Dynamic Threshold Adjustment Strategy of Supercapacitor Energy Storage System based on No-load Voltage Identification in Urban Rail Transit

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***Abstract*—The stationary supercapacitor energy storage systems (SCESS) in urban rail transit systems can effectively recover the regenerative braking energy of the trains and reduce the fluctuation of the traction network voltage. Generally, the charge/discharge states of SCESS is determined by the voltage of the traction network; however, in actual operation, the fluctuation of the no-load voltage of the substation may result in unexpected working states of SCESS, such as barely charge/discharge. Therefore, a dynamic threshold adjustment strategy based on no-load voltage identification is proposed in this paper: the output characteristic equation of substation is fitted in real-time with the recorded substation currents and voltages, and the present value of no-load voltage is predicted by the neural network, based on which the charge and discharge thresholds of the SCESS are adjusted dynamically. Through the proposed identification method, the variation trend of the no-load voltage of Liyuan Substation in Beijing Metro Batong Line in the whole day is analyzed. Besides, simulation results show that with the proposed dynamic threshold adjustment strategy, the SCESS is charged and discharged more effectively, and the energy saving effect is significantly improved.**

Keywords—traction substation, no-load voltage, energy storage, control strategy, urban rail

I. Introduction

Nowadays, regenerative braking is used widely in urban railway vehicles. Due to the short distance between stations, the trains start and stop frequently, generating impressive regenerative braking energy. In order to reduce the operating energy consumption of urban rail transit, different regenerative braking energy recovery methods have been extensively studied and applied to actual subway lines [1], including train operation adjustment [2], energy feeding system and energy storage systems such as batteries, super capacitors, flywheels, etc [3]. As the super capacitor has the advantages of high power density and long cycle life, it presents good regenerative braking energy recovery potential [4].

The control of the SCESS mainly concerns energy management and converter control: the energy management strategy (EMS) regulates the power flow between the energy storage system, the urban rail train and the substation. At present, a large number of literatures have proposed different types of EMSs, including EMS based on traction network voltage [5, 6], SOC tracking strategy [7, 8] and optimization-based strategies [9]. As the traction network voltage is the joint result of multiple trains and traction substations in the subway line section, it directly reflects the energy consumption and regeneration in the power system. Therefore, the control strategy based on the traction network voltage is applied widely in actual operation of energy storage systems in metro systems. However, under the fixed-threshold voltage strategy, the energy-saving effect of SCESS is affected by train operation states, departure interval, no-load voltage of the traction substation, etc. In order to adapt the working state of the energy storage system to the changes of the state of trains and substations, and optimize the energy saving effect of SCESS, different dynamic threshold adjustment methods are proposed. In [10], the charge threshold voltage is calculated with respect to the distance between the train and the energy storage device as well as the train's pantograph voltage to reduce the intervention of braking resistors, and optimize the regeneration energy transmission efficiency. An online optimization control strategy is proposed in [11], which optimize the voltage thresholds offline at different headways, and then make adjustment in real time according to the changes of energy savings rate. As the voltage of the urban AC grid varies with the load of the city electrical load, the no-load voltage of the substation will also fluctuate within a certain range throughout the day, which will also affect the charge and discharge state of the energy storage device and the power distribution between the substation and the energy storage system. In order to alleviate the influence of no-load voltage fluctuation on SCESS operation, [12] detects the voltage of 10kV AC network, and calculates the no-load voltage of the rectifier unit with respect to the theoretical relationship of input and output voltage of the rectifier. However, the calculation formula is based on the premise that the medium-voltage AC network is an ideal power source for the traction power supply system. As a matter of fact, in addition to the influence of the city electrical load, the powering and braking of the trains in the traction power supply system also have a large impact on the voltage of medium-voltage AC network. Therefore, the results calculated with theoretical formula in [12] may deviates from the actual value.

In order to identify the no-load voltage of the substation more accurately and improve the energy-saving and voltageregulating effect of the SCESS, a no-load voltage identification method based on the output characteristics of the substation is proposed in this paper: firstly, according to the historical operation data of the substation, the discharge cycle is extracted, and the output voltage-current equation of the substation are fitted in the past time instants, based on which the corresponding no-load voltage is obtained by linearly extrapolatin; then the identification values of the no-load voltage in the past time instants are input into the neural network to predict the no-load voltage at the current time instant; Finally, with respect to the obtained no-load voltage prediction value, the charge and discharge voltage threshold of the SCESS is adjusted dynamically. The no-load voltage of Liyuan substation of Beijing Metro Batong Line in the whole day is extracted and analyzed with the proposed identification method, and the effectiveness of the dynamic threshold adjustment method based on the no-load voltage identification results is verified through simulation.

