Research of Hybrid Energy Pack for Rail Transit

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Abstract Low carbon, green and energy-efficient are the important development directions of railway transit. Based on the operational requirements of rail transit and the characteristics of various energy storage components, this paper introduces a new type of E-E hybrid drive technology with super capacitors and batteries, and proposes a new configuration structure of super capacitors and batteries. The power allocation method and the key technical requirements of the technology are described, and the DC/DC voltage control optimization method is proposed for the regenerative braking energy feedback. The energy package scheme can effectively improve the performance of rail transit operation, which can provide reference for other green power drive system design.

Keyword Hybrid energy pack · Energy storage power supply · Super capacitor

1 Introduction

At present, the energy source for rail transit is mainly from catenary or vehicle internal combustion. The operating conditions of rolling stock are limited by catenary. Meanwhile, with the development of railway electrification and the application of more strict emission standards [1, 2], those rolling stocks powered by internal combustion become less popular. The use of on board power pack can

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effectively solve the problem of internal combustion pollution and it enables rolling stock to operate without catenary. In general, the rolling stock should have the characteristics of long running time, big power under complicated operating environment. Therefore, as the driving power, energy package must have the characteristics of high energy, high power, long life cycle and good environmental adaptability.

There are several types of electric energy storage components, which can be divided into two categories, energy-based and power-based storage components respectively. Energy-based storage components such as lead-acid battery, lithium battery, etc., have the advantages of high energy density, long discharging time, but the disadvantages are low power density, short life cycle [3]. Power-based storage components such as super capacitors, have the advantages of high power density, short response time and long life cycle, but the disadvantages are low energy density, high self-discharging rate [4]. It is not possible to meet all the requirements by a single energy storage component because of the performance limits listed above. Through the application of hybrid energy storage components, based on their own characteristics and taking full advantages of them, rail transit can realize high power traction and braking and achieve green driving in non-electrified zone without pollution and emission.

2 Overview of Power Storage Technology

As a power source of rail transit, it should have the characteristics of big capacity, high energy and power density, long life cycle, wide operating temperature range, safety, reliability, environmental friendly and non-pollution, etc.

At present, the main energy storage components are batteries, super capacitors etc. Batteries include lead-acid batteries, alkaline batteries, lithium batteries. Power batteries generally are lithium batteries which have a relatively large energy and power density. The super capacitor is a new type of capacitor which has much bigger capacity compared to conventional capacitor. Although power battery has been widely used on pure electric vehicles and hybrid vehicles, its life and efficiency is affected by the huge current shock, which is a problem recognized widely by the industry. Super capacitor can be quickly charged and discharged with much higher current, but the lower energy ratio of which decides that it is not suitable as a vehicle energy storage alone. Therefore, the combination of power-based super capacitor and energy-based battery is an effective solution for the power source of rail transit.

By combining super capacitor with battery, the hybrid energy pack has the advantages as follows.

(1) It offsets the deficiencies, and takes advantages of each component. The hybrid energy storage system has the characteristics of high power and energy density, which fulfils the locomotive power requirements.

(2) It extends the battery life. The super capacitor undertakes the tasks of high power charging or discharging, while the battery works within its power limit, so that the battery is free from the huge current shock which extends its life.
(3) It utilizes regenerative braking energy. Due to the characteristics of fast charging and discharging the super capacitor can absorb and store the regenerative braking energy which is released during the next traction phase of the vehicle so that the regenerative braking energy is efficiently recycled.
(4) It has excellent low-temperature characteristics [2]. The capacity of battery decreases sharply when the temperature decreases [5], the attenuation of which may rise more than 70%. By contrast, the attenuation of super capacitor is very small, because the charge transfer occurs mostly on the surface of the active material of the electrode during the charge and discharge processes. Therefore, the application of super capacitor is conducive to enhance the vehicle low-temperature performance.

Table 1 compares the comprehensive performances of mainstream energy storage components in applications [6].

