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Hybrid energy management strategy based on dynamic setting and coordinated control for urban rail train with PMSM

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Abstract
Due to the short distance between stations, frequent acceleration and braking for urban rail trains cause voltage fluctuation in the traction network and the regenerative braking energy loss. In this study, a hybrid energy storage system (HESS) was proposed to recover braking energy and stabilize the traction network voltage, where the on-board ultracapacitors were used to accommodate the rapid exchange of acceleration and braking energy of the permanent magnet traction system while the lithium batteries installed in the bilateral stations provided stable and long-lasting energy exchange, which can stabilize traction network voltage and be charged at off-peak night time. In order to realize the energy coordinated control between the permanent magnet traction system and HESS, a real-time energy management strategy was proposed to dynamically allocate the traction power based on the principle of giving priority to on-board ultracapacitors while lithium batteries as auxiliary power supply. Moreover, the charging and discharging voltage thresholds of the lithium batteries were dynamically set according to train positions and their charge status. Comparing with the traditional strategies, the RT-LAB semi-physical real-time simulation shows that the proposed strategy can provide more effective energy allocation, and stabilize the voltage fluctuation while maximizing the energy saving.

1 | INTRODUCTION

A large amount of energy is consumed for urban rail transit trains at acceleration while a large amount of regenerative braking energy is generated when braking [1]. Due to the short distance between stations, frequent acceleration and braking of urban rail transit trains cause voltage fluctuation in the traction networks as well as the loss of regenerative braking energy. How to suppress the traction network voltage fluctuation, recover the braking energy effectively and improve the train traction and braking characteristics are becoming more and more important recently in the rail transit research field [2].

Due to the random nature of regenerative braking energy, it is often stored to be used later [3]. The systems of braking energy storage can be roughly divided into vehicle-mounted and ground-mounted system according to where they are positioned. The former can quickly recover part of the braking energy, which is then used to start and accelerate the train. The advantage of this method is the small transmission power loss [4], but it suffers from the extra load of the train. The latter does not take up train space and cargo capacity, but its line loss can be large [5].

As a new type of energy storage devices, ultracapacitors have attracted much attention in the field of rail transit due to its advantages such as high-power density, fast response and long cycle life [6, 7]. Combined with the ultracapacitors, an energy management strategy, based on status of charge (SOC), was proposed in [8], which can effectively reduce power consumption and implement braking energy recovery by making full use of ultracapacitor's capacity. An ultracapacitor-based dual-mode control active stabiliser was proposed in [9], where the hardware-in-the-loop simulation results showed that the system stability was improved and the DC voltage fluctuation was reduced. However, these devices are not able to meet the dual
requirements of high power and high energy, therefore new techniques are needed. In recent years, hybrid energy storage systems (HESS) with batteries and ultracapacitors have been widely used in electric vehicles, which are able to take full advantages of ultracapacitors with large instantaneous power, battery with large energy and extended battery life [10, 11].

In the field of urban rail transit, an optimal method with the minimum energy storage capacity configuration and an optimal recovery power target has been proposed for an on-board HESS [12], which can quickly recover braking energy and be used for starting and accelerating. The results showed that this method can effectively reduce operating costs and save energy, but in reality, the capacity of pure on-board energy storage system (ESS) is difficult to configure and increases train load, resulting in high costs. Therefore, it is necessary to consider a reasonable energy storage structure associated with a well-designed energy management coordination strategy for controlling the charging and discharging of HESS, which will enable two-way energy flow among the trains, power supply network and the energy storage devices [13].

In terms of control strategies, the traditional charge and discharge control strategies usually adopt voltage–current double closed loop control with full state variable feedback [14], which directly sets the charge and discharge voltage threshold and detects the traction network voltage to determine the working mode of the ESS. Such control strategies are simple and easy to implement. However, due to the time-varying and non-linear nature of the DC traction power supply networks, a constant charge and discharge threshold without combining with the train dynamic operating characteristics would not lead to optimal energy storage effect. Therefore, it is necessary to set the charging and discharging voltage thresholds of the energy storage elements according to the actual status and real-time data. In [15], a traction power supply model is established based on an ESS with ultracapacitor, and a braking voltage following energy management strategy considering the train operation state, which effectively improved energy saving during train braking. [16] considered the line loss and proposed a useful method for predicting the instantaneous regenerative energy as well as a reasonable configuration of the ground ultracapacitor's capacity for each station, which is delivered to each station before applying ESS. The results showed that the energy-saving effect and economic benefit were excellent, but the train model was simulated by a simplified controlled current source which still has a gap with the real train operating conditions. In [17], lithium capacitors were used to recover braking energy, which combined the power density of ultracapacitors and the energy density of lithium batteries, and calculated the voltage and current in real time based on train inertia and acceleration estimates. However, the energy exchange between the permanent magnet traction system and ESS were not considered.