II. SYSTEM CONFIGURATION

A. The SCESS

The DC traction power supply system with SCESS in urban rail transit is shown in Fig. 1. The traction substation obtains 10/35 kV AC medium voltage from the urban power grid regional substation or the main power substation of the subway, converts it to 750/1500V DC voltage through buck and rectification, and provide power for trains. At present, regenerative braking has become the main braking method for urban rail trains: when the train brakes, the kinetic energy is converted into regenerative electric energy and fed back to the traction net through the pantograph. The train is usually equipped with an on-board braking resistor. When the voltage of the pantograph exceeds the starting voltage of the braking resistor, the braking resistor is put into operation, and the regenerative braking energy is converted into thermal energy dissipation, thereby suppressing the surge of the traction network voltage. The energy storage system is installed in the traction substation and connected to the contact network through a bidirectional DC/DC converter. When the train is powering, the energy stored in SCESS is released together with the substation, and the braking energy is recovered and stored in SCESS during the train braking.

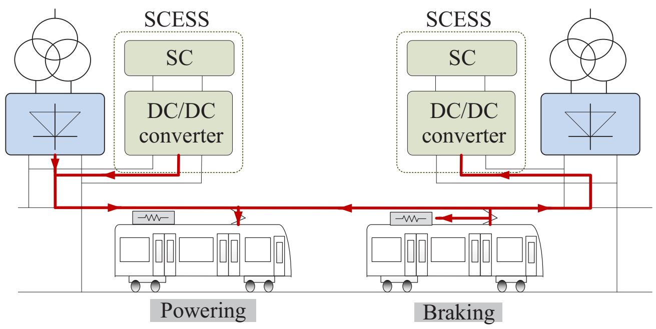


Fig.1 The systematic diagram of the traction power system with energy storage systems

B. The twenty-four pulse rectifier

In order to improve the voltage quality of the traction power supply system and reduce harmonics, the twenty-four pulse uncontrolled rectifiers are used widely in traction substations, as shown in Fig. 2 [13]: the rectifier unit consists of two 12-pulse rectifier transformers and four sets of rectifier bridges. The primary windings of the two rectifier transformers operating in parallel are phase-shifted by ±7.5° by the delta-edge delta connection, so that the line voltages of the four windings of the two rectifier transformers are 15° out of phase with each other, and finally, and finally the 24 pulse DC voltage is obtained with full-wave rectification and parallel operation of the rectifiers.

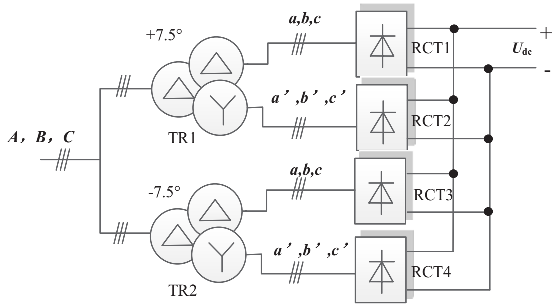


Fig.2 The schematic diagram of the twenty-four pulse rectifier

The characteristic curve of the rectifier unit reflects the relationship between the output voltage of the rectifier unit and the load current. For the 24 pulse rectifier unit, its output characteristic curve is in three straight lines within the rated load range, as shown in Fig. 3. It can be seen from [12] that the ideal DC no-load voltage U_{d0} of the P-pulse rectifier unit is calculated by (1). According to the GBl2325-90 standard, the voltage tolerance of the 10kV AC grid is ±7%, and the output voltage of the secondary side of the rectifier transformer fluctuates with fluctuations in the AC grid voltage.