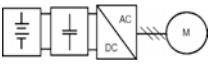
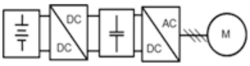
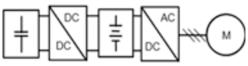
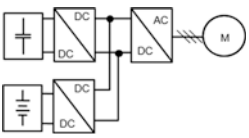
Table 1 The comprehensive performance comparison of mainstream energy storage components in applications

Performance	Super capacitor (9500 F)	Super capacitor (60,000 F)	Lead-acid battery	Phosphoric acid iron battery ($LiFePo_4$)	Lithium titanate battery (LTO)
Energy density (Wh/kg)	3	19.49	18.86	56.91	36
Power density (kW/kg)	0.28	0.23	0.02 (1C, 0.5 h)	0.07 (1C, 1 h)	0.2 (5C, 0.2 h)
Power per volume (Wh/L)	1.6	11	45.79	56.61	45.26
Cycle life	>1,000,000 times (monomer 300A, 100%DOD)	>30,000 times (1C, 100% DOD)	>1200 times (1C, 80% DOD)	>3000 times (1C, 100% DOD)	>10,000 times (1C, 100% DOD)
Operating temperature (low/high limit value)	−40 °C	−20 °C	Under 0 °C needs to be heat	Under 0 °C needs to be heat	−25 °C
	+55 °C	+55 °C	+45 °C	+45 °C	+55 °C

2.1 Configuration of Energy Storage Components

By combining super capacitors with batteries, we can get a hybrid energy system. There are mainly 4 kinds of combinations, and each has its own characteristics based on the different characteristics of the battery and capacitor [7] as shown in Table 2.

Table 2 Comparison of different combinations

Framework	Robustness	Configuration	Operation mode	Summary
	The charge and discharge power of the batteries and capacitors cannot be controlled. Large voltage fluctuations on DC side	Both voltage should be configured to DC-Link	Full dynamic of capacitor current, high speed state response	The power and energy of both components cannot be managed effectively due to the different characteristic of them
	1. Stable DC voltage 2. DC/DC converter runs continuously for long periods of time	1. DC/DC converter is needed 2. The voltage of super capacitors is configured to DC-Link	1. Fast state response of super capacitors 2. The continuous energy output depends on the battery	With the rapid increase of the capacity of super capacitors, the DC stability of which is enhanced greatly
	1. Stable DC voltage 2. DC/DC converter runs intermittently	1. DC/DC converter is needed 2. The voltage of batteries is configured to DC-Link	Energy output mainly depends on batteries, while big power output and regenerative braking depend on super capacitors	Now popular for matching
	1. High requirements for the control strategies and synchronization of these two DC/DC converter 2. Complex structure affects system stability	More configuration of DC/DC converter, more complex design	The super capacitors and batteries are output via separate DC/DC converter	Application in part of trams in China [8]

Now, the super capacitor technology products with high capacity are upgraded constantly, 30,000 and 60,000 F and even higher capacity super capacitors are already introduced and applied in the market. The higher the capacity is, the less the change rate of voltage is. Super capacitor with high capacity can effectively stabilize the voltage of DC-Link, response promptly to the power requirement of the vehicle. It plays a more and more important role in power and energy supply in the traction and braking process of the vehicle. Therefore, the second matching scheme in Table 2 has become the development trend of hybrid energy storage system, and will be further developed and applied with the development of super capacitor technology.

2.2 Power Configuration Principle

Combined the operational requirements of the rail transit mode with the characteristics of batteries and super capacitors, the power of super capacitors and batteries is managed by DC/DC converter under different operation modes which are described below.

1. Charge the super capacitors with batteries

Since the energy stored in super capacitors is less than that in batteries, the batteries can charge capacitors through a DC/DC converter when the vehicle starts up for operation. The schematic diagram is shown in Fig. 1.

2. Charge both the super capacitors and batteries with the catenary

In the catenary mode, through a charger on board the DC-Link of traction invertor charges the super capacitors as well as the batteries through the DC/DC converter, as shown in Fig. 2.

