Research on Energy Management Strategy of Supercapacitor Energy Storage System in Urban Rail Transit Based on Fuzzy Logic Control

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***Abstract*—In order to reasonably control the charging/ discharging of the energy storage system and maximize the recovery of regenerative braking energy, this paper proposes a dynamic charging/discharging threshold strategy based on fuzzy logic control. The effects of train operation state, SOC and current of supercapacitors are considered comprehensively. And the effectiveness of the control strategy is validated by taking the Beijing Metro Batong Line as an example. The results show that the output energy of the rectifier unit decreases by 14% and the cumulative output energy of the supercapacitors increases by 23.7% after adding the fuzzy logic controller.**

***Keywords*—supercapacitor, energy storage system, power flow calculation, dynamic charge and discharge threshold, fuzzy logic control**

I. Introduction

In urban rail transit applications, the supercapacitor energy storage system (ESS) is the main energy recovery device, which plays an important role in stabilizing DC network pressure and reducing regeneration failure. In order to coordinate the energy flow relationship between the trains, the ESS and the traction substations, and effectively recovering the regenerative braking energy, it is necessary to rationally design the energy management strategy of the ESS.

For the research of energy management strategy of ESS, many literatures put forward different methods. A control strategy is proposed based on the management in real time of voltage levels at catenary point connections in order to optimize the energy flow among the running tramcars and substations [1]. Braking voltage following control of supercapacitor energy storage system is proposed based on train operation state, but the influence of the ESS parameters is not considered [2]. Fuzzy logic controller based on grid voltage and supercapacitor charging/discharging current ripple is used to adjust the given voltage of DC bus on line, and the energy saving rate of ESS is improved [3], [4]. The fuzzy inference system in [5-6] is used to reduce the fluctuation of the power grid and increase the cycle life of the ESS. At present, most of the researches on energy management strategies of ESS only consider some of the influencing factors.

In this paper, an energy management strategy based on fuzzy logic controller is proposed considering synthetically the influence of train operation state, state of charge (SOC) and charging/discharging current of supercapacitors [7-9]. The structure of this paper is as follows: Firstly, the power flow analysis of traction power supply system for urban rail transit is carried out, and the effects of different charging thresholds on energy flow and recovery efficiency of ESS are analyzed; secondly, a dynamic charging/discharging threshold control strategy based on fuzzy logic control is proposed; finally, taking Beijing Metro Batong Line as an example, the effectiveness of the proposed control strategy is verified by simulation, and the simulation results are analyzed.

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II. Simulation Analysis of Power Flow Calculation for Urban Rail Transit Traction Power Supply System

In order to study the effect of charging threshold of ESS on the recovery of regenerative braking energy and the interaction between trains, the power flow analysis of single train and double train models is carried out in this section.

A. Single Train Model

Under different charging thresholds, the recovery efficiency of ESS is different. In order to reduce the loss during the train braking process as much as possible and increase the efficiency of the system, the single train braking situation is modeled. Fig.1 (a) is a single train operation model, in which u_{oc}, r_s and i_{s1} are the no-load voltage, the equivalent internal resistance and the output current of the substation; r_1~r_3 are the contact network resistances, and r_4~r_6 are the rail resistances; u_{ch} and i_{ch} are the charging voltage and current of the ESS respectively. When the train brakes, the equivalent circuit model is shown in Fig.1 (b), where r_{net} is the line resistance, i_{gr} is the pantograph current, and u_{br} and i_{br} are the starting voltage and current of the braking resistance. When the braking resistance is not in operation, the expression of train voltage and current can be deduced from the expression of equivalent circuit model.

$$\begin{cases} (u_t - u_{ch}) \cdot y_{rs} = i_{gr} \\ i_{gr} = i_t \\ y_{rs} = \dfrac{1}{r_{net} + r_t} \\ p_t = u_t i_t \end{cases} \Rightarrow \begin{cases} u_t = \dfrac{u_{ch} y_{rs} + \sqrt{4 p_t y_{rs} + (u_{ch} y_{rs})^2}}{2 y_{rs}} \\ i_t = \dfrac{1}{2}(-u_{ch} y_{rs} + \sqrt{4 p_t y_{rs} + (u_{ch} y_{rs})^2}) \end{cases} \quad (1)$$