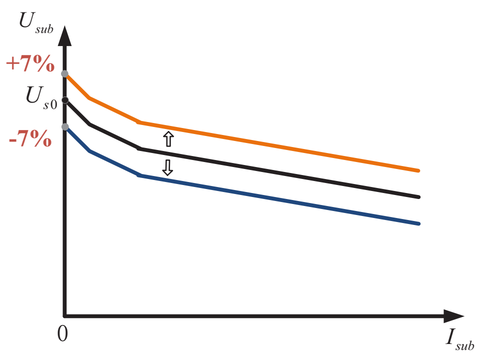


Fig.3 The characteristic curve of the rectifier in traction substations

$$U_{d0} = \frac{P}{2\pi}\int_{-\frac{\pi}{P}}^{\frac{\pi}{P}} \sqrt{2}U_2 \cos\theta d\theta = \frac{\sqrt{2}PU_2}{\pi}\sin\frac{\pi}{p} \qquad (1)$$

Where:

U_{d0} ——no-load voltage of rectifier;

P——number of pulses;

U_{max} ——peak voltage on valve side;

III. CONTROL STRATEGY BASED ON NOLOAD VOLTAGE IDENTIFICATION

A. No-load voltage Indentification

Due to the impact of the urban rail traction network load on the medium voltage AC grid, the no-load voltage of the substation calculated by (1) has a certain deviation from the actual. Therefore, this paper proposes a method for identifying the no-load voltage of substations based on U-I characteristic fitting. The algorithm flow is shown in Fig. 4.

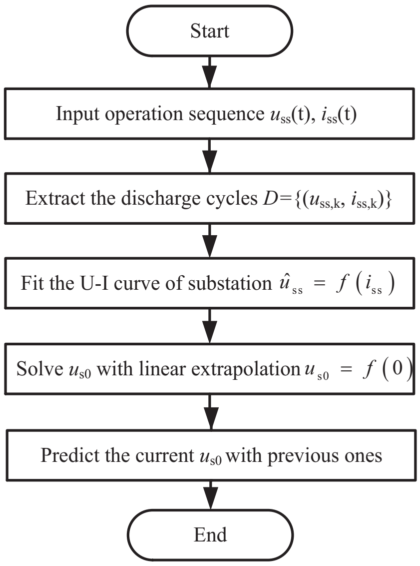


Fig.4 The flowchart of proposed no-load voltage identification method

Step 1: Extract the rectification unit discharge cycle based on the recorded output voltage and current sequence of the rectifier unit. The discharge cycle is a process in which the current of the substation first increases and then gradually decreases when the train near the substation is powering. The discharge cycle starting point t_{st} is defined as the substation current i_{ss} is larger than i_{st}; and the end point of the discharge cycle is when i_{ss} is less than i_{end}. Thereby, a data set of output voltages and currents of the substation in a discharge cycle is obtained as $D=\{(i_{ss,1}, u_{ss,1}); (i_{ss,2}, u_{ss,2}); (i_{ss,i}, u_{ss,i}); ...; (i_{ss,N}, u_{ss,N})\}$.

Step 2: Linearly fit the output U-I curve of the substation with the data set D by the least squares method, i.e., define an one-order function (2) of u_{ss} with respect to i_{ss}, and calculate the parameters of k and b, so that the sum of the squares of deviations between actual values u_{ss} and fitted values u_{ss}' is the smallest, as shown in equation (3).

$$\hat{u}_{ss}(i_{ss}) = k \cdot i_{ss} + b \quad (2)$$

$$\min\ J(k,b) = \sum_{i=1}^{N}\left[u_{ss,i} - \hat{u}_{ss}(k,b;i_{ss,i})\right]^2 \quad (3)$$

Let $\partial J/\partial k = 0$, $\partial J/\partial b = 0$, then a binary quadratic equation group of k and b is obtained, and the optimal estimates of k and b can be obtained by solving the equations.

Step 3: Perform linear extrapolation on the fitted output characteristic equation (2), i.e. substitute $i_{ss} = 0$ into (2), and the identified no-load voltage value is obtained.

Step 4: Since the discharge cycle of the rectifier unit can only obtain the no-load voltage value at the historical time, and the no-load voltage of the substation is time-varying, in order to obtain the present no-load voltage more accurately, this paper uses a two-layer LSTM neural network followed with two fully-connected layers to predict the present no-load voltage. In this paper, the input of the neural network is the historical no-load voltage identification values $u_{s0,k}$, $u_{s0,k-1}$, ..., and the output is the predicted value of the no-load voltage at the $(k+1)$th time instant.