Therefore, there is an urgent need to study how to combine the train operating characteristics with the maximum energy-saving charge and discharge threshold selection and the minimum power line loss to achieve the optimal utilisation of braking energy and effectively stabilise the DC traction voltage.

Here, based on the traditional braking energy recovery structure, a minimum line loss HESS structure, combined with the on-board ultracapacitors and the complementary characteristics of the station bilateral batteries, and an energy management strategy of dynamic setting and coordination optimisation is proposed to achieve coordinated energy control and the optimal energy saving while stabilising the voltage. The on-board ultracapacitors are used for train acceleration and braking energy exchange of the permanent magnet traction system, and the batteries installed in the stations are used to stabilise the DC traction network voltage. The permanent magnet traction power is allocated dynamically in real time according to the on-board ultracapacitor charge status. Moreover, the charge and discharge thresholds of station bilateral batteries are dynamically set in terms of train traction positions and their charge status. Each unit in the proposed control strategy is designed and its feasibility is verified with RT-LAB semi-physical real-time simulation. The rest of this paper is organised as follows: Section 2 introduces HESS structure and the proposed control strategy in details. In Section 3, the details of the experiments are provided for the purpose of validation of the proposed control strategy. Finally, conclusions are drawn in Section 4.

2 | TRACTION POWER SUPPLY STRUCTURE

2.1 | System components

The proposed traction power supply structure of an urban rail train is shown in Figure 1, which is composed of four parts: traction substations, DC traction grids, station bilateral battery ESS, an urban rail train with permanent magnet synchronous motor (PMSM) and on-board ultracapacitor ESS. The urban medium-voltage AC grid is transmitted to DC traction power grid through feeder lines after voltage reduction and rectification of traction substations. The 750 or 1500 V direct current required for the normal operation of the urban rail train is supplied through the catenary and the train pantograph, and a loop is then formed through the third rail (steel rail) and the return lines. The on-board ultracapacitor bank and station batteries are connected in parallel to the DC traction grids through bidirectional DC-DC power converters (BDC) to achieve energy exchange between HESS and the DC traction grids.
The train travels in a power supply section between adjacent substations, and the substations within the same power supply section supply power to the train at the same time, that is, the bilateral parallel power supply mode [18]. Compared with the traditional unilateral power supply mode, it can guarantee uninterrupted train power supply and improve the reliability of power supply and the train’s operation safety. However, in current bilateral mode, individual ESS operates independently and there are no coordinated control strategies for energy flows among these ESS, leading to energy saving and maximum utilisation unguaranteed. Therefore, this study will consider the energy coordination and optimal control between the permanent magnet traction system and HESS in the same power supply section for a PMSM train.

2.2 Energy management strategy of HESS based on dynamic setting and coordinated control

The overall schematic diagram of HESS with dynamic settings and coordinated control is shown in Figure 2. It is divided into the following parts: the coordinated control of the permanent magnet traction system and HESS, the dual-loop cascade control of the on-board ultracapacitors, the dual-loop cascade control of the station batteries based on dynamic threshold setting, the station battery current limit link and the BDC. The coordinated control of the permanent magnet traction system and HESS perform real-time dynamic allocation of the traction power according to the charge status of ultracapacitors. The dual-loop cascade control of on-board ultracapacitors mainly accommodates the rapid exchange of accelerating and braking energy with permanent magnet traction system, and the station battery double-loop cascade control dynamically sets the battery charging and discharging voltage threshold by tracking the train real-time positions and the bilateral battery charge–discharge status. This system finally realises the energy coordinated control between permanent magnet traction and HESS to achieve optimal energy saving and voltage stabilisation.

2.2.1 Coordinated control of permanent magnet traction system and HESS

The schematic diagram of the hybrid energy storage coordination control strategy based on traction power feedforward is shown in Figure 3. Based on the principle that the on-board ultracapacitors is responsible for the main traction power exchange while the station bilateral batteries stabilise the DC traction voltage and auxiliary power supply, the focus is on the coordinated control and energy management of HESS and the permanent magnet traction system. First, the traction power demand \( P_{\text{load}} \) is calculated by detecting angular speed \( \omega \) and electromagnetic torque \( T_e \) in the PMSM speed control loop. The power demand of HESS \( P_{\text{hess}} \) is got by power correction value \( \Delta P \) and \( P_{\text{load}} \) from PI loop of traction network voltage through feedforward. \( U_{\text{sc}} \) and \( U_{\text{sc char}} \) are the given charge and discharge thresholds of ultracapacitors, respectively. \( U_{\text{dc}} \) is the DC traction network voltage. The given power assigned to the on-board ultracapacitors \( P_{\text{sc ref}} \), the given station battery power \( P_{\text{bat ref}} \) and the given grid power \( P_{\text{dc ref}} \) is then got by dynamic power allocation proportional link \( \alpha \). \( \text{SOC}_{\text{uc}} \) is the ultracapacitor charge status. \( i_{\text{sc ref}} \) is the current allocated to the on-board ultracapacitors. \( I_{\text{L-sc}} \) is the inductive current of the DC–DC converter in parallel with the ultracapacitors. The energy allocation of each energy storage element is got by actual train traction power coordination control.

