Dynamic Power Threshold Control Strategy of Wayside Hybrid Energy Storage System Based on Battery SOC Tracking

Mingcheng Ai, Zhongping Yang, Fei Lin and Qiangqiang Qin

Abstract In order to extend battery service life and increase the total revenue of the hybrid energy storage system(HESS), this paper put forward a dynamic power threshold control strategy(DPTCS). The battery charge and discharge power threshold is adjusted in real time according to the battery state of charge(SOC), and the battery SOC is controlled within a certain range. Firstly, the model of urban rail traction power supply system with HESS is established. Then the paper uses the intelligent algorithm and urban rail train power supply system simulation platform to optimize the control parameters of DPTCS. Finally, the simulation results show the effectiveness of the proposed control strategy.

Keywords: Hybrid energy storage system · battery state of charge · intelligent algorithm · battery life · total energy saving benefit.

1. Introduction

With the increase in mileage of urban rail transit operations, the importance of energy-saving and emission reduction work for rail transit has become increasingly prominent. The cost of electricity accounts for about 50% of the total operating cost of the subway, and the energy generated during vehicle braking accounts for about 33% of the vehicle's power consumption [1].

The energy storage system recycles the braking energy of the vehicle, and stabilize the network voltage and reduce regeneration failure rate, which can effectively reduce the operating cost, achieve energy saving and emission reduction. So far, batteries, super capacitors(SC), flywheels, etc. are used as the energy storage components [2-6]. Because a single type of energy storage component can not meet the demand of urban rail transit well, the hybrid energy storage system of battery and supercapacitor is proposed.

1

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At present, there is little research on the control strategy of HESS in DC power supply system. A fixed power threshold control strategy(FPTCS) is proposed in [7], which sets a power threshold for the lithium battery. The power requirement within the threshold is provided by the lithium battery, and the rest power is provided by the super capacitor. This method is highly efficient and has strong engineering applicability. In [8], a filtering strategy to decouple the power demand and assigns separately to the super capacitor and battery. This strategy fails to maintain the battery SOC within the required range, and the engineering applicability is low. [9] proposed a control strategy for one station corresponding to a ratio of super capacitors and lithium batteries. Essentially it is still a fixed threshold strategy.

The organization of this work is as follow: In Sec.2, the simulation model of traction power supply system with HESS is built; In Sec.3, the control strategy of dynamic power threshold is introduced; In Sec.4, the battery life model and optimization objective function are built. In Sec.5, the control parameters are optimized by genetic algorithm and the validity and rationality of DPTCS are verified through the simulation of an actual line; In Sec.6, the summary is given.

2. Urban rail transit power supply system simulation model

The simulation model includes the train operation module TPS, the DC network power flow simulation module DC-RLS, and HESS module. The TPS is based on the input line parameters, the output vehicle parameter of the position of trains and the electric power. TPS also contains the train braking resistor. The HESS module can set the energy management strategy and capacity configuration scheme. The DC network parameters can be set in DC-RLS. This module is mainly used to simulate the operating conditions of multiple trains on the line. The voltage and current of the substation and the charge and discharge power of HESS are obtained by the power flow analysis.

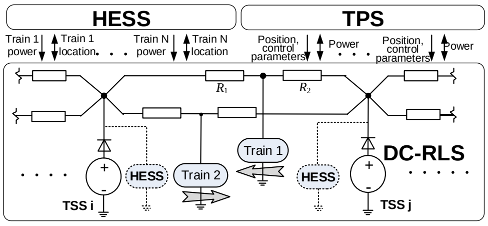

Fig. 1. Urban rail train power supply system simulation platform

HESS includes energy storage component and bidirectional DC/DC converter. The super capacitor and the lithium battery are respectively connected to the DC network through the bidirectional DC/DC converter. The control of the bidirectional DC/DC converter adopts the traditional double loop control, the outer voltage loop stabilizes the DC network voltage, and the inner current loop adjusts the charge and discharge current of the energy storage component. The specific structure is shown in Figure 2. $P_{HESSref}$ is the total charge and discharge power command of HESS. U_{net} is the DC network voltage, U_{char} is the charging threshold, U_{dis} is the discharging threshold, and I_{batref} and I_{SCref} are respectively the current command of the lithium battery and the super capacitor. PWM is the IGBT control pulse.

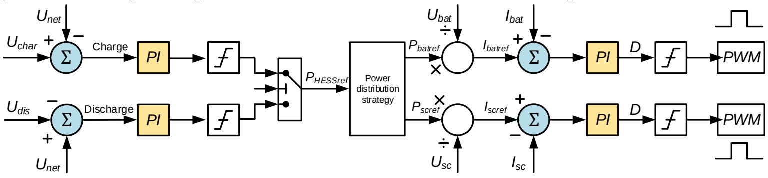

Fig. 2. Traditional double loop energy management strategy.