B. Dynamic threshold adjustment method

Fig. 5 shows the block diagram of the dynamic threshold adjustment strategy control proposed in this paper, including threshold adjustment module, working mode selection module and voltage and current double closed loop module. The threshold adjustment module performs the no-load voltage identification of the substation according to Fig. 3, and then calculates the charging threshold and the discharging threshold by (4) and (5).

$$u_{ch} = \hat{u}_0 + \triangle \quad (4)$$

$$u_{ds} = \hat{u}_0 - \triangle \quad (5)$$

Where $\hat{u}_0$ is the predicted value of no-load voltage, $\triangle$ and $\triangle$ denote the differences between charge/discharge threshold voltages and the no-load voltage respectively.

The working mode selection module determines the operating mode of the energy storage system according to the *SOC* (state of charge) value and the substation voltage, as shown in Fig. 6, where u_{ds} and u_{ch} are the discharge threshold and the charging threshold respectively, and u_{sub} is the substation voltage where the SCESS is installed, SOC_{max} and SOC_{min} are the upper and lower limits of *SOC*. When the voltage of the substation is lower than u_{ds}, the energy storage system enters the discharge mode, and the voltage of the substation is stabilized at u_{ds}; when the voltage of the substation is higher than u_{ch}, the energy storage system enters the charging mode, and the regenerative braking energy of the train is recovered, the voltage of the substation is stabled at u_{ch}; when the super capacitor SOC reaches SOC_{max} or SOC_{min}, the energy storage system prohibits charging and discharging, thereby protecting the system. Finally, the voltage-current double-closed loop module uses PI controllers to control the duty cycle of the IGBT drive pulse of the bidirectional DC/DC converter, thereby adjusting the supercapacitor current and stabilizes the network voltage at the reference charge or discharge threshold.

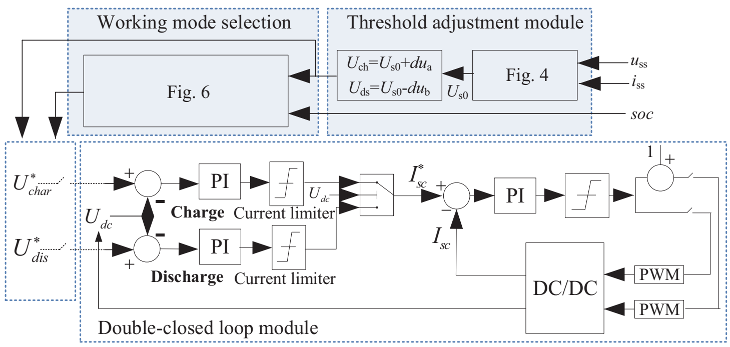


Fig.5 The control block diagram of proposed dynamic threshold adjustment strategy

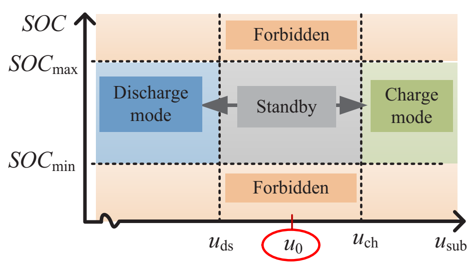


Fig. 6 The working mode selection of SCESS

IV. Strategy Verification

A. Resuts of no-load voltage identification and prediction

In this section, based on the measured data of the Liyuan substation of the Beijing Metro Batong Line, the identification and prediction methods of the no-load voltage proposed in this paper are verified, and the variation trend of the load voltage in the whole day is explained and analyzed.

Fig. 7 shows the waveforms of the 10kV side voltage, the output voltage of the rectifier unit and the output current of the rectifier unit during one day in Liyuan substation. As can be seen from Fig. 7, at 7.99h, the rectifier unit current is nearly 3000A, and the 10kV side network voltage drops abruptl. The author thinks that the equivalent load of 10kV medium voltage AC power supply consists of three parts, namely the equivalent city load, equivalent adjacent substation load and equivalent substation load. For the equivalent urban load, it is related to the fluctuation of the daily electricity consumption of the city; and for the load of the subway system, it is related to the traction and braking conditions of the trains of the station and other stations. As can be seen from Fig. 7, the 10kV side voltage is greatly affected by the load on the traction network side, which is not considered by equation (1).