The dynamic power allocation ratio link \( \alpha \) is to coordinate the power allocation of HESS, and \( \alpha \) is determined by real-time detection of \( \text{SOC}_{\text{uc}} \) charge status of the ultracapacitors, as shown in Figure 4. \( \alpha_{\text{char}} \) and \( \alpha_{\text{dis}} \) are the ratio of charging and discharging in the \( \alpha \) link, respectively. When the train starts, the ultracapacitors take full advantage of their fast response characteristics and bear the main fluctuating power peak until the ultracapacitors capacity gradually drops to the minimum protection range. In order to avoid damage due to over-discharge, \( \alpha_{\text{dis}} \) is gradually reduced at this time, so that the station batteries and power grid can obtain more traction power allocation.
and over-discharging protection for ultracapacitors. The calculation of $\alpha_{\text{dis}}$ is shown in Equation (1). Similarly, the ultracapacitors bear the main fluctuating power during train braking. The given power allocated to the ultracapacitors is decreased by gradually reducing $\alpha_{\text{char}}$ while the power given to the batteries and the grid is increased to avoid the ultracapacitor damage due to overcharge as shown in Equation (2):

$$\alpha_{\text{dis}} = \begin{cases} 
0, & \text{SOC}_{\text{uc}} \leq 0.25 \\
20 \times (\text{SOC}_{\text{uc}} - 0.25), & 0.25 < \text{SOC}_{\text{uc}} < 0.3 \\
1, & \text{SOC}_{\text{uc}} \geq 0.3
\end{cases}$$ (1)

$$\alpha_{\text{char}} = \begin{cases} 
1, & \text{SOC}_{\text{uc}} \leq 0.85 \\
20 \times (1 - \text{SOC}_{\text{uc}}), & 0.85 < \text{SOC}_{\text{uc}} \leq 1
\end{cases}$$ (2)

A dynamic capacitance correction factor $C_u$ based on electromotive force is used to calculate the charge status of the ultracapacitors [19], as shown in Equation (3). The maximum estimated errors are reduced to 3.4%, 2.8% and 2.5%, respectively, at random currents under the temperatures 10, 25 and 40$^\circ$C.

$$\text{SOC}_{\text{uc}} = \frac{U(t) - U_{\text{scmin}}}{U_{\text{scmax}} - U_{\text{scmin}}} C_u$$ (3)

where, $U(t)$ is the real-time electromotive force of the ultracapacitors, and $U_{\text{scmax}}$ and $U_{\text{scmin}}$ are the maximum and minimum discharge voltages before normalisation, respectively. $C_u$ is the correction factor.

### 2.2.2 On-board ultracapacitor double-loop cascade control

The on-board ultracapacitors adds traction power feedforward based on the voltage and current double-loop cascade control, which is used to accommodate the rapid exchange of acceleration and braking energy of permanent magnet traction system. The control block diagram is shown in Figure 5. The charge and discharge reference current $I_{\text{SC,ref}}$ is got after $P_{\text{SC,ref}}$ given by $\alpha$. The difference between $I_{\text{SC,ref}}$ and the actual charge and discharge feedback inductor current $I_{\text{L,dc}}$ is adjusted by the current PI inner loop and the duty ratio $D$ driving the BDC switching device is got through PWM control.

In Figure 5, $G_{\text{eq}}$ and $G_{\text{eq}}$ are the open-loop small-signal transfer functions of $D$ to inductor current $I_{\text{L}}$ and $I_{\text{L}}$ to traction network voltage $U_{\text{dc}}$, respectively. Their calculation is given in Equation (4) [20]:

$$G_{I_{\text{L}},d}(j) = \frac{K_p K_f U_{\text{dc}} C_{\text{sc}}}{L C_{\text{sc}}^2 + R_{\text{ES}} C_{\text{sc}} + 1},$$

$$G_{E_{\text{eq}},I_{\text{L}}}(j) = \frac{K_p K_f U_{\text{dc}} C_{\text{sc}}}{L C_{\text{sc}}^2 + R_{\text{ES}} C_{\text{sc}} + 1},$$ (4)

where $U_{\text{dc}}$ is the DC traction network voltage, $K_p$ and $K_f$ are the proportional and integral coefficients of current compensation link $CR$, $K_f$ is the proportional coefficient of voltage compensation link $VR$, $L$ is the inductance, $R_{\text{ES}}$ is the equivalent resistance value. According to Equation (4), current controller $CR$ and voltage PID controller parameters are designed.