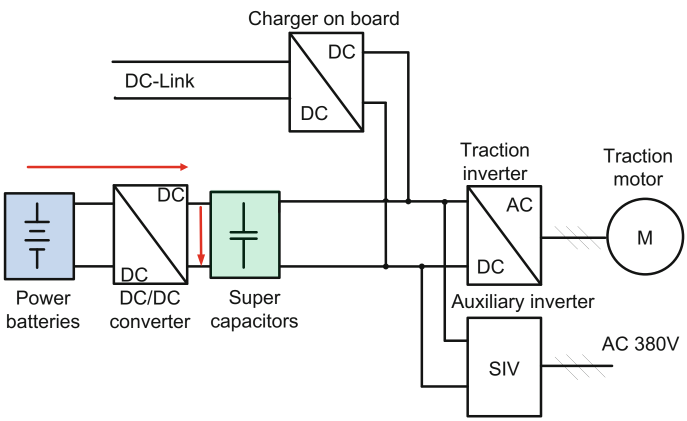


Fig. 1 Operating of charging super capacitors

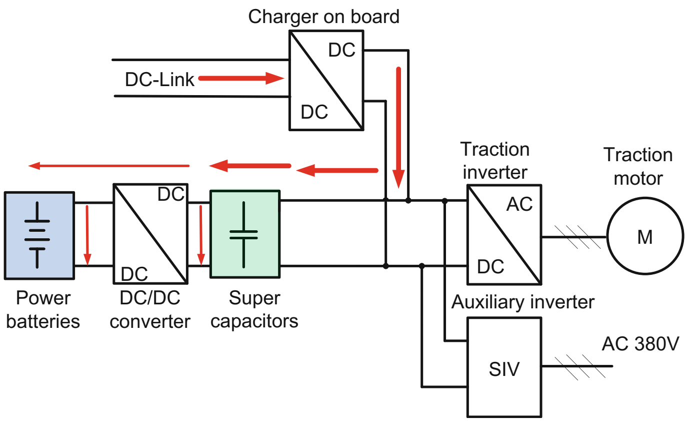


Fig. 2 Operating of charging hybrid energy pack

3. Low power traction mode

When the vehicle is in low power traction mode, the traction power can be fulfilled by the batteries only. In this case, the super capacitors are used to stabilize the DC-Link voltage.

While supplying power for traction and auxiliaries, the batteries can also charge the super capacitors when the energy of the latter is too low. See Fig. 3.

4. High power traction mode

When the locomotive power increases (e.g. climbing, starting, heavy load running etc.), the batteries and super capacitors output together, and the power of the former is limited by the DC/DC converter. See Fig. 4.

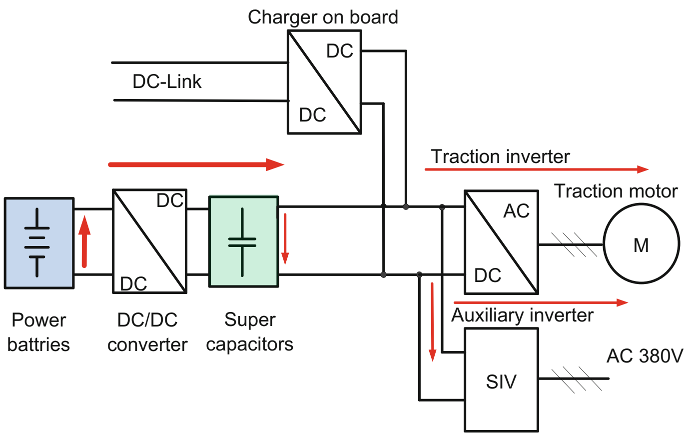


Fig. 3 Operating of low power traction

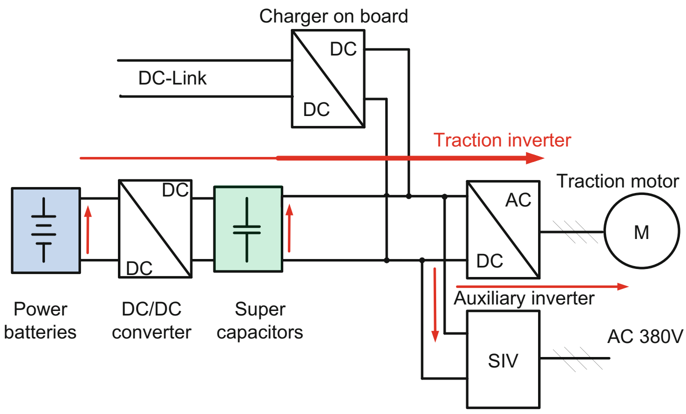


Fig. 4 Operating of high power traction

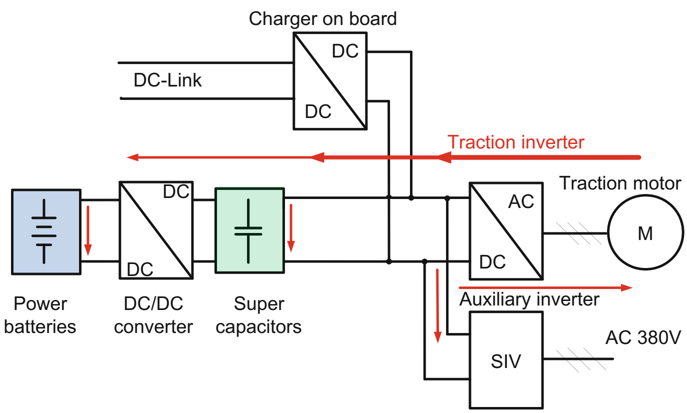


Fig. 5 Operating of regenerative breaking

5. Regenerative braking

In the regenerative braking mode, energy generated by the traction inverter is directly transmitted to the super capacitors. When the super capacitors are full charged, the batteries will be charged through the DC/DC converter as shown in Fig. 5.