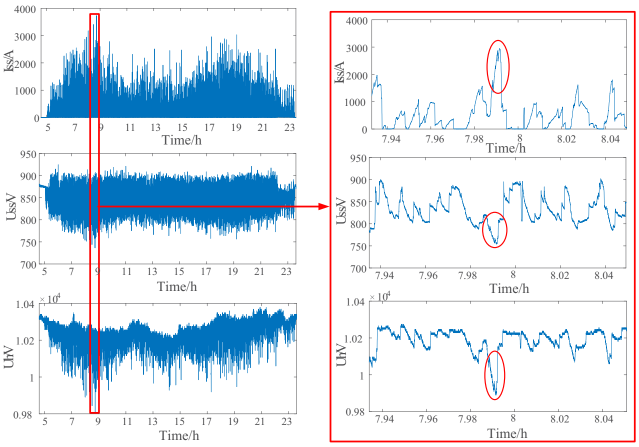
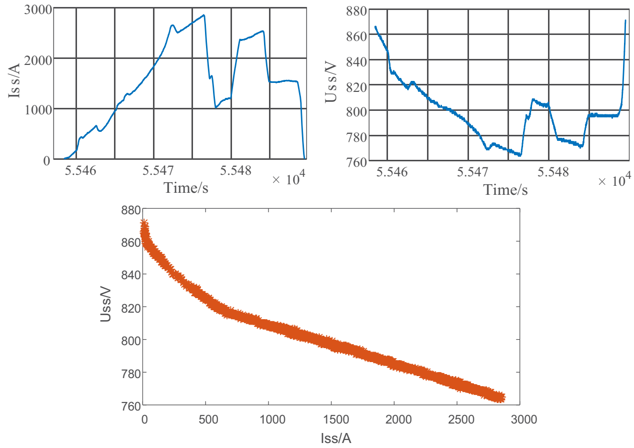


Fig. 7 The operating curves of Liyuan Station in one day

The no-load voltage of the substation is identified and predicted by the method shown in Fig. 3 presented in this paper. Fig. 8 shows the voltages and currents of substation in a discharge cycle, (a) is the substation current, (b) is the substation voltage, and (c) is the current-voltage scatter plot, which is consistent with the theoretical output characteristic curve in Fig. 8, consisting of three segments of straight lines. According to step (2) in Section III. A, linear fitting is performed by least square method to obtain the output characteristic formula of the substation, as shown in (6); and the no-load voltage value at that moment is obtained with linear extrapolation in step (3) , which is 861.3V .



(c)

Fig. 8 The voltages and currents of substation in a discharge cycle

$$u_{ss}=\begin{cases}876.86-0.463\cdot i_{ss}\ ,\ i_{ss}\le 39\\ 861.3-0.067\cdot i_{ss}\ ,\ 39\le i_{ss}\le 672\\ 832.1-0.0236\cdot i_{ss}\ ,\ i_{ss}\ge 672\end{cases}\tag{6}$$

Similarly, the curve of no-load voltage in the whole day is obtained, as shown in Fig. 9. It's observed from Fig. 9 that the no-load voltage is higher in the morning and night, it gradually decreases during 05:00-10:00, and a small peak appears at around 12:00, finally keeps rising during14:00-23:00, which is consistent with the daily variation trend of city electricity load, which validates the effectiveness of the identification method in proposed this paper. And the lowest no-load voltage in the day appears at 14:00, which is 870V; and the highest no-load voltage occurs at 05:00 in early morning, which is 899V.

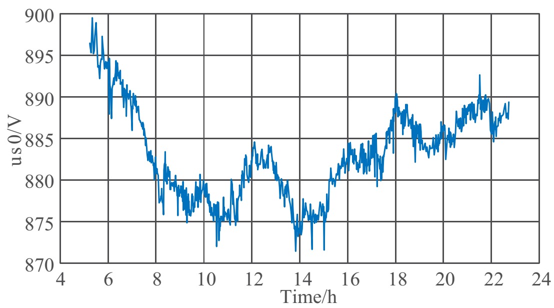


Fig. 9 The curve of no-load voltage in Liyuan Station during one day

Fig. 10 shows the change of no-load voltage within one week. The trend of no-load voltage change in substations in different days is similar to that in Fig. 9. It gradually decreases from the morning, with a small peak at noon and finally rises from afternoon to evening. It's noticed from Fig. 10 (a), (b), (c) that there is a sudden increase when the no-load voltage is below 870V; and in Fig. 10 (c), a voltage jump occurs when the no-load voltage is above 900V, which ensures that the output voltage of the substation is within a reasonable range.