### 2.2.3 Double-loop cascade control of current and voltage for station batteries

The station battery control strategy is similar to the ultracapacitor cascade control except traction power feedforward link, the given voltage of the outer ring is determined by the dynamic threshold calculation module, as shown in Figure 6, where battery charging and discharging thresholds are dynamically set by train real-time position $L$ and bilateral station battery charging and discharging status $\text{SOC}_{\text{bat}}$. $i$ indicates the distance between the train real-time position and the next station.

In Figure 6, $U_{\text{ref1}}$ and $U_{\text{ref2}}$ are the battery charging and discharging thresholds reference, $U_{\text{bat, char}}$ and $U_{\text{bat, dis}}$ are the battery charging and discharging thresholds, respectively, $U_{\text{dc, ref}}$ is the rated voltage of the DC traction networks, $\Delta_{\text{bat, max}}$ and $\Delta_{\text{bat, min}}$ are the maximum and minimum given battery current change rate, respectively, The current change rate limit can effectively smooth the given value of battery current, which enable the battery to bear the low-frequency load. The minimum limit $K_c$ is the battery current limit link, $k_c_{\text{char}}$ and $k_c_{\text{dis}}$ are the battery charging and discharging current rate, respectively, $I_{\text{L, bat}}$ is the inductive current of the DC–DC converter in parallel with the battery.

As the $\text{SOC}_{\text{bat}}$ varies with temperature, discharge ratio and cycle time, the ampere–time integral method based on capacity real-time correction is adopted for station battery $\text{SOC}_{\text{bat}}$ calculation to improve its estimation accuracy [21], as shown in Equation (5):

$$\text{SOC}_{\text{bat}}(t) = \text{SOC}_{\text{bat}}(0) + \int_{0}^{t} \frac{\mu I_{\text{bat}}(t) \ dt}{\mu C_{\text{bat}}},$$ (5)

where, $\text{SOC}_{\text{bat}}(0)$ is the battery initial charge status, $I_{\text{bat}}(t)$ is the battery current, $\mu$ is the coulombic efficiency, $\mu_i$ is the multiplier.
correction factor to the battery capacity, $\mu_T$ is the temperature correction factor to the battery capacity, $\mu_H$ is the cycle life correction factor to the battery capacity and $C_{\text{bat}}$ is the capacitive capacity.

Since the line resistance of the train running between stations is time-varying, the line resistance will change in the real simulation. Taking two stations as an example, for each time point, the equation of actual line resistance is as follows [16]:

$$
\begin{align*}
R' &= \frac{k d}{1000} \\
R'' &= \frac{k (d-l)}{1000},
\end{align*}
$$

(6)

where $R'$ is grid lines between the train and the next station resistance ($\Omega$/km). $R''$ is between the train and the station before the grid line resistance ($\Omega$/km); $k$ is the line resistance coefficient, which is set to 0.019 $\Omega$/km, $d$ is the distance between the departure station and the next station, $l$ is the distance between the train and the next station.

The loss in the DC traction networks is considered, ignoring other influence factors such as wire diameter and ambient temperature. The line loss calculation on the transmission line is given as follows:

$$
\begin{align*}
\Delta P' &= \int_{0}^{t} I_{\text{dc}}^2(t) R'(t) dt \\
\Delta P'' &= \int_{0}^{t} I_{\text{dc}}'^2(t) R''(t) dt \\
\Delta P &= \Delta P' + \Delta P''
\end{align*}
$$

(7)

where $\Delta P$ is the line loss power between the train and the battery at the next station, $I_{\text{dc}}'(t)$ is the transmission current between the train and the next station, $I_{\text{dc}}''(t)$ is the transmission current between the train and the departure station and $\Delta P$ is the total line loss power.

In the dynamic threshold calculation module, suppose that the train is towed and started from station A, and braked when entering station B, and the two stations are equipped with station batteries, the train position during the running process is used as the reference. In order to reduce the line losses, the batteries nearer to the train is used mainly to stabilise the energy
consumption. At the same time, the charging and discharging voltage thresholds are set according to the battery charge status, where the higher discharge threshold $U_{\text{bat, dis}}$ to discharge load, the greater the discharge, the lower the threshold $U_{\text{bat, char}}$, the greater the charge. As shown in Equation (8), when the train starts off station A, if $\text{SOC}_{\text{bat}} \geq 0.3$, namely, the station A battery with sufficient discharge margin, then it can get higher discharge threshold and corresponding larger discharge current, while the discharge threshold of station B battery is relatively low. The discharge threshold of station A battery is gradually decreased with the increase of $l$, while the discharge threshold of station B battery is gradually increased. When the station A battery discharge continues, $0 < \text{SOC}_{\text{bat}} < 0.3$, the discharge threshold of station A battery is decreased to the lowest, thus reducing the discharge current, while the discharge threshold of station B battery is increased, thus bearing more voltage stabilization load.

$$U_{\text{bat, dis}} = \begin{cases} U_{\text{ref2}} + k_2 \cdot \text{SOC}_{\text{bat}} \geq 0.3 \\ U_{\text{ref2}} + k_2 \cdot \text{SOC}_{\text{bat}} \leq 0.3, \end{cases}$$

(8)

where $U_{\text{ref2}}$ is the reference constant discharge threshold of a given battery, $k_2$ and $k_20$ are control parameters.