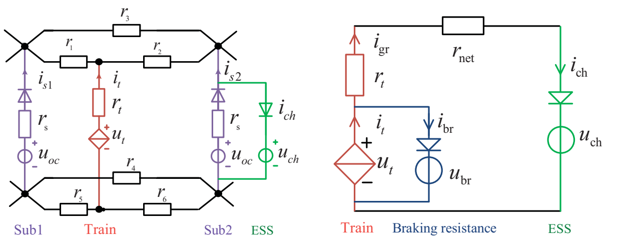

Fig. 1. Single train operation model (a) and equivalent circuit model (b)

The recovery efficiency of the ESS is as follows.

$$\eta_{ch} = \frac{u_{ch} \cdot i_{ch}}{p_t} = \frac{u_{ch} \cdot \frac{1}{2}(-u_{ch} y_{rs} + \sqrt{4 p_t y_{rs} + (u_{ch} y_{rs})^2})}{p_t} \tag{2}$$

The derivative of η_{ch} is obtained.

$$\frac{\partial \eta_{ch}}{\partial u_{ch}} = \frac{2 y_{rs} i_t (u_t - u_{ch}))}{p_t \sqrt{y_{rs}(4 p_t + u_{ch}{}^2 y_{rs})}} \tag{3}$$

Because the terminal voltage of traction converter is less than the charging threshold, when the braking resistance is not in operation, the efficiency of the system increases with the increase of charging threshold. Also, when the charging threshold increases, the DC side voltage of the converter increases, and when this voltage just increases to the starting threshold of the braking resistance, the efficiency of the system reaches the maximum. The expression of charging threshold is obtained as shown in (4) when the system efficiency reaches its maximum.

$$u_{ch} = u_{br} - \frac{p_t}{y_{rs} \cdot u_{br}} \tag{4}$$

Where $y_{rs}=1/(r_t+(r_1+r_3)\|r_2+(r_4+r_5)\|r_6)$. When the starting threshold of braking resistance is fixed, the optimal charging threshold is related to the position and braking power of train.

B. Double Train Model

When two trains are running, the circuit model is shown in Fig. 2. Assuming that the power and position of the train are constant at a certain time, power flow calculation of the static DC traction network at the current time is carried out. Because the train adopts controlled power source model, the equations of traction train and braking train are coupled in power flow analysis, so the current vector iteration method is used to solve the problem [10]. The position relationship of trains, substations and the ESS is shown in Fig. 4. The distance L between stations is 2 km, the distance between two trains is L1, and the distance between train 2 and the ESS is L2. Next, two kinds of operation are analyzed in detail. Table I is the simulation parameters of power supply system, in which r_c is the unit contact rail resistance and r_l is the unit rail resistance.

In order to analyze the influence of charging threshold on recovery efficiency of regenerative braking energy and energy interaction between traction trains and braking trains, the power flow calculation and analysis of two kinds of dual-train models are carried out in this section.

Case 1: Train 1 is in traction and train 2 is in braking.

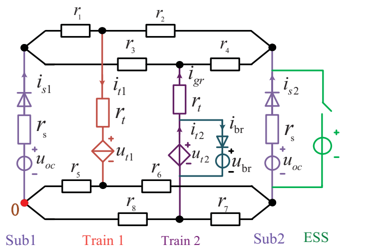

Fig. 2. Double train model

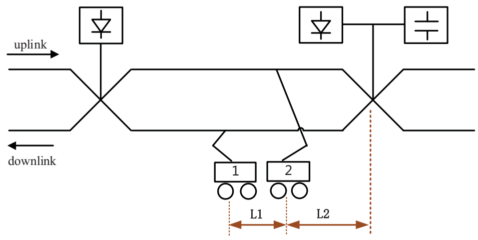

Fig. 3. The positional relationship between the train, the substation and ESS.

