Research on battery-supercapacitor hybrid energy storage control scheme for mine electric locomotive

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Abstract. The starting and acceleration of the mine electric locomotive requires instantaneous high-power output of the power supply. The power density of lead-acid battery is low, which cannot meet the high-power demand of the mine electric locomotive. In order to make up for the shortage of the battery as a single power supply for the mine electric locomotive, A battery-supercapacitor hybrid storage system (HES) with lead-acid battery as main power supply and supercapacitor as auxiliary power supply is proposed. A multi-input DC/DC converter is adopted to control the output of the HES under different working conditions of the electric locomotive, and the bidirectional power control of the HES is realized. The simulation results show that the HES scheme plays a good role in driving and energy feedback of the mine electric locomotive.

1. Introduction

At present, lead-acid batteries are the main power supply for mine electric locomotive (MEL). The batteries have the advantages of high energy efficiency, high energy density and high specific energy, but the power density of the battery is low, which cannot meet the higher power requirements of MEL. Supercapacitors (SC) have the advantages of long life, high power density and superior charge and discharge performance. If supercapacitor is used in MEL that can effectively improve the motion performance of MEL when starting and accelerating [1]. Therefore, a hybrid energy storage system (HES) of battery-supercapacitor is proposed, which uses battery as main power supply and supercapacitor as auxiliary power supply. The HES for MEL can make up for the shortage of lead-acid battery as a single power supply, give full play to the superior performance of supercapacitors.

The SC and battery hybrid power system has been widely studied in electric vehicles, but the research based on MEL is scarce.

The hybrid power system of supercapacitor (SC) and battery has been widely studied in electric vehicles. In [2-3], the application of fuzzy control strategy in hybrid electric vehicle is studied. In [4], Optimized control strategy of on-board composite power supply system, the optimized fuzzy energy management strategy can effectively reduce fuel consumption and improve braking energy recovery of hybrid electric vehicles. In [5], the application of supercapacitor in dual-power electric vehicles is studied. The dual-power system can effectively reduce the charging and discharging current of lithium batteries and protect the batteries. In [6], the application of supercapacitor in electric vehicle is studied, and the topology of various supercapacitor-battery composite power supply is analyzed. However, there is little research on hybrid power system of the MEL.
This paper presents a hybrid energy storage (HES) Control Scheme for mine electric locomotive. Batteries and supercapacitors are used as hybrid energy storage devices. A multi-input DC/DC converter with bidirectional power transmission capability and simple control strategy is adopted to provide power for mining locomotive. The instantaneous high power is provided by supercapacitors when starting or accelerating, and the power is supplied by batteries when running at uniform speed. Absorbing the feedback energy of deceleration and braking of mine electric locomotive. The topology and working principle of the scheme are studied. Finally, the feasibility of the scheme is verified by simulation waveform.

2. Topological structure of the HES

The circuit topology of hybrid power system for mine electric locomotive presented in this paper is shown in Figure 1. Among them, \( V_{BT} \) is a battery, \( V_{SC} \) is a supercapacitor, \( S_1-S_4, Q_1-Q_3, D_1-D_3 \) and \( L \) constitute a multi-input DC/DC circuit, and \( C \) is a filter voltage-stabilized capacitor. The topology can work in boost, buck and buck-boost modes. In this paper, a new type of hybrid power system topology circuit for mine locomotive can work in driving mode and energy feedback mode.

![Figure 1. Circuit topology of the HES for mine electric locomotive.](image)

In drive mode: \( Q_3 \) is always off, and the converter works in boost mode. When the locomotive starts and accelerates, it is powered by supercapacitor, that is, \( S_1 \) turn on, \( S_2, S_3, S_4 \) turn off; when the locomotive runs at uniform speed, it is powered by battery, that is, \( S_3 \) turn on, \( S_1, S_2, S_4 \) turn off. The DC voltage of the energy storage device is converted into AC by three-phase inverters after boosting, which is supplied to permanent magnet synchronous motor drive.

In feedback mode: The converter can work in step-down or step-up mode, \( Q_3 \) is always off in step-down mode. When the locomotive is decelerated or braked, the permanent magnet synchronous motor is used as a generator. The AC generated by the motor is rectified and charged for the supercapacitor after the converter buck or boost. At this time, \( S_2 \) is turned on and \( S_1, S_3 \) and \( S_4 \) are turned off.