Similarly, when the train decelerates into station B, $U_{\text{bat, char}}$ is determined by Equation (9). When $\text{SOC}_{\text{bat}} \leq 0.85$ at station B, the station B battery gets a lower charging threshold and a larger charging current accordingly compared with that of station A due to the train running distance. When $0.85 < \text{SOC}_{\text{bat}} < 1$ at station B, the station B battery charge is close to full load, and the charging voltage threshold of station A battery is lowered, so that the station A battery can share more regulated load, thereby reducing the burden on the station B battery. Therefore, the energy flow of the bilateral battery ESS is coordinated and controlled by tracking the train real-time travel distance and the $\text{SOC}_{\text{bat}}$ values at each station.

$$U_{\text{bat, char}} = \begin{cases} U_{\text{ref1}} + k_1 \cdot \text{SOC}_{\text{bat}} \leq 0.85 \\ U_{\text{ref1}} + k_1 \cdot \text{SOC}_{\text{bat}} > 0.85, \end{cases}$$

(9)

where $U_{\text{ref1}}$ is the reference constant charge threshold of a given battery, $k_1$ and $k_10$ are control parameters.

### 2.2.4 Model switch

In order to prevent the damage caused by the excessive ESS charging and discharging, the ban mode is set. The switching mode principle of the bilateral battery ESS is shown in Figure 7.

#### 2.2.5 Battery current limit link $k_c$

It is important to consider the safe working range of the station batteries, and prevent them from exiting operation when they are close to full load or insufficient capacity because this will cause a great impact loss to ESS and shock changes in the traction power supply system. Therefore, a battery current limiting link $k_c$ is added to limit the charge and discharge current rate to smoothen the battery power. The battery current limit link $K_c$ is related to $\text{SOC}_{\text{bat}}$, and its discharge current limit coefficient $k_{c, \text{dis}}$ and charging current limit coefficient $k_{c, \text{char}}$ are shown in Equations (10) and (11), respectively. Similar to the power allocation link $\alpha$, when the batteries discharge to a certain depth in the discharge mode, the discharge current is limited; when the battery charge is close to full load, the charging current is limited, which acts as a buffer, effectively avoiding overcharge and over discharge damage of the batteries.

$$k_{c, \text{dis}} = \begin{cases} 0, \text{SOC}_{\text{bat}} \leq 0.25 \\ 20 \times (\text{SOC}_{\text{bat}} - 0.25), 0.25 < \text{SOC}_{\text{bat}} < 0.3, \end{cases}$$

$$k_{c, \text{char}} = \begin{cases} 1, \text{SOC}_{\text{bat}} \geq 0.3 \\ \frac{20}{3} \times (1 - \text{SOC}_{\text{bat}}), 0.85 < \text{SOC}_{\text{bat}} \leq 1. \end{cases}$$

(10)

(11)

### 2.2.6 Half-bridge non-isolated BDC

The BDC is used as the energy exchange link of ultracapacitors or batteries [22], two-way energy transmission between different voltage levels can be achieved by reasonably controlling the conduction ratio of power electronic switching equipment. The half-bridge non-isolated BDC topology is shown in Figure 8.

BDC is actually a reverse parallel combination of Boost-Buck chopper circuits. By controlling the on–off ratio of the two switching tubes $T_1$ and $T_2$, it is possible to switch among the booster, standby and step-down modes to achieve two-way BDC power transmission and input/output quadrants. In the case of starting and accelerating the train, BDC works in acceleration mode, and HESS releases energy to the traction grid. When the train is sliding, HESS is in standby mode. In the case
of train braking deceleration, BDC operates in step-down mode, and HESS recovers energy from the train braking to the traction networks.

3 | SIMULATION AND RESULTS

3.1 | RT-LAB semi-physical real-time simulation

The simulation was done based on the above analysis and the traction network and urban rail transit model established. The simulation adopted a RT-LAB semi-physical real-time simulation system shown in Figure 9, where the traction and train parts adopted a scaled down physical system for verification and RT-LAB DSP simulated the train, substation and HESS.