TABLE I. SIMULATION PARAMETERS OF POWER SUPPLY SYSTEM

parameter	**value**	**parameter**	**value**
r_c/Ω/km	0.0085	r_s/Ω	0.0161
r_l/Ω/km	0.029	U_{br}/V	920
r_t/Ω	0.015	U_{oc}/V	860

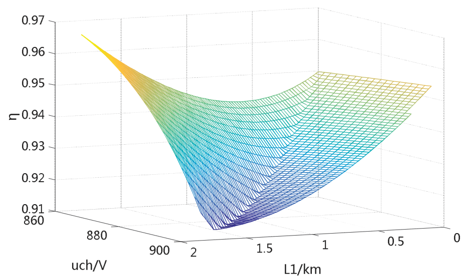

Fig. 4. A curve of system efficiency without considering braking resistance operation.

Assuming that the traction power is constant at 1MW, the braking power is constant at 1.1MW, and the value of L2 is constant at 0.1km, the value of L1 increases gradually, and the range of change is [0.1, 1.8].

When the ESS operates and the rectifier unit does not start, the power conservation equation and the efficiency expression of the system are shown in (5) and (6), where p_{t1}, p_{t2}, p_{sc} and p_r are traction train power, braking train power, absorption power of the ESS and line loss power, respectively.

$$p_{t2} = p_{sc} + p_{t1} + p_r \tag{5}$$

$$\eta = \frac{p_{sc} + p_{t1}}{p_{t2}} \tag{6}$$

When both the ESS and the rectifier unit are started, the power balance equation and efficiency expression of the system are respectively

$$p_{t2} + p_{ss} = p_{sc} + p_{t1} + p_r \tag{7}$$

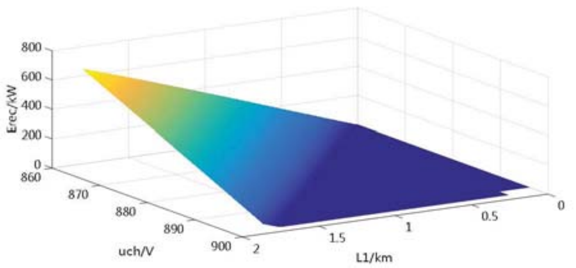

Fig. 5. Variation curve of rectifier unit output energy

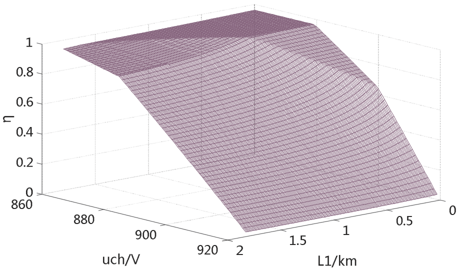

Fig. 6. Curve of system efficiency under two trains braking

$$\eta = \frac{p_{sc} + p_{t1}}{p_{t2} + p_{ss}} . \tag{8}$$

Fig. 4 shows the varation trend of system efficiency when the braking resistance is not in operation. The following conclusions can be drawn: (1) The charging threshold of the system should be increased as much as possible so that the system is in the state where only the ESS is started and the operation of the rectifier unit is reduced, and the efficiency increases with the increase of charging threshold; (2) In the state where the ESS and the rectifier unit are simultaneously started, when the distance between the two trains is large, the efficiency of the ESS increases as the charging threshold decreases, which is because the rectifier unit provides a large part of the traction energy and the energy of train interaction is reduced, resulting in the reduction in line losses.

Fig. 5 shows the curve of output power of rectifier unit changing with charging threshold and distance between trains. It can be seen that the energy released by rectifier unit decreases with the increase of charging threshold after the rectifier unit is in operation, that is, the energy of interaction between trains increases with the increase of charging threshold of ESS.