3.Dynamic power threshold control strategy(DPTCS)

3.1 Control logic

To control the battery SOC, the battery can be charged with small current when SOC is large and discharged with small current when SOC is small. When HESS is charging, and the battery SOC is less than SOC_{low}, the battery charge power threshold P_{chth} takes the minimum value -P_{bmax}; When it is larger than SOC_{low}, P_{chth} gradually increases until the battery SOC reaches SOC_{ceil}, and P_{chth} is 0. When HESS is discharging, and the battery SOC is greater than the SOC_{up}, the battery discharge power threshold P_{disth} takes the maximum value P_{bmax}; When it is smaller than the SOC_{up}, P_{disth} gradually decreases until the battery SOC reaches SOC_{floor}, and P_{disth} is 0. The battery charge and discharge power threshold curve is shown in Figure 3.

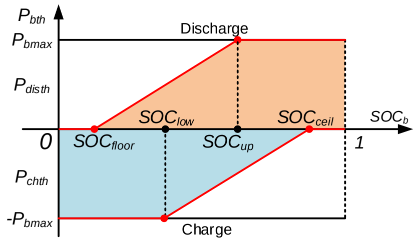

Fig. 3. Battery charge and discharge power threshold curve

According to the battery power threshold variation, the battery SOC is divided into five areas in figure 5: over discharge prohibited area 1, over discharge adjustment area 2, reasonable area 3, over charge adjustment area 4, over charge prohibited area 5. The battery charging energy is S_1 under DPTCS during a single traction braking process, the discharging energy is S_2. S_3 is the difference of battery charging energy between FPTCS and DPTCS. And S_4 is the discharging one. It can be seen from Figure 4 that as the battery SOC increases, S_1 gradually decreases, and S_2 gradually increases. Compared to the FPTCS, the increase of the battery SOC is well suppressed with larger battery SOC. Conversely, with smaller battery SOC, the battery SOC reduction is suppressed compared to the FPTCS.

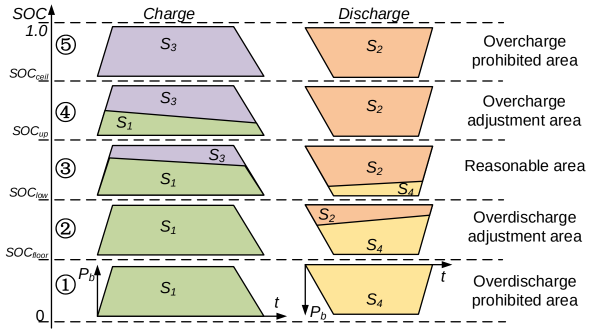

Fig. 4. Battery SOC division Charging and discharging energy of battery in each area

3.2 Dynamic power threshold calculation

As shown in the figure 5, the battery charging threshold P_{chth} is set to 0 in area 5 and $-P_{bmax}$ in area 1 and 2. In area 3 and 4, the charging threshold is adjusted by a SOC loop, whose SOC reference value is SOC_{ceil}; The battery discharging threshold P_{disth} is set to 0 in area 1 and P_{bmax} in area 4 and 5. In area 2 and 3, the discharging threshold is adjusted by another SOC loop, whose SOC reference value is SOC_{floor}.

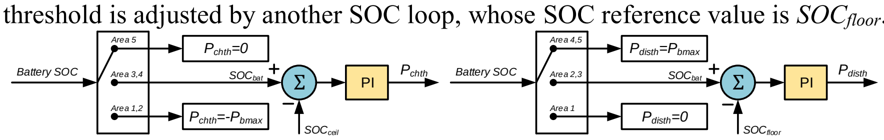

Fig. 5. Battery power threshold calculation

DPTCS block diagram is shown in figure 6. Where P_{Hchmax}=P_{chth}-P_{SCava}, P_{Hchmax} is the maximum charge power of HESS, P_{SCava} is the available power of SC.

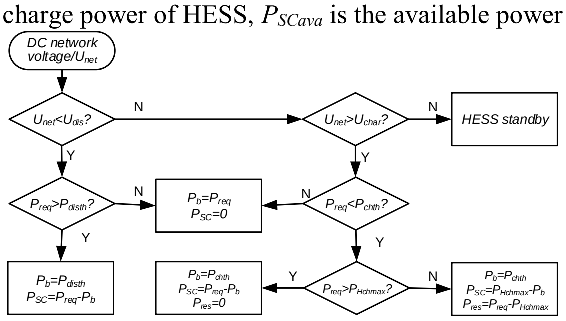

Fig. 6. Dynamic power threshold control strategy block diagram

4. Control parameter optimization

4.1 Battery life prediction model

Since the battery life is closely related to its charge and discharge current, DOD and other factors. The battery life model considering the DOD is established to estimate the battery life loss during the actual working process.

