

# Power Distribution Control Strategy of On-board Supercapacitor Energy Storage System of Railway Vehicle

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**Abstract**—Supercapacitor, with high power density and long cycle life, has unique advantages and development prospects in avoiding regeneration failure, improving the braking force in high-speed range and realizing catenary-free operation in urban railway. First, the characteristic curves of the vehicle and characteristics of supercapacitors are studied. Based on matching their characteristics, a power distribution control strategy for on-board supercapacitor energy storage system is proposed. A simulation model and a 3kW experimental platform are set up, in order to simulate single vehicle and single substation. Both of the simulation results and experimental results have verified the feasibility of the control strategy.

**Keywords**—supercapacitor; SOC; power distribution; energy management; regeneration failure

## I. INTRODUCTION

Currently, the "energy saving and emission reduction" and "low-carbon economy" have become the hot issues of social development. Subway system has attracted more and more attentions, due to its advantages of environmental protection and energy saving. With the rapid development of power electronics, AC traction drive technology and regenerative braking have been widely used on the rail vehicle [1]. Regenerative braking energy can be absorbed by the other powering vehicles in the same power supply interval, which can further reduce energy consumption and make the energy-saving advantages of the rail transit more prominent. However, when the vehicles operate at a low density, the probability that the regenerative energy is absorbed by other vehicles will be greatly reduced. If there are not enough loads on the line to absorb the regenerative energy, it can easily lead the vehicle pantograph voltage to rise beyond the allowable value [2,3]. Then the main circuit must be cut off, and regenerative braking fails. How to effectively use the surplus energy of regenerative braking, prevent regeneration failure has been a hot point in recent years. The supercapacitor has demonstrated excellent performance in reducing energy loss and stabilizing the line voltage, because of its high power density, long cycle-life [4].

In this paper, the characteristic curves of the vehicle and characteristics of the supercapacitor are studied, and the characteristics matching relationship of them is analyzed. A new control strategy for the energy storage system based on the power distribution between the supercapacitor and the substation is proposed. This strategy has a good effect in suppressing voltage fluctuation, preventing the failure of regenerative braking, and saving energy consumption of vehicle operation [5,6]. Simulation and experiment have verified the feasibility of this strategy.

## II. CHARACTERISTICS OF SUPERCAPACITOR AND VEHICLE

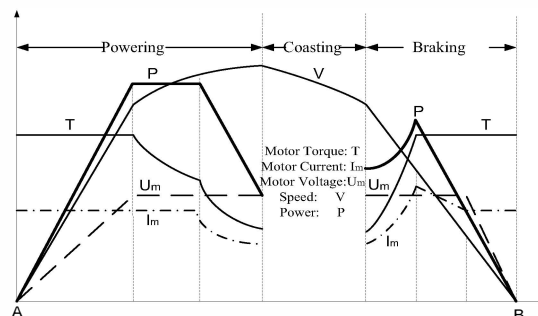


Fig.1 Vehicle traction motor characteristic

Fig. 1 shows the characteristic curves of railway vehicle, including voltage, current, torque speed and power. In theory, motor operation states can be divided into three modes: constant torque, constant power and natural characteristics while the vehicle works at powering, coasting and braking condition. When powering, the vehicle absorbs energy from the feeder line, causing the voltage drop; when braking, the vehicle feeds energy to the feeder, leading to voltage rise. The unexpected voltage fluctuation deteriorates the characteristic of the vehicle [7,8].

As a new energy storage component, supercapacitor has many advantages [9]. Table I shows the specification of Maxwell BCAP3000. Supercapacitor can match the characteristics of the rail vehicle well (Fig.2).