Case 2: Train 1 and train 2 are in braking state

When both trains brake simultaneously, the efficiency expression of the system is as follows.

$$\eta = \frac{p_{sc}}{p_{t2} + p_{t2}} \tag{9}$$

When the braking power of train 1 and train 2 is 1MW and 2MW respectively, the efficiency curve of the system is shown in Fig. 6. The critical charging threshold is defined as the charging threshold of the ESS when the braking resistance of each braking train reaches a critical start state. It can be seen from Fig. 6 that when the charging threshold is less than the minimum value of the critical charging thresholds of the two braking trains, the efficiency of the system is the highest; when the charging threshold is between the critical charging thresholds, the braking resistance of one of the trains is started, and the efficiency of the system is relatively decreased; When the braking resistances of both trains are started, the efficiency drops significantly. Therefore, when there are only braking trains near the ESS, the minimum critical charging thresholds should be selected as the charging threshold of the ESS.

The simulation results of single train and double trains can be concluded as follows: (1) When the braking resistance is not in operation, the charging threshold of the ESS is larger, the efficiency of the system is higher, and when the charging threshold just reaches the critical charging threshold, the efficiency of the system is maximized; (2) When there is more than one braking train near the ESS, the critical charging threshold is calculated separately when the braking resistance of each braking train is just started, and the minimum value of them is the optimal charging threshold.

III. Design of Fuzzy Control Strategy for the ESS

When there are a large number of traction and braking trains near the ESS, the effects of factors such as the running state of the train and the SOC of the supercapacitors should be considered comprehensively to set the charging/discharging threshold reasonably [11-12]. In order to maximize the energy interaction between trains, recover the regenerative braking energy, and increase the efficiency of energy saving, based on the simulation results in the previous section, this section designs fuzzy logic controllor to adjust the charging/ discharging threshold of the ESS online.

A. Charging Control Strategy

Fig. 7 is a control strategy based on the operation state of the train [13]. The basic idea is to let the traction converter voltage of the braking trains on both sides of the ESS be equal to the starting voltage of the braking resistor. The critical charging threshold for each train is calculated by (10), and then the average value is taken as the ESS charging threshold. In (10), r_k is the distance from the braking train to the ESS, and i_{rk} is the corresponding line current, k is the serial number of the braking train.

$$u_{ch}(k) = u_{br} - (i_{tb}(k) \cdot r_t + i_{rk} \cdot r_k) \tag{10}$$

In order to avoid the situation that the above control strategy does not have a good effect on regenerative braking energy recovery in some cases, a dynamic threshold charging strategy based on fuzzy control is proposed, considering the influence of the train operation state, SOC of supercapacitor and charging current.

Based on the simulation analysis of the second section, a fuzzy logic controller for charging is designed. After adding the fuzzy control, the block diagram of charging control strategy is shown in Fig. 8 [14]. The input of the fuzzy logic controller (FLC) is the SOC and difference between the present and previous samples of supercapacitors current, and the output is the charging threshold of the ESS. Input fuzzy sets are defined as N = Negative, Z = Zero, P = Positive, H = High, M = Medium, L = Low, and output fuzzy sets are defined as H = High, M = Medium, L = Low.

Table II shows the fuzzy control rules for charging. When SOC is very small, the ESS has enough capacity to absorb regenerative braking energy. According to the simulation results in the previous section, the charging threshold of the

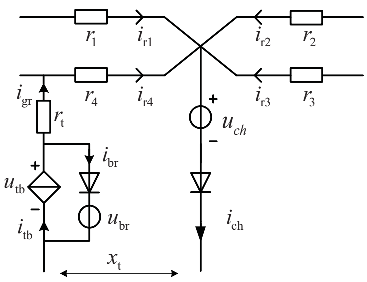

Fig. 7. Schematic diagram of charging control strategy based on train operating state