The relationship between the maximum charge and discharge times of the battery and the DOD is shown in Equation 1, where D_r is the rated DOD and the corresponding number of cycles is N_r; D_a is the DOD of the actual discharge process, and the corresponding cycle number is N_a; α, β are the fitting coefficients.

$$N_a = N_r (\frac{D_r}{D_a})^{\alpha} e^{\beta(1-\frac{D_a}{D_r})} \tag{1}$$

Since the battery charge and discharge mode is irregular during the actual operation, the DOD changes in real time. Therefore, the rain flow counting method is used to calculate the battery DOD. Assume that the DOD corresponding to each cycle of the battery is D_1, D_2... D_k, and the corresponding cycle number is N_1, N_2... N_k, and the battery life calculation formula is shown in Equation 2-3, where L_b is the battery life, *floor* is a round-down function, L_{day} is the battery life loss per day, θ is the number of cycles, the full cycle takes 1 and the half cycle takes 0.5.

$$L_{day} = \theta \sum_{i=1}^{k} 1 / N_i \tag{2}$$

$$L_b = floor(1 / L_{day}) \tag{3}$$

4.2 Optimization objective function ObjV

In order to quantitatively compare the energy-saving gain difference between DPTCS and FPTCS, we take the total energy-saving return E as the objective function. According to the change of train departure interval, it is divided into peak, flat peak and low peak period. The corresponding Beijing electricity price is peak price C_p, flat peak price C_g and low peak price C_d. Taking the sum of the product of energy saved during each period and the corresponding electricity price, the total energy saving income of HESS in a day can be obtained, then we get the total energy saving income E during the service life of HESS.

$$E = e_g * C_p + e_p * C_g + e_d * C_d \tag{4}$$

The total energy saving benefit under DPTCS is E_{dyn}, and benefit under FPTCS is E_{fix}, so the objective function is as shown in the equation 5.

$$ObjV = E_{dyn} - E_{fix} \tag{5}$$

5. Case analysis and simulation verification

5.1 Genetic algorithm(GA)

In order to obtain the energy management strategy control parameters under the maximum total energy saving benefit, this paper uses genetic algorithm to optimize the control parameters and PI parameters of the control strategy.

The optimization variables are as shown in the equation 6, wherein the first four parameters are the battery charge and discharge SOC loop PI parameters, and the last four parameters are SOC_{floor}, SOC_{low}, SOC_{up}, and SOC_{ceil}.

$$\mathrm{X} = [K_{p1} K_{i1} K_{p2} K_{i2}, x_1 x_2 x_3 x_4] \tag{6}$$

The genetic algorithm optimization flow chart is shown in Figure 7. The GA continuously optimizes the variables and inputs them to the simulation platform. After simulation, the corresponding objective function is obtained, and the next generation optimization is performed. With the continuous increase of genetic generation, the GA can obtain the maximum objective function, and obtain the optimal control parameters of the dynamic power threshold control strategy.

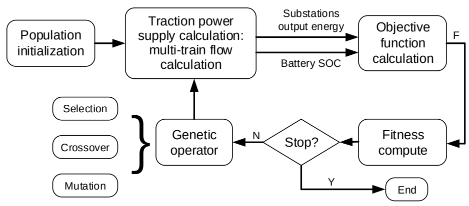

Fig. 7. Block diagram of the control parameters optimization

In this paper, the optimization of the control parameters is achieved by finding the largest objective function, so the value of the objective function *ObjV* is taken as the fitness value of the individual. The larger the objective function, the larger the individual fitness value, indicating that the individual is better. Since DPTCS is an improvement of FPTCS, in order to prevent the total energy saving gain from decreasing, the fitness function is as shown in Equation 7. *ObjV[X]* is the objective function obtained by the parameter group of the X chromosome for the control parameter.

$$\text{Fitness}[X] = \begin{cases} ObjV[X], ObjV[X] \geq 0 \\ 0, ObjV[X] < 0 \end{cases} \tag{7}$$

The parameters of GA are set as shown in the table 1, where *NIND* is the population size, *MAXGEN* is the genetic generation, P_c is the crossover probability, P_m is the mutation probability, and *GGAP* is the population generation ditch.

Table 1. GA's parameters

NIND	*MAXGEN*	P_c	P_m	*GGAP*
20	*100*	*0.7*	*0.015*	*0.95*

In order to prevent the battery from overcharging and over discharging, and ensuring that the battery has sufficient energy for emergency rescue, the battery SOC must be larger than 0.4 and smaller than 0.8. The super capacitor SOC range limits is 0.25-1.0.