2.3 DC/DC Converter

As a core device for the management of super capacitors and batteries, DC/DC converter is responsible for the power and energy management of the whole

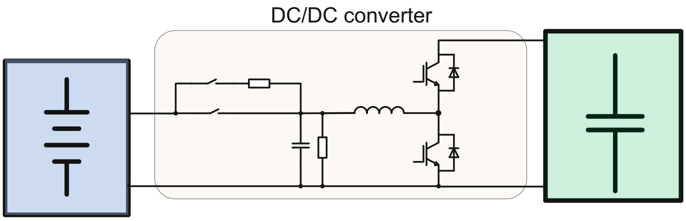


Fig. 6 Basic topology of DC/DC converter

system [8]. DC/DC converter is a Buck-Boost circuit in principle which is widely used in the field of power electronics, and the basic topology is shown in Fig. 6.

In view of the operating conditions and application requirements of rail transit, the following characteristics of DC/DC converter need to be considered.

1. Wide range of operating voltage

Since the operating voltage of the batteries and super capacitors varies within a few hundred volts, the DC/DC converter must work reliably in normal operating voltage ranges of both the energy components.

2. Bi-directional buck and boost function

Because the voltage range of these two energy components connected to DC/DC converter is very broad and in extreme circumstances the voltage of capacitors may be discharged to 0 V, the DC/DC converter must realize the bi-directional buck and boost function.

3. High efficiency

Since the DC/DC converter needs to run for a long time in the operating process of the vehicle, long term efficient operation becomes particularly important so that energy loss is minimized. Normally, the efficiency of DC/DC converter should be more than 95% under its own operating voltage range.

3 Parameter Configuration of Energy Pack

The configuration of super capacitors, batteries and DC/DC converter directly affect the configuration of energy pack and the performance of the whole vehicle. By giving full play to the advantages of each storage component, combining with the vehicle existing main circuit, considering the weight, volume and cost constraints of engineering application, the parameters of super capacitors, batteries and DC/DC converter are selected from the point of view of power cycle and average power of the vehicle [9]. The configuration of parameters for each section is analyzed below.

3.1 Configuration of Super Capacitors

1. Voltage of super capacitors in group

Since the super capacitor group is directly connected with the DC-Link, the voltage range of which needs to match the operating voltage range of the vehicle electric system (including traction inverter, traction motor and auxiliary inverter).

2. Power

The power of the super capacitor must at least meet the requirement of the equation below.

$$P_{supercap} = P_{DC\ linkpower} - (P_{battery} \times Efficiency_{DC/DC}) \tag{1}$$

3. Energy

The capacity configuration of super capacitors is often limited by the weight and installation space of the vehicle. The energy decreases (discharging during traction) and increases (recharging during regenerative braking) intermittently when the vehicle runs. So at least the capacity configuration needs to meet the requirements for continuously running of the vehicle.

3.2 Configuration of Batteries

1. Voltage of batteries in group

The battery voltage is controlled by DC/DC converter under buck/boost mode. On the one hand, if the voltage of batteries is too low, the operating current of the batteries and DC/DC converter will increase for the same power output; on the other hand, if this voltage is too close to the super capacitors, the switch frequency of DC/DC converter will rise up, which will increase the control difficulty and reduce the reliability and control accuracy. Usually, the voltage ratio of the batteries to DC/DC converter is set to 0.5–0.7.

2. Power

The life and safety of batteries are affected by unexpected large power which has to be limited. Usually, for lead-acid, iron-phosphate batteries, lithium titanate batteries, the charging ratio is respectively selected as 0.2, 1, 3 C, while discharging ratio as 0.2, 0.5, 2 C.

3. Energy

Since the energy of batteries determines the operating time of the vehicle, configuration needs to meet the minimum energy requirements of the whole working conditions of the vehicle.

4 Optimization Method of Boost Control

Generally, the output voltage of the Boost circuit (super capacitor terminal) is a fixed value [10]. Under this condition, if the energy of super capacitors and batteries are almost full, the regenerative energy cannot be absorbed effectively while the vehicle is braking, and the brake resistance of the vehicle is required to consume the surplus regenerative braking energy.