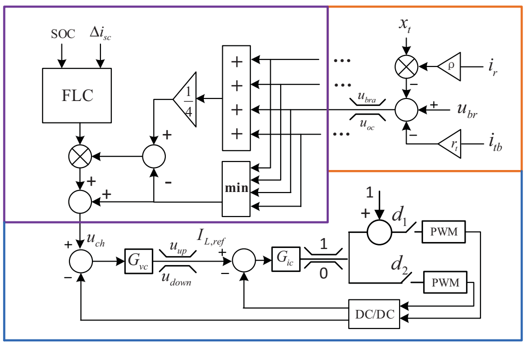

Fig. 8. Charging control strategy based on fuzzy logic control

TABLE II. FUZZY CONTROL RULES FOR CHARGING

SOC	△*Isc*		
	N	***Z***	***P***
L	L	M	L
M	L	H	M
H	L	H	H

ESS should be set to close to the minimum value of the critical charging thresholds, so as to minimize the operation times of braking resistance and ensure that energy can be effectively recovered; when SOC is large, the charging threshold should be increased appropriately to increase the energy interaction between trains more. When SOC is close to the permissible upper limit, the charging threshold should be increased to approach the average of critical charging threshold to reduce energy absorption by ESS and increase energy interaction between trains to a greater extent. When the current of the ESS decreases rapidly, the charging threshold is reduced to increase the output power of ESS. Fig. 9 is the membership function of SOC, ΔI_{sc} and charging threshold respectively, where ΔI_{sc} and charging threshold are normalized results.

B. Discharging Control Strategy

The discharging control strategy of ESS with fuzzy logic controller is shown in Fig. 10. The input of the fuzzy control is the SOC and current difference of the supercapacitors. The output of the fuzzy control is the discharging reference voltage. The concept of fuzzy sets is the same as that of charging. $U_{\text{dis,ref,max}}$ and $U_{\text{dis,ref,min}}$ are the maximum and minimum values of the reference discharging voltage, respectively. When the bus voltage reaches the discharging threshold, the ESS discharges with the discharging reference voltage of fuzzy control output.

Table III is the discharging fuzzy control rules. The specific control strategies are as follows: when SOC is large, the discharging reference voltage is set to be greater than or equal to the no-load voltage, which keeps the ESS dischargs