Figure 8 shows the change of the optimal objective function value of each generation under the optimization of genetic algorithm. It can be seen that from the 52th generation, the objective function value which means total energy save benefits of HESS within the life span remains 77000￥, and the corresponding control parameter is the optimal solution.

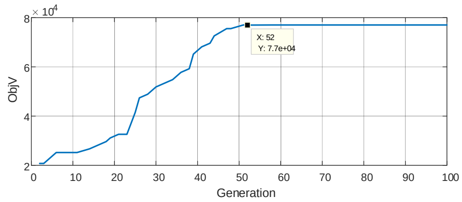

Fig. 8. Objective function iterative process

5.2 Simulation verification

The simulation parameters are shown in Table 2. Control parameters are the aforementioned optimization results. The departure interval is 180s.

Table 2. Simulation parameters

Parameters	*Value*	*Parameters*	*Value*	*Parameters*	*Value*
U_o	*836V*	SOC_{floor}	*0.4000*	SOC_{ceil}	*0.8000*
U_{char}	*850V*	SOC_{low}	*0.5429*	SOC_{up}	*0.6857*
U_{dis}	*819V*	*Battery power*	*200kW*	*SC power*	*800kW*

The figure 9 shows the battery current and SOC curve under the two control strategies respectively when the initial SOC of the battery is 0.6, which is in the area 3. It can be seen that the output power of the battery changes dynamically with the SOC of the battery, and the current under DPTCS is reduced compared to the one under FPTCS. And the battery DOD difference between two strategies is small.

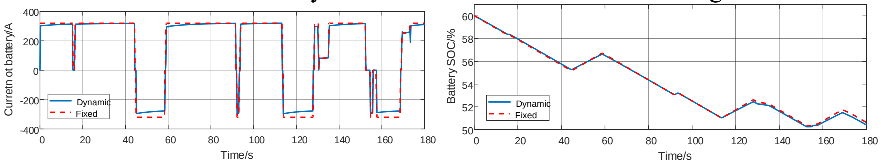

Fig. 9. Initial battery SOC is 0.6

Then we change the initial battery SOC to 0.42, which is in the area 2. The battery current curve shown in figure 10-left shows that the discharge current under DPTCS is significantly decreased than FPTCS, and the charge current is the same. Hence it results in battery SOC curve under DPTCS varies smaller than FPTCS after a departure interval in figure 10-right. In other words, the change of battery SOC is effectively suppressed to make it run in a certain range.

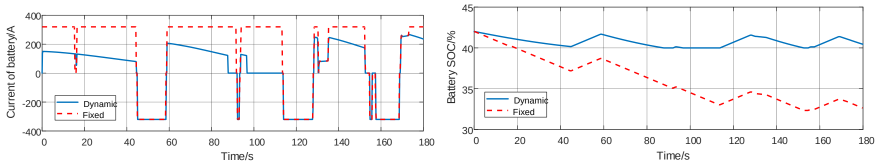

Fig. 10. Initial battery SOC is 0.42

At last we change the initial battery SOC to 0.78, which is in the area 4. The battery current curve shown in figure 11-left shows that the charge current under DPTCS is decreased than FPTCS, and the discharge current is the same. The battery under DPTCS charges less than FPTCS after a departure interval. It can be seen that the charging energy of battery is effectively suppressed in the figure 11-right.

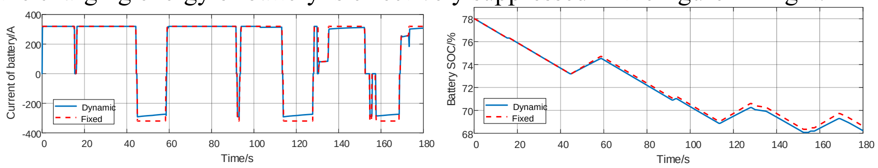

Fig. 11. Initial battery SOC is 0.78

From the simulation results above we can conclude that DPTCS could effectively adjust the battery power threshold to keep the battery SOC in a certain range. Current under DPTCS is smaller than FPTCS.

6. Conclusion

In this paper, the simulation platform of urban rail train power supply system including train and HESS is established. Considering the influence of battery current and DOD on battery life, a DPTCS based on battery SOC tracking is proposed. Based on the actual operating characteristics of the battery, a battery life prediction model was established to calculate the total energy saving benefit of HESS. Finally, based on the difference between the total energy-saving benefits of the two strategies, a method based on genetic algorithm to optimize the control parameters is proposed. It is verified with the actual line data in the simulation, and it can be a reference to prolong the service life of the battery and improve the total energy-saving benefit of HESS.

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