TABLE I. SPECIFICATION OF SUPERCAPACITOR(MAXWELL)

Energy Density(Wh/kg)	5.96
Power Density (W/kg)	5,900
Cycle-life (times)	1000,000
Endurance(hours)	1500

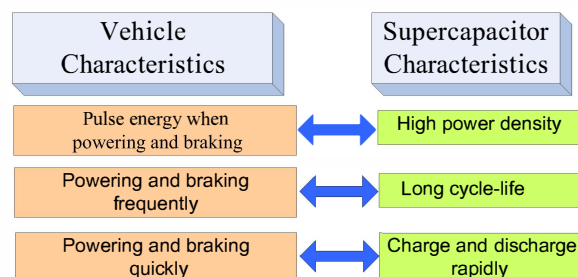


Fig.2 match of vehicle and supercapacitor characteristics

### III. POWER DISTRIBUTION CONTROL STRATEGY OF ON-BOARD SUPERCAPACITOR ENERGY STORAGE SYSTEM

#### A. Supercapacitor Energy Storage System On board

Fig. 3 shows the structure of supercapacitor energy storage system on board of railway vehicle. The system consists of two parts: the energy conversion device bidirectional DC-DC converter(BDC) and supercapacitors. Bidirectional DC-DC converter control and traction inverter are controlled respectively. Without changing the existing vehicle control strategy, the supercapacitor energy storage system can be directly installed on the existing urban rail vehicles to operate.

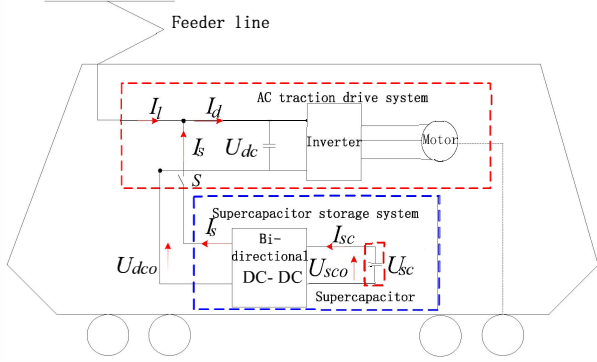


Fig.3 The structure of supercapacitor energy storage system on board of Railway Vehicle

In Fig.3,  $I_l$  is the feeder wire current;  $I_d$  is the current vehicle needs when powering or braking;  $I_s$  is the storage system current, which is related to  $I_{sc}$  with duty.  $U_{dc}$  is the front-end voltage of the inverter;  $U_{dco}$  is the front-end voltage of the energy storage system, and  $U_{dco} = U_{dc}$ .  $U_{sc}$  is the voltage of the supercapacitor, and isolating switch S is off when the super capacitor is in standby state.

#### B. Control Strategy Description

In the traditional wayside supercapacitor energy storage system control, the charging and discharging currents are given according to the changes of the feeder line voltage. At the high voltage, supercapacitor absorbs current; at the low voltage, supercapacitor releases current to dc link. Without the weight and size restrictions, a great capacity for the supercapacitor can be chosen to stabilize the whole line voltage.

Owing to the supercapacitor's low energy density and space constraints on the vehicle, energy management of on-board supercapacitor system should take more consideration to single vehicle. When the vehicle is powering, the energy system feeds out energy to suppress the voltage at the pantograph fall and improve the acceleration characteristic. When braking, the system absorbs braking energy to prevent the voltage at the pantograph from pumping up and regeneration failure, and improve the electrical braking performance. Based on the power distribution between the supercapacitor and the substation, this paper proposes a control strategy for the energy storage system. Fig.4 is the control diagram.