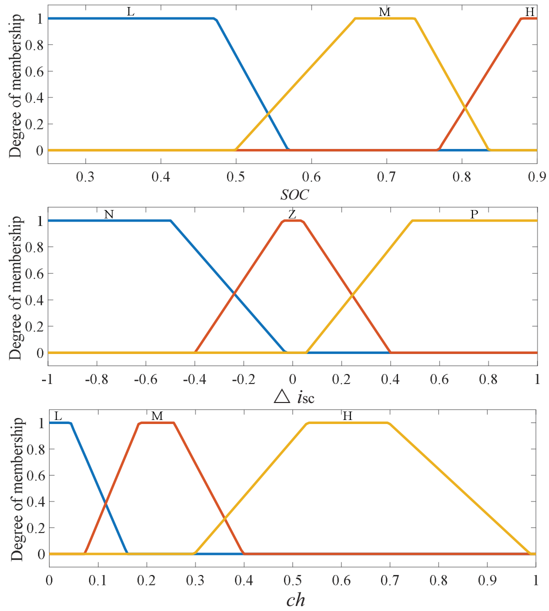

Fig. 9. Membership functions of input and output variables

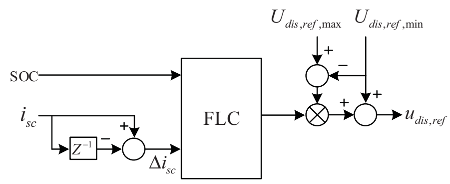

Fig. 10. Discharging control strategy based on fuzzy logic control

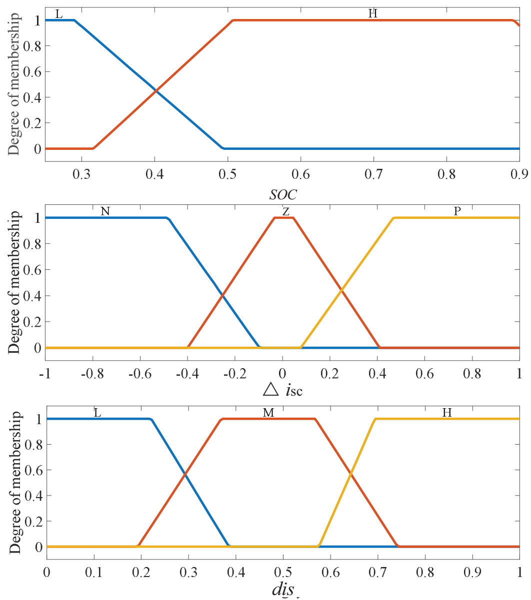

Fig. 11. Membership functions of input and output variables

first and reduces the output of the rectifier unit; when SOC is small, the discharging reference voltage should be reduced appropriately, and the energy requirement of traction train should be provided by the ESS and rectifier unit together. In this process, the maximum discharging reference voltage should be guaranteed to be less than the minimum charging threshold of the ESS to prevent its misoperation. The membership functions of input and output variables are shown in Fig. 11.

TABLE III. FUZZY CONTROL RULES FOR DISCHARGING

SOC	△Isc		
	N	*Z*	*P*
L	L	M	M
H	M	H	M

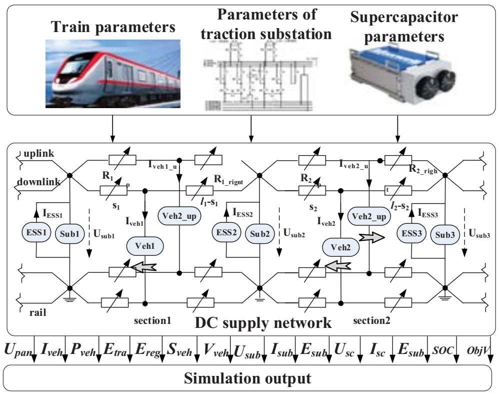

Fig. 12. Traction power supply simulation platform

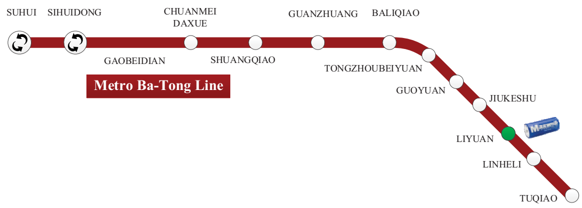

Fig. 13. Line diagram of Batong Line

TABLE IV. PARAMETERS OF THE ESS

Parameter	Value	Parameter	Value
Input voltage	500~1000 V	**Capacity**	235.6 F
Rated current	4000A	**Rated voltage**	672 V
Output voltage	336~637 V	**Internal resistance**	4.41mΩ
SOC range	0.25~0.9	**Energy**	14.8kWh

TABLE V. PARAMETERS OF CONTROL STRATEGY

Parameter	Value	Parameter	Value
$U_{dis,ref,max}$/V	860.9	$U_{dis,ref,min}$/V	859
U_{dis_th}/V	859	U_{ch_min}/V	861

TABLE VI. STATISTICAL RESULTS OF ENERGY BEFORE AND AFTER ADDING FUZZY CONTROL

Parameter	Before	After
Output energy of rectifier Unit /kWh	43.5	37.4
Cumulative release energy of the ESS /kWh	51.9	64.2

IV. SIMULATION VERIFICATION

A. Simulation Condition

In order to verify the effectiveness of the fuzzy control strategy for regenerative braking energy recovery, a simulation model of the fuzzy logic control strategy is built on the basis of the traction power supply simulation system of Beijing Metro Batong Line. Fig. 12 is a simulation platform for urban rail power supply system, which includes multi-train operation model, traction substation model and ESS model , and the energy interaction among traction substation, energy storage device and train is obtained by power flow analysis [15-16]. Fig. 13 is the route diagram of Batong Line, in which Liyuan Station is a traction substation with supercapacitor energy storage system. Table IV and Table V are the simulation parameters, where U_{dis_th} is the discharging threshold, when the network voltage is less than the discharging threshold, the ESS starts to discharge with the discharging reference voltage. U_{ch_min} is the minimum value of charging threshold, which is greater than the maximum value of the discharging reference voltage to prevent mischarging .