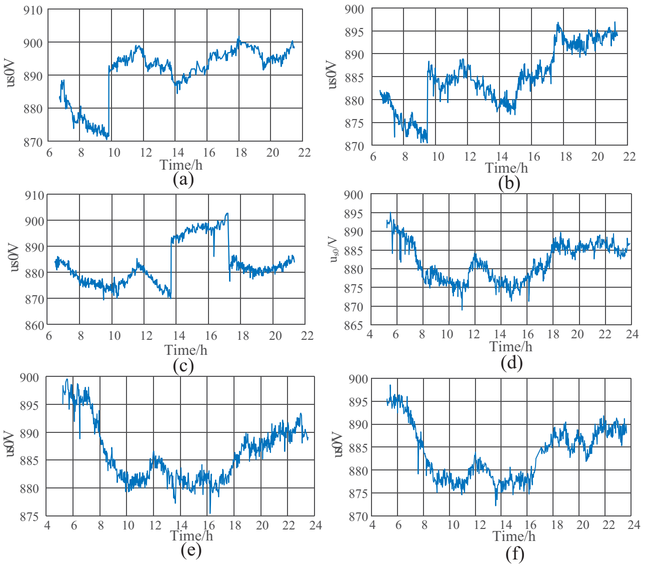


Fig. 10 The curve of no-load voltage in Liyuan Station in different days

In order to obtain the current no-load voltage, the identification values at k time instants before are input to the neural network shown in Fig. 4, and the no-load voltage predicted value at the (k+1)th time instant is output by the neural network. The data in the last five days are used to train the neural network, and the data of the sixth day is used for evaluation. Fig. 11 shows the predicted and identified values of the full-day no-load voltage. It's shown that the predicted results match well with the identification value, the maximum error is within 6V, which occurs rarely in the abrupt-change point, thus the accuracy of the prediction method is verified.

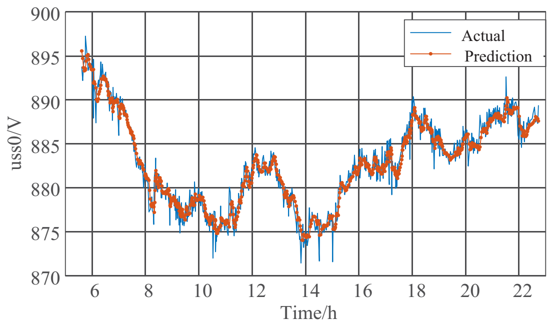


Fig. 11 The predicted results of no-load voltage

B. *Verification of threshold voltage adjustment*

In this section, simulations are conducted to illustrate the influence of no-load voltage fluctuation on working states of SCESS, as well as verify the proposed dynamic threshold adjustment strategy based on no-load voltage identification. Fig. 12 shows the route map of simulation section, which contains 3 traction substations (Guoyuan, Liyuan and Tuqiao) and 2 passenger stations (Jiukeshu and Linheli), the SCESS is installed at Liyuan station, which has a peak power of 1.34MW and the stored energy is 7.4 kWh. In simulation, the headway of trains is 360s, and the no-load voltage of substation is 870V during the first headway, and rises to 895V in the second headway.

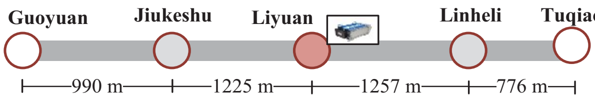


Fig. 12 The simulation section of Batong Line

TABLE I. SIMULATION PARAMETERS

Parameters	*Unit*	*Value*
Train set	-	3M3T
Weight in AW3	t	312.9
Rated motor power	kW	180
Rated voltage of power system	V	750
Regenerative limit voltage	V	900/970
Unit contact line impedance	Ω/km	0.007
Unit rail impedance	Ω/km	0.009
SCESS modules	-	Maxwell 48V/165F
SCESS connections	-	14S10P
SCESS rated voltage	V	672
SCESS rated capacitance	F	117.8