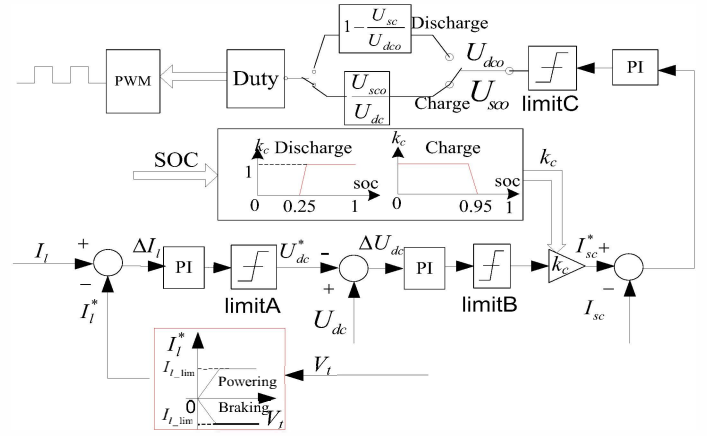


Fig.4 Power distribution control diagram

Different from wayside system control method,  $U_{dc}^*$  is given through indirectly control of the line current. In detail  $U_{dc}^*$  is given through comparing the line current to a reference line current. If logical conditions are met, Supercapacitor energy storage system can take actions correctly according to the energy management strategy designed. The feeder line current limiter is shown in Fig.5.

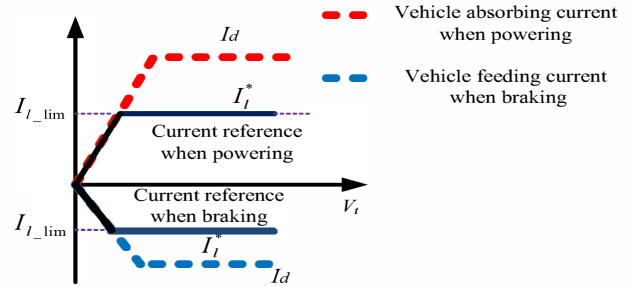


Fig.5 Line current limiter

$I_l^*$  is the line current reference, which changes corresponding to the vehicle speed.  $I_l^*$  is different at powering and braking. According to Kirchoff's current law we can see:  $I_s^* = I_d - I_l^*$ .  $I_d$  is the current vehicle required when powering or braking;  $I_s^*$  is the current flowing out of the energy storage system.

Adding a current loop increases the complexity of the system control, however, many benefits are gained.

1) Avoiding unwanted inflow and outflow between the supercapacitor and the feeder line.

- Prevention of outflow from the supercapacitor to the feeder line when powering:  $I_l \geq 0$ .
- Prevention of inflow from the feeder line to the supercapacitor when regenerating:  $I_l \leq 0$ .

2) Deciding the voltage action value and the stable value.

$$\begin{cases} I_{l\_lim} \uparrow \rightarrow \Delta I_l \downarrow \rightarrow U_{dc}^* \downarrow \\ I_{l\_lim} \downarrow \rightarrow \Delta I_l \uparrow \rightarrow U_{dc}^* \uparrow \end{cases}$$

3) Deciding the distribution of the power between the feeder line and the supercapacitor.

Power the vehicle needs:  $U_{dc}^* I_d = U_{dc}^* I_s^* + U_{dc}^* I_1$

Where  $U_{dc}^* I_s^*$  is the power the supercapacitor provides or absorbs;  $U_{dc}^* I_1$  is the power which is from/to the substation.

There are three limiters in Fig.4 diagram.

1) Limiter A is the voltage limiter, which decides the storage system operation threshold voltage. Taking 1500V system for example, for a wider range of voltage fluctuation,  $U_{dc}^*$  must have a hysteresis loop in order to ensure the reliability of directive. The reference hysteresis value is closely related to the charge and discharge current, as shown in Fig.6.

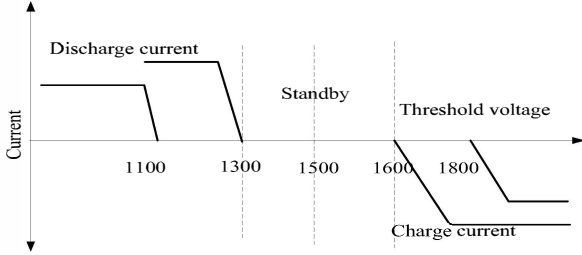


Fig.6 Relationship between hysteresis value and current

2) LimitB limits the maximum charge and discharge current to protect the supercapacitor.

