| SOC     | L                | M  | M  | M | M  | LD |
| M       | M  | M  | M | M  | LD |
| H       | M  | M  | M | M  | LD |

Table 3. The fuzzy reasoning rules of $P_{\text{uc},d}$ for FLC 2

| SOE = L | $P_{\text{bus},d}$ | HB | LB | M | LT | HT |
|---------|------------------|----|----|---|----|----|
| SOC     | L                | HC | HC | HC | LC | M  |
| M       | HC | HC | HC | LC | LD |
| H       | HC | HC | HC | LC | LD |

| SOE = M | $P_{\text{bus},d}$ | HB | LB | M | LT | HT |
|---------|------------------|----|----|---|----|----|
| SOC     | L                | HC | HC | HC | LC | M  |
| M       | HC | HC | HC | LC | LD |
| H       | HC | HC | HC | LC | LD |

| SOE = H | $P_{\text{bus},d}$ | HB | LB | M | LT | HT |
|---------|------------------|----|----|---|----|----|
| SOC     | L                | M  | M  | M | M  | LD |
| M       | M  | M  | M | M  | LD |
| H       | M  | M  | M | M  | LD |
There are three input variables and two output variable for the FLC 2, the fuzzy domain scope of $P_{uc,d}$ is defined as [-1,1], the fuzzy subset of $P_{bus,d}$ is \{HB, LB, M, LT, HT\}. The fuzzy subset of $P_{uc,d}$ is \{HC, LC, M, LD, HD\}. Figure 6 shows the membership functions, table 2 and table 3 shows the fuzzy reasoning rules of No.2 FLC.

![Figure 6. The membership functions of FLC 2](image)

4. Results and discussion

In order to verify the indexes of dynamic property and fuel economy of the hybrid tramway, the proposed control strategies is simulated in the MATLAB/Simulink environment. In this paper, a 100% low floor tramway is used as prototype vehicle which is designed by CRRC TANGSHAN CO., LTD., and a planning line is used as the real driving cycle. The main parameters of EMS shows in table 4.

| ESS Type | Parameter | Value |
|----------|-----------|-------|
| Ultracapacitor | Rated voltage(V) | 480 |
|          | Rated capacity(F) | 28.125 |
|          | Maximum discharge current(A) | 200 |
|          | Discharge SOE cut-off value(%) | 45 |
|          | Maximum charge current(A) | 200 |
|          | Charge SOE cut-off value(%) | 100 |
| Battery  | Rated voltage(V) | 480 |
|          | Rated capacity(Ah) | 50 |
|          | Discharge rate(C) | 2.4 |
|          | Charge rate(C) | 0.8 |
|          | Discharge SOC cut-off value(%) | 30 |
|          | Charge SOC cut-off value(%) | 100 |

As the results of the simulation of the hybrid tramway based on the proposed fuzzy logic control strategy, the tramway desired speed, tramway real speed, SOC, SOE, and acceleration are given in Figure 7, the dc power, the battery power, UC power, and catenary power are presented in Figure 8, respectively.

![Figure 7. Dynamic performance curves of tramway](image)

![Figure 8. Output power curves of tramway](image)
It can be stated that the proposed EMS can guarantee the reliable operation of the hybrid system during the real drive cycle. Battery and UC can well work together to meet the needs of the dc bus power, UC provides the peak power of traction in the catenary-less zone. In the catenary zone, the catenary provides the traction power for the tramway, and discharge for ESS. In addition, and when the traction power is larger, the ESS can output power, which reduces the output power of catenary.

5. Conclusions
In the paper, a hybrid system based on catenary, battery, ultracapacitor is discussed, and the simulation model of hybrid system are developed, then a double fuzzy logic control method is adopted to design energy management strategies for catenary-battery-ultracapacitor powered hybrid modern tramway for the improvement of fuel economy and dynamic performance. The results indicate that the proposed EMS based on double fuzzy logic control can guarantee the reliable operation of the hybrid system during the real drive cycle, and recycling more regenerative braking energy, which will provide an importance guiding role for the design of energy management system for the hybrid tramway.

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