The terminal voltage fluctuation range of the ultracapacitors was generally set to one third to two thirds of the traction network voltage, and the working voltage range of the ultracapacitors was 500 to 1000 V when $U_{dc_{\text{ref}}}=1500$ V. The capacity specifications of ultracapacitors and lithium batteries were selected according to the actual operating energy range of urban rail transit. Their control parameters are shown in Table 1. The capacity was reduced according to the simulation time and the simulation time was scaled to 2.5 s. The charge and discharge thresholds of on-board ultracapacitors were $U_{sc_{\text{char}}}=1550$ V, $U_{sc_{\text{dis}}}=1450$ V. The initial charge and discharge thresholds of the station batteries were $U_{ref1}=1600$ V, $U_{ref2}=1400$ V.

The conversion relationship between the traction angular speed and the train running speed is given as follows [23]:

$$\omega^* = \frac{1000\mu_a V}{60\pi D_r},$$

where $\omega^*$ is the angular speed in r/min; $\mu_a$ is the transmission ratio, which is set to 6.68; $V$ is the train running speed in km/h; $D_r$ is the wheel diameter in a semi-wear condition, which is set to 0.805 m.

Some simplifications were made in the simulation. The traction acceleration and braking deceleration of the train were approximately regarded as ideal uniform acceleration and the train operation conditions were simplified as constant acceleration traction-constant, power-constant, speed operation-constant deceleration braking when the train run from station A to station B on the simulation platform. The train on this line adopted the form of four EMUs, two trailers and eight motors. The real data was scaled down according to the simulation time and the control parameters $k_1$, $k_{10}$, $k_2$, $k_{20}$ are got in terms of experimental results.
3.2 Simulation result analysis

Assume that the train starts off from station A to station B, leaving station A with starting acceleration at the time of 0 s and arriving at station B with braking deceleration at the time of 1.5 s. The train traction simulation curve is shown in Figure 10, the DC traction voltage comparison under different control strategies is shown in Figure 11, DC traction voltage and energy consumption from station A to station B under different control strategies are shown in Tables 2 and 3, respectively.

As shown in Figure 11 and Tables 2 and 3, under the same initial charge–discharge voltage threshold conditions, when the traction control without HESS is used, the traction network voltage drops to 1320 V in train traction acceleration while increases to 1640 V in train braking deceleration, which has a great impact on the traction network voltage stability. When the traditional voltage–current double closed loop control with station bilateral batteries and ultracapacitor device (HESS1) is used, the traction network voltage drops to 1350 V in train traction acceleration, then begins to slow and steadily increases and stabilises at about 1560 V in train braking deceleration, which is still a gap compared with the given ultracapacitor charge voltage threshold 1550 V. When the proposed control strategy with HESS is used, the energy exchange is on the principle of giving priority to on-board ultracapacitors while station bilateral batteries as auxiliary power supply, which plays a role of peak cutting and valley filling. The traction network voltage drops to 1400 V in train traction acceleration, then rapidly increases and stabilises at about 1550 V. Compared with the traditional control, the proposed HESS can get faster response and make the traction network voltage return to stability faster. When the train is in train braking deceleration, the traction network voltage can be stabilised in the range of 1400 to 1550 V. Moreover, as shown in Table 3, the braking energy absorbed and released by proposed HESS can be greatly improved through dynamic and coordinated control. Its energy-saving efficiency reaches 37.6%, which is a significant improvement of 12.6% compared with the traditional control.

The real-time allocation of traction power is shown in Figure 12 and power variation range is shown in Table 4. It can be observed that the ultracapacitors exit the discharge work and the bilateral batteries continue to accommodate the voltage regulation with the proposed control when \( P_{sc\_ref} \) gradually decreases and finally drops to 0 at the time of 0.5 s. Therefore, the ultracapacitors in the proposed control can bear the traction power peak, and the station batteries can accommodate the stable traction power. Similarly, \( P_{sc\_ref} \) gradually decreases at the time of 1.9 s due to the insufficient ultracapacitor’s capacity. The bilateral batteries then accommodate excess traction braking power.

### Table 2: Traction network voltage under different control strategies

| Energy storing device | Lowest traction network voltage (V) | Traction network voltage peak (V) | Traction network voltage fluctuation range (V) |
|-----------------------|-------------------------------------|----------------------------------|-----------------------------------------------|
| Traction control without HESS | 1320 | 1640 | 1320–1640 |
| Traditional HESS1 | 1350 | 1560 | 1350–1560 |
| Proposed HESS | 1400 | 1550 | 1400–1550 |