3) LimitC decides the upper and lower limits of the supercapacitor voltage, that is, the limit of SOC. To ensure the boost mode of BDC works properly, the supercapacitor voltage cannot be too low. Considering a certain margin, the SOC of supercapacitors is usually chosen from 0.25 to 0.95. Simply, when the SOC of supercapacitor is close to 0.25 at discharge, the discharge current decreases until 0 by adjusting  $k_c$ ; when the SOC of supercapacitor is close to 0.95 at charge, the charge current also decreases to 0, to protect the supercapacitor.

The control algorithm flow chart is shown in Fig. 7. In the control strategy, supercapacitor energy storage system can take the correct action, only when both of the logical conditions below are satisfied at the same time:

1) Current logical condition

When powering:  $I_1 \geq 0$ , supercapacitor discharges.

When regenerating:  $I_1 \leq 0$ , supercapacitor is charged.

2) Voltage logical condition

When powering:  $U_{dc}^* \geq U_{dc}$ , supercapacitor discharges.

When regenerating:  $U_{dc}^* \leq U_{dc}$ , supercapacitor is charged.

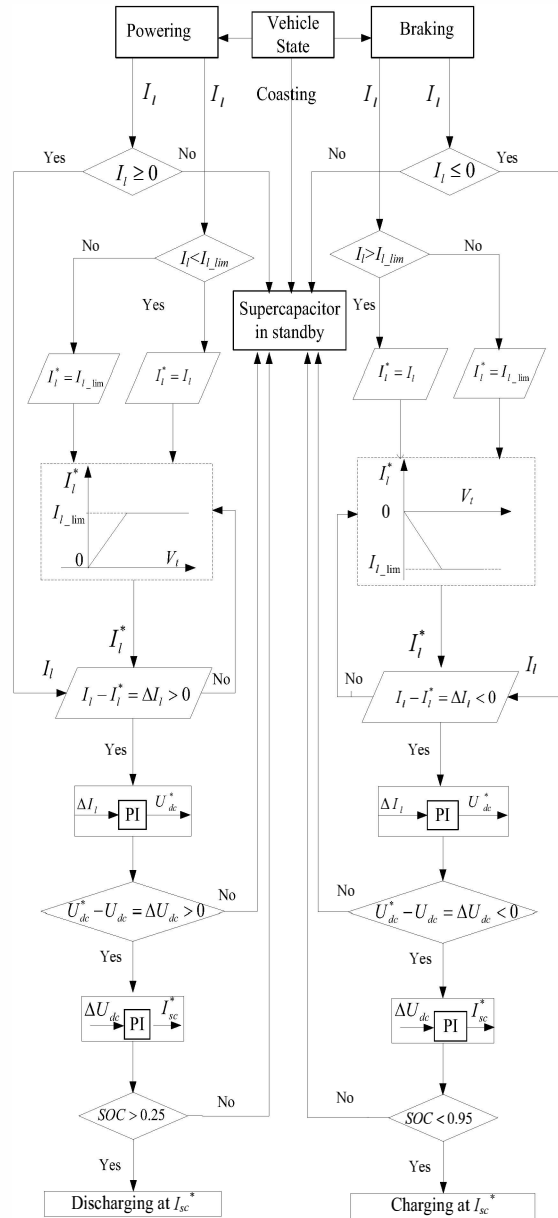


Fig.7 Control algorithm diagram of on-board supercapacitor storage system

#### IV. CONTROL SIMULATION

##### A. Simulation Parameters

In order to verify the feasibility of the previous algorithm, a model of single vehicle and single substation is built by Matlab/Simulink software. Based on this model, the whole working conditions of the vehicle, including powering, coasting and braking conditions, are simulated. Table II shows the parameters of simulation platform and table III shows the parameters of the supercapacitor.