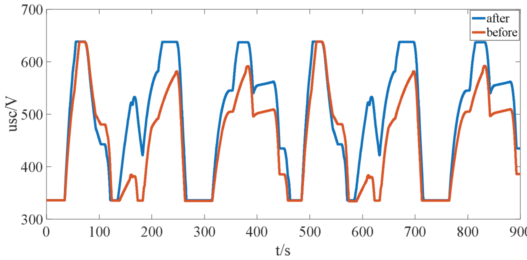

Fig. 14. Comparison curve of super capacitor voltage under two strategies

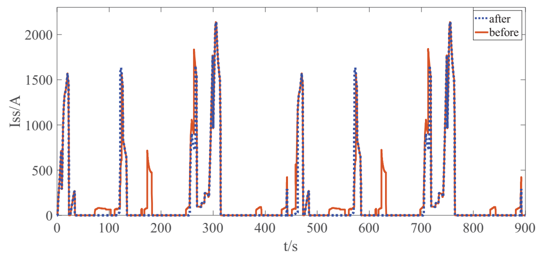

Fig. 15. Comparison curve of output current of rectifier unit under two strategies

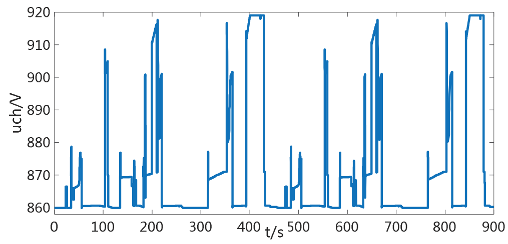

Fig. 16. Dynamic charge/discharge threshold curve based on fuzzy control

B. Simulation Result

The ESS is controlled by the control strategy based on train operation state and the dynamic charging/discharging threshold strategy based on fuzzy logic control proposed in this paper. When the departure interval is 450s, the voltage waveform of the supercapacitors and the output current waveform of the rectifier unit are obtained as shown in Fig. 14 and Fig. 15, respectively. From Fig. 14, it can be seen that the ESS absorbs more regenerative braking energy after adding the fuzzy logic controller. In Fig. 15, when the time is 100s, 170s, 400s and 620s respectively, the ESS gives priority to discharge, the operation times of rectifier unit are reduced and the energy saving is increased.

Fig. 16 is the variation curve of charging/discharging threshold of ESS based on fuzzy control strategy. It can be seen that the charging/discharging threshold of the system can be reasonably adjusted in real time by using the fuzzy logic control. Table VI shows the statistical results of energy release of rectifier unit and ESS under two strategies. After adding fuzzy logic controller, the output energy of rectifier unit decreases by 14%, the cumulative output energy of supercapacitors increases by 23.7%, and the recovery utilization rate of regenerative braking energy is increased, which verifies the effectiveness of the control strategy proposed in this paper.

V. Conclusion

In this paper, aiming at improving the recovery efficiency of regenerative braking energy of urban rail transit trains, a dynamic charging/discharging threshold based on fuzzy logic controllor is proposed considering the influence of train operation state, SOC and charging/discharging current of the ESS. Simulation verification of the effectiveness of the control strategy is performed based on the actual subway line. The results show that the system recovers more regenerative braking energy after adding fuzzy control, the output of the rectifier unit is significantly reduced, and the energy saving of the system is increased, which effectively proves the feasibility of the control strategy. In the subsequent research, the parameters of the fuzzy logic control will be optimized by comprehensively considering the lifetime and energy savings of the ESS.

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