[FIGURE 10] Train traction simulation curve. (a) Angular speed and (b) train running distance /
TABLE 3 Energy consumption from station A to B under different control strategies

| Energy link                        | Train traction starting energy consumption (KWH) | Train traction braking energy consumption (KWH) | Brake energy released (KWH) | Braking energy absorbed (KWH) | Energy-saving efficiency (%) |
|------------------------------------|-------------------------------------------------|------------------------------------------------|-----------------------------|------------------------------|------------------------------|
| Traction control without HESS      | 15.5                                            | 7.7                                            | 0                           | 0                            | 0                            |
| Traditional HESS1                  | 13.5                                            | 3.7                                            | 1.94                        | 3.88                         | 25                           |
| Proposed HESS                      | 11.1                                            | 3.1                                            | 4.27                        | 4.46                         | 37.6                         |

FIGURE 12 Real-time allocation of traction power

FIGURE 13 Power proportional allocation link variation

to achieve voltage stabilisation and effectively maintain the stability of the DC traction network voltage as well as make the energy flow between HESS and the traction network more efficient and energy saving. The current change rate limit makes the battery to bear the low-frequency load.

The power proportional allocation link variation is shown in Figure 13. It can be observed that $\alpha_{\text{dis}}$ gradually decreases and finally drops to 0 when the ultracapacitors power is close to the lower limit at the time of 0.5 s, thereby the given ultracapacitors power $P_{\text{sc_ref}}$ and the ultracapacitor discharge current are reduced, and the remaining starting power is allocated to the batteries and the grid. $P_{\text{sc_ref}}$ is rapidly decreased by reducing the braking power allocation ratio $\alpha_{\text{char}}$ when the ultracapacitor power is close to the upper limit at the time of 1.9 s, thereby the ultracapacitor charging current is reduced and the ultracapacitor charge–discharge buffer protection is achieved, as well as the remaining traction power is accommodated by the batteries and the traction networks. Similarly, the battery discharging current is rapidly decreased by the station battery current limiting link when the battery power is low and the battery charging current is rapidly decreased when the battery charging is close to full load, so as to avoid energy storage element damage and play a role in smoothing the power.

$U_{\text{sc}}$ and SOC$_{\text{sc}}$ variation with power proportional allocation link are shown in Figure 14. According to $U_{\text{sc}}$ variation, the ultracapacitors can work stably within a safe working voltage range due to the SOC limit, that is, the minimum working terminal voltage is 250 V and the maximum working terminal voltage is 500 V. On the other hand, SOC$_{\text{sc}}$ without SOC limit drops below 0.2 with a large discharge current, while SOC$_{\text{sc}}$ with the SOC limit slowly drops to 0.25 and stops discharging within the safety limit. Under the condition of undertaking the same braking power, the ultracapacitors with the SOC limit can achieve the maximum charging effect, while the terminal voltage drops too sharply when the ultracapacitors without the SOC limit is used, which also cannot be fully charged when the braking energy is recovered. Therefore, adding SOC limit can

TABLE 4 Power variation range

| Energy storage device (KW) | Actual traction power $P_{\text{load}}$ | HESS traction power $P_{\text{hess_ref}}$ | On-board ultracapacitor power $P_{\text{sc_ref}}$ |
|---------------------------|----------------------------------------|-----------------------------------------|-----------------------------------------------|
| Proposed HESS             | $-98$ to $60$                          | $-100$ to $62$                         | $-100$ to $62$                                |

TABLE 5 Simulation results for on-board ultracapacitors

| Energy storing device      | Lowest terminal discharging voltage (V) | Highest terminal charging voltage (V) | Lowest SOC$_{\text{sc}}$ | Highest SOC$_{\text{sc}}$ |
|----------------------------|-----------------------------------------|---------------------------------------|--------------------------|---------------------------|
| Traditional HESS1          | 425                                     | 590                                   | 0.7                      | 1                         |
| Proposed HESS              | 250                                     | 490                                   | 0.25                     | 0.98                      |
effectively protect the on-board ultracapacitors and achieving the best energy-saving effect.

$U_{sc}$ and $SOC_{uc}$ comparison with the traditional control is shown in Figure 15, their simulation results are shown in Table 5. It can be observed that, compared with the traditional control, the permanent magnet traction power is coordinately controlled. Also, the on-board ultracapacitors can get a faster charge–discharge response and lower discharge depth, indicating that they are able to release and recover more braking energy with the proposed strategy.

To verify the control effect of on-board ultracapacitors under the condition of multiple stations in the same line, four stations on one line are scaled according to the simulation time, which is set to 20.5 s. The train operation in one line is shown in Figure 16.