Considering the above situations, we choose the boost voltage as a linear change value. The higher the locomotive speed, the lower the boost voltage limit is; contrarily, when the vehicle speed decreases, this limit increase, equal to that the DC-Link voltage varies linearly with the locomotive speed.

Furthermore, the vehicle creates more regenerative braking energy at a high speed, when the super capacitors can absorb more energy. On the other side, the vehicle creates less energy at a low speed when the super capacitors can absorb less energy. By doing so, it can make full use of the super capacitors to absorb the regenerative braking energy, effectively reducing even eliminating the configuration of the braking resistor.

5 Running Test

After installation of the energy package on one locomotive, some tests (such as light load, heavy load, low speed and high speed) are carried out according to different operational conditions. The parameters of the tests are shown in Table 3.

Running on the main electrified line, operating under different conditions with different load, the main test results are shown in Table 4.

Table 3 Main parameters of test system

Definition	Parameter
Locomotive weight	87.4 t
Maximum tractive force	120 kN
Maximum wheel power	300 kW
Rated voltage of battery pack	DC500 V
Capacity of battery pack	285 Ah
Rated voltage of super capacitor pack	DC900 V
Available energy of super capacitor pack	12 kwh
Test line	Main electric locomotive line
Ambient temperature	0–5 °C

Table 4 Test result

Operating condition	Condition 1 The locomotive pulls the 70 t load and runs continuously at 45 km/h	Condition 2 The locomotive pulls the 600 t load and runs continuously at 10 km/h	Condition 3 The locomotive pulls the 1500 t load and runs in 200 m shunting for an hour with the maximum speed–10 km/h
Continuous tractive force	9.6 KN	23 KN	60 KN
Continuous speed	45 km/h	10 km/h	9 km/h
Maximum speed	65 km/h	10 km/h	10 km/h
Maximum current of battery pack	280 A	280 A	280 A
Maximum current of super capacitor pack	200 A (acceleration)	300 A	300 A
Initial energy	95.2% (energy pack)	70% (batteries) 60% (super capacitors)	100% (energy pack)
Final energy	46% (energy pack)	45% (energy pack)	44% (energy pack)
Distance	45 km	2.5 km	3 km

6 Conclusion

At the present, energy storage components are developed and upgraded rapidly, and the power and energy density of which are also enhanced. A single type of energy storage component cannot meet the requirements of large power and high energy for rail transit traction. By combining different energy storage components using respective advantages and offsetting respective disadvantages, and controlling the power and energy by DC/DC converter, the energy pack can effectively fulfil the operational requirements of vehicle thus improve the driving capability.

Currently, the energy package scheme presented above has been applied in Austria for a shunting locomotive and a series of tests have been carried out with good results, which has received widespread attention in the industry.

References

1. Fan Y, Gao D (2012) Research and development of dual power electric shunting locomotives. Electric Locomotives Mass Transit Veh (5):11–15 (in Chinese)
2. Zhang Y (2011) Study on key technology and product simplification of double energy battery electric locomotive. Electric Locomotives Mass Transit Veh (3):20–22 (in Chinese)
3. Yu G (2012) Application of Li-ion battery in the field of rail transit vehicle. Chinese battery industry (5):299–305 (in Chinese)
4. Jianpu W (2015) Research of onboard energy storage system for urban railway transit vehicle braking. Electric Drive Locomotives 4:76–79 (in Chinese)
5. Zhao S, Guo S, Zhao J, Song Y, Nan C (2016) Development on low-temperature performance of lithium ion batteries. J Chinese Ceramic Soc 1:19–28 (in Chinese)
6. Chen Q, Liu G, He J, Ma X, Yang R, Hu S, Wu J (2015) Analysis and comparison between standard systems of power battery in China and abroad. Adv New Renew Energy (2):151–156 (in Chinese)
7. Miller JM (2011) Ultracapacitor applications. Institution of Engineering and Technology, pp 61–75
8. Chen H, Xia H, Yang Z, Li X (2015) Study of output impedance optimization for stationary super-capacitor energy storage applied in urban rail power supply system. In: IEEE 2015 54th annual conference of the society of instrument and control engineers of Japan (SICE), Hangzhou, China, pp 124–129
9. Pen R, Zhang K, Song P, Chen Y, Zhang J (2015) Research on energy management strategy of on-board hybrid power source for trains. Chinese J Power Sour (11):64–68 (in Chinese)
10. Huang Z, Yao D, Yang G, Li H, Wu F, Ning X (2016) Study on piecewise control strategy of braking energy regeneration for hybrid power system of electric vehicle. Mech & Electr Eng Mag (3):280–286 (in Chinese)