TABLE II. PARAMETERS OF SIMULINK PLATFORM

Rate Power	2000kW
DC-link Voltage	1500V
Powering Voltage Action Range	1100V-1300V
Braking Voltage Action Range	1600V-1800V

TABLE III. PARAMETERS OF ON-BORAD SUPERCAPACITOR

Cell	Vmax=2.5V
Total capacity	48F
Internal resistance	0.2Ω
Energy	5.1kWh
Maximum Voltage	1000V

B. Simulation Results

Fig.8 shows the variation of three currents and line voltage during the whole operation simulation. In Fig.8, when the vehicle is powering, the dc link voltage drops. When the line current needed by the vehicle exceeds the limit and the voltage drops below the action value 1300V, the supercapacitor releases energy to reduce the line current and suppress the voltage drop at the pantograph. At last, the dc link voltage maintains at 1200V. When the vehicle is coasting, supercapacitor energy storage system is in standby mode. When the vehicle is braking, the dc link voltage rises. When the braking current exceeds the limit and the voltage rises above the action value 1700V, the supercapacitor absorbs regenerative braking current to suppress the voltage rise at the pantograph and prevent the regeneration failure.

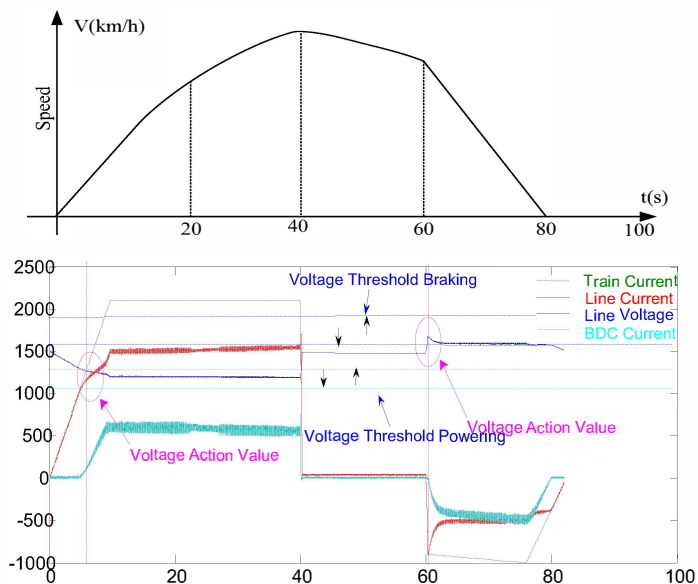


Fig.8 Current relation and voltage variation

V. RESULTS OF EXPERIMENTAL PLATFORM

A. Experimental Platform

Based on the above analysis, a 3kW supercapacitor experimental platform was set up. The block diagram of the experimental platform is shown in Fig.9. The platform consists of three parts: substation simulation system, vehicle simulation systems, and super capacitor energy storage system.

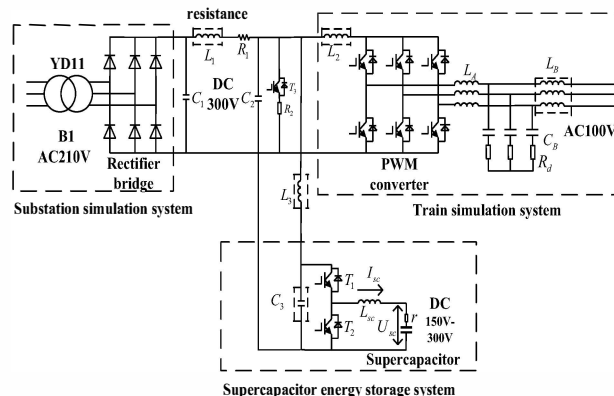


Fig.9 Block diagram of 3kW supercapacitor platform

The substation simulation system converts 210V AC to 300V DC through the diode rectifier. 210V AC is turned into by 380V AC through an auto-regulator and a three-phase isolation transformer (ensure the vehicle simulation system and substation systems connecting to the grid at the same time).