Station battery charge–discharge threshold variation with dynamic setting is shown in Figure 17. It can be observed that the charging and discharging thresholds are dynamically set. When the train starts off station A, the traction network voltage drops in traction acceleration, HESS begins to discharge, and the on-board ultracapacitors accommodate the main starting traction energy needed. The station A battery closer to the train is used to ensure the main voltage stabilisation so as to reduce the line loss during the discharging process of HESS. In this case, the station A battery discharge threshold is relatively high. The station B battery ensures the main voltage stabilisation when the train running distance increases and the $SOC_{bat}$ of station A battery decreases within the safe range until the time of about 0.5 s. Its discharge threshold gradually exceeds that of station A, and its discharge current increases during this time. When the train is arriving at station B in braking deceleration at the time of 1.5 s, the ultracapacitors accommodate the main braking energy needed and the station B battery closer to the train ensures the main voltage stabilisation. In this case, the station B battery charging threshold is lower than that of station A and the station A battery charging threshold is reduced with the station B battery charging overload protection at the end of braking, so as to coordinate the energy flow between batteries and reduce the line loss during the charging process of HESS.

$SOC_{bat}$ variation with the current limit link is shown in Figure 18 and line loss comparison is shown in Table 6. It can be observed that, when the train leaves station A, the station A battery has a relatively high discharge threshold and its discharge
The SOC\text{bat} value of the station A battery with the current limiting link finally stabilises at about 0.25, leading to exit discharge status, while the station B battery discharge threshold is increased and the station B battery continues to ensure voltage stabilisation. When the train is arriving at station B, station B battery has a relatively low charging threshold, leading to higher battery charge than that of station A, while the station A charging threshold is decreased with the station B battery close to full load and the station A battery continues to ensure voltage stabilisation. The coordinated energy management between stations is achieved by dynamically setting the charging and discharging thresholds of bilateral batteries and the line loss during charging and discharging is reduced, as well as the traction network voltage is effectively stabilised.

| Energy storing device | Total line loss (KWH) |
|-----------------------|-----------------------|
| Traditional HESS1     | 0.82                  |
| Proposed HESS         | 0.636                 |

FIGURE 16    Train operation in a line. (a) Angular speed, (b) traction network voltage and (c) SOC\text{bat}

FIGURE 17    Station battery charge–discharge threshold variations with dynamic setting. (a) Discharge threshold \(U_{\text{bat\_dis}}\) and (b) charge threshold \(U_{\text{bat\_char}}\)
As shown in Table 6, the line loss is relatively high during the charging and discharging process because HESS is often placed on the stations in traditional control strategies. However, the line loss increase is not obvious due to small charge and discharge capacity. On the other hand, the lower line loss can be achieved with the proposed control strategy, which can be reduced by approximately 22.4% through the use of on-board ultracapacitors and the dynamic setting and coordinated control of bilateral station batteries.

The simulation results above show the on-board ultracapacitors can ensure the main traction power exchange and bear the high-frequency power peak. At the same time, the bilateral station batteries can ensure the low-frequency power and stabilise the DC traction voltage fluctuation. It is beneficial to make full use of the advantages of each energy storage element and reduce line loss through better capacity configuration with the proposed control strategy. In the same power supply section, the bilateral battery charge and discharge thresholds are dynamically set according to the distance between the train and the stations and the SOC\textsubscript{bat} values, which can make the station battery closer to the train get a greater regulated load, and reduce line loss by tracking the train real-time positions and the SOC\textsubscript{bat} of station batteries, it can dynamically adjust the charging and discharging thresholds of the station battery ESS to coordinate the energy flow of the batteries between two stations. Using this method can make the utilisation of each ESS tend to be balanced and reasonable. The simulation results have shown that, compared with the traditional control strategy, this method effectively stabilises the DC traction voltage fluctuations and makes the “peak shaving and valley filling” effect more significant, and provides a better energy-saving effect. Future work will focus on how to implement and apply this to the metro project.

FIGURE 18   SOC\textsubscript{bat} variations with the current limit link

4    CONCLUSIONS

An energy management strategy of HESS based on dynamic setting and coordinated control has been proposed. It has been shown that the utilisation of real-time traction power feedforward on the basis of traditional ultracapacitor double-loop cascade control can ensure the rapid exchange of acceleration and braking energy between the permanent magnet traction system and the on-board ultracapacitors, achieving the goal of reducing station power supply. Through dynamic power allocation link and the given current change rate limit of batteries, it can realise that the on-board ultracapacitors accommodate high-frequency traction power, the station batteries and power grids accommodate the low-frequency traction power and effectively smoothen the traction network power fluctuations. In addition, in order to further reduce line loss, by tracking the train real-time positions and the SOC\textsubscript{bat} of station batteries, it can dynamically adjust the charging and discharging thresholds of the station battery ESS to coordinate the energy flow of the batteries between two stations. Using this method can make the utilisation of each ESS tend to be balanced and reasonable. The simulation results have shown that, compared with the traditional control strategy, this method effectively stabilises the DC traction voltage fluctuations and makes the “peak shaving and valley filling” effect more significant, and provides a better energy-saving effect. Future work will focus on how to implement and apply this to the metro project.

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