Fig. 13 (a) and (b) compare the supercapacitor voltages under the fixed-threshold strategy and the proposed strategy with no-load voltage identification, Fig. 13 (c) shows the charge/discharge threshold voltages under the proposed strategy. For the fixed-threshold strategy, u_{ch}=875V, and u_{ds}=865V. In the first headway, the SCESS charges and discharges effectively under the two strategies, and the total energy consumption is 80.0 kWh. However, during the second headway, when the no-load voltage of substation rises to 890V, the SCESS is barely discharged under the fixed-threshold strategy. It's explained with Fig. 14: when the no-load voltage rises higher than u_{ch}, the SCESS charges even when the trains are powering and the substation voltage is lower than no-load voltage, which is undesired as the SCESS is easy to be fully-charged and cannot recover regenerative energy when the trains are braking. Therefore in the second headway, the energy consumption is increased to 94.3 kWh under the fixed-threshold strategy. However, under the proposed strategy, the threshold voltages are adjusted dynamically with respect the identified no-load voltage (as seen in Fig. 13 (c), the identification method including step 1-3 is conducted, and the rise of no-load voltage is recognized at 411s), and the SCESS is working on the appropriate mode, thus it's able to recover the regenerative braking energy more effectively, and the energy consumption in the second headway is 85.0 kWh, which is similar with that in the first headway, verifying the SCESS adapts to the change of substation state and keeps good energy saving ability.

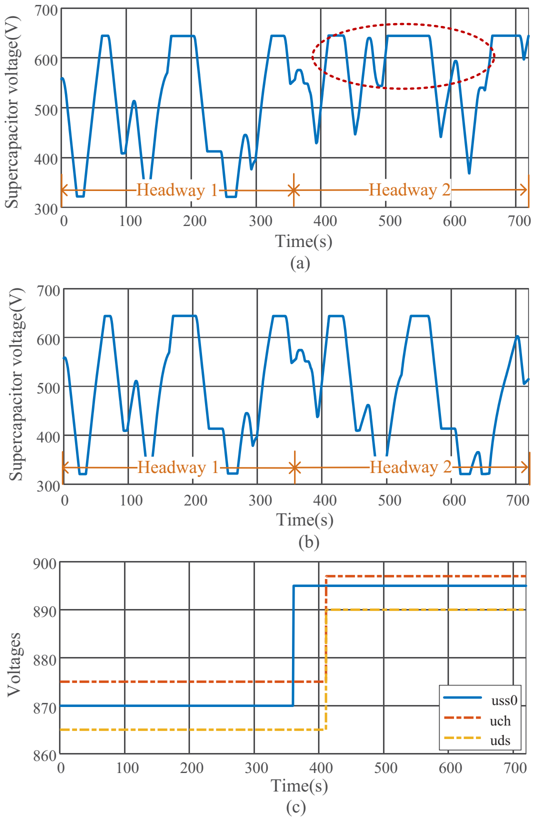


Fig. 13 The operating curves of SCESS

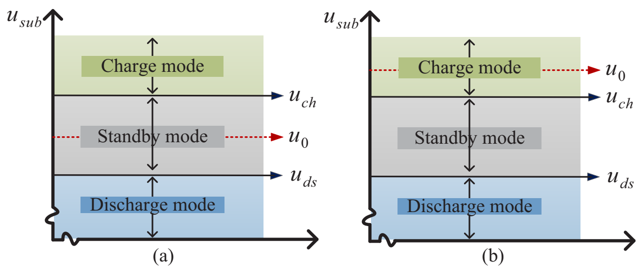


Fig. 14 The influence of no-load voltage fluctuation on working states of SCESS

V. Conclusion

Considering that the medium voltage AC power grid is affected by the load of the traction power supply system, this paper proposes a no-load voltage identification method, which is based on the real-time fitting of the output characteristics of the substation. The variation trend of no-load voltage throughout the day is analyzed with the measured operation data of Liyuan substation of Beijing Batong Line, providing a reference for the control strategy design of the energy storage system. Based on the no-load voltage identification, a dynamic threshold adjustment scheme is proposed, which attemps to realize the adaptation of ESS working states to the change of the operating state of the substation. The simulation results show that after identifying the no-load voltage, the energy storage system is operating in more reasonable states, which makes the ESS recover braking energy more effectively. And compared with the fixed threshold strategy, the system energy consumption is significantly reduced.

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