Vehicle simulation system is realized by a PWM converter, whose current is fed back to the grid through LCL filter. PWM converter uses grid voltage oriented control method. The reference value  $I_d$  is calculated according to the characteristics of the vehicle. When the  $I_d > 0$ , the PWM converter operates in rectifier state, which means the vehicle works in powering condition; when  $I_d < 0$ , the PWM converter operates in inverter state, which means the vehicle is powering or coasting. The characteristic of the vehicle simulated in the experiment is shown in Fig.10.

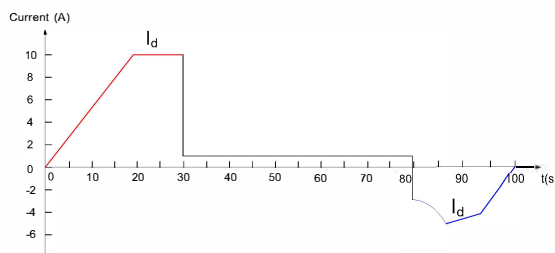


Fig.10 Characteristic of the vehicle simulated

The supercapacitor bank is the product of Beijing Supreme Power Systems Co., Ltd. Parameters are as follows: rate voltage 320V, capacity 1.5F and internal resistance 2.75Ω. The picture of experimental platform is shown in Fig.11.

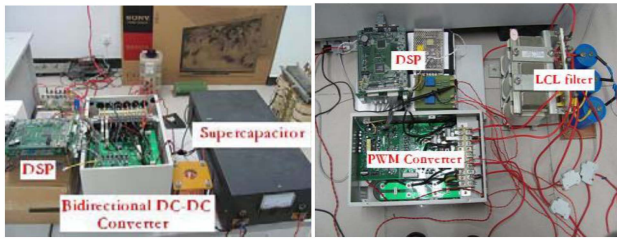


Fig.11 Prototype of 3kW supercapacitor platform

## B. Experimental results

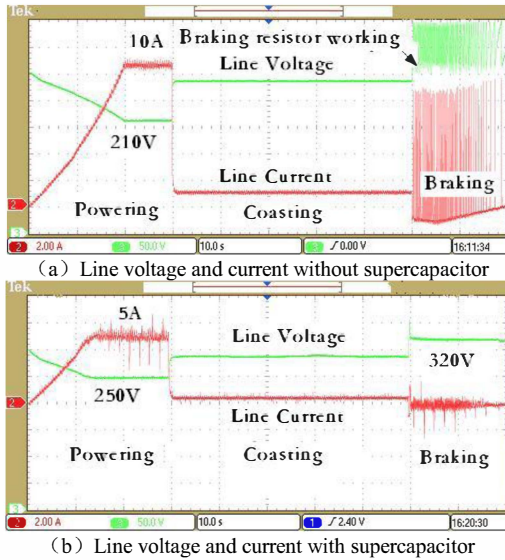


Fig.12 Line voltage and current waveforms

Fig.12 shows the experimental results in two situations: without supercapacitor and with supercapacitor. When the vehicle is powering, the dc link voltage drops to 210V without supercapacitor, while it is 250V with supercapacitor. When the vehicle is braking, the dc link voltage rises to 400V without supercapacitor, and the braking resistance works to absorb the regenerative energy. While the supercapacitor is put into use, the maximum voltage is only 320V. The voltage fluctuation range reduces from 190V to 70V.

Besides, the current limiter designed has an obvious effect. Compared to 10A without supercapacitor, the line current is limited to 5A.

## VI. CONCLUSION

The main subject of this paper is the research on the energy management of on-board supercapacitor of urban rail vehicle. A control strategy based on the power distribution between the supercapacitor and substation is proposed. At last, the simulation model and experimental platform, for single vehicle and single substation, are set up. Simulation and experiment has verified that the control strategy has a significant effect in

suppressing the voltage fluctuation and preventing the regeneration failure.

The research on the energy management strategy for multi-vehicle and the capacity configuration is ongoing.

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