3. Control strategy of the HES

3.1. Output control strategy of HES

The output control block diagram of the locomotive power supply is shown in Figure 2. The locomotive starts from zero initial speed. For the given speed sampling, the initial sampling time is \( t_1 \), the sampling interval of \( t_1 \) is 0.1 seconds, and the sampling time \( t_2 \) is obtained by 0.5 seconds delay of \( t_1 \). The differential output is divided into four channels by making a difference between the given speed at \( t_2 \) and \( t_1 \). The control signal of switching \( S_1 \) is obtained by selector 1; the control signal of switch \( S_2 \) is obtained by way of selector 2 after the second path is multiplied by -1; The third way passes through the comparator 1 and then passes through the AND gate and OR gate to get the control signal of the switch \( S_3 \). The fourth way passes through the comparator 4 and then gets the control signal of the switch \( S_4 \) through the AND gate 2. Among them, comparator 2 and 5 are used to judge whether the supercapacitor is full of electricity, and comparator 3 is used to judge whether the
supercapacitor is fully discharged. Through the above operations, the switching states of $S_1$, $S_2$, $S_3$, and $S_4$ under different working conditions of electric locomotive are obtained, as shown in Table 1.

**Table 1. Switching state of switches S$_1$-S$_4$ under different working conditions.**

| Working conditions       | $S_1$ | $S_2$ | $S_3$ | $S_4$ |
|--------------------------|-------|-------|-------|-------|
| Start or accelerate      | 1     | 0     | 0     | 0     |
| Constant speed           | 0     | 0     | 1     | 0     |
| Decelerate or braking    | 0$^a$ | 1     | 0     | 1$^b$ |

$^a$ Supercapacitors are already full of electricity.  
$^b$ Supercapacitors are not fully charged

### 3.2. Bidirectional DC/DC Converter Control

Figure 2 shows the circuit of the multi-input bidirectional DC/DC converter. When the circuit is in the driving mode, if the locomotive is running at acceleration or uniform speed, the converter works in the boost mode, and the output voltage of the energy storage device is raised to the required voltage level on the DC side of the three-phase converter, and the voltage is used to drive the permanent magnet synchronous motor [6-7]. When the circuit is in the feedback mode, the locomotive is decelerated or...
braked, and the converter works in the step-down or step-up mode. The voltage is converted to charge the supercapacitor [8-9].

Driving control: When the circuit is in the driving mode, in order to drive the permanent magnet synchronous motor, the control switches Q_2 and Q_3 are always turned off, the diode D_1 is in the cut-off state, and L, Q_1 and D_2 constitute the boost circuit. According to the formula (1):

\[ V_0 = \frac{1}{1-D} V_i \]  

In the formula, \( V_i (i = 1 \text{ or } 2) \) is the output voltage of the energy storage device that is being supplied at that time. D is duty cycle, and boosting control can be realized by adjusting duty cycle D of switch Q_1.

Because the rated voltage of permanent magnet synchronous motor used in mine locomotive is 380V AC, the given voltage of DC side of three-phase converter is 600V. In order to make the output voltage of the converter reach a given value, the multi-input bidirectional DC/DC converter adopts a double closed-loop control strategy [10]. The control block diagram is shown in Figure 3. Among them, \( V_0^* \) is the given voltage on the DC side of the three-phase converter, \( i_i \) is the actual discharge current of the energy storage device, and \( i_i^* \) is the discharge current required by the energy storage device. The error signal obtained after the difference between \( V_0^* \) and \( V_0 \) is treated by voltage regulator to get \( i_i^* \), and then to make difference with \( i_i \). The error signal is processed by current regulator and PWM generator to get "PWM-Q_1" control pulse, which is used to control switch Q_1, so as to realize the drive of permanent magnet synchronous motor.

![Figure 3](image)

**Figure 3.** Driving control circuit of multi-input bidirectional DC/DC converter.

Feedback control: When the circuit is in the feedback process, the circuit structure and formula are the same as charging. Because the capacitor C on the DC side of three-phase converter will store energy in the driving state, when switching to the feedback state, the voltage on the DC side will be higher than the given value. In order to keep the voltage of the capacitor C within a constant range, the extra energy will be supplied to the supercapacitor to realize the power feedback. Because the feedback current in the process of feedback braking is much less than the charging current, the control strategy block diagram of switch Q_2 is shown in Figure 4. In the figure, \( U_0 \) is the actual DC side voltage of three-phase inverters, and \( U_0^* \) is the given voltage. The error signal obtained after the difference between \( U_0^* \) and \( U_0 \) is treated by voltage regulator to get \( i_i^* \), and then to make difference
with $-i_i$. The error signal is processed by current regulator and PWM generator to get "PWM-Q$_2$" control pulse, which is used to control the switch Q$_2$ to realize the charging of the supercapacitor or battery.

![Bidirectional DC/DC converter feedback control block diagram](image)

**Figure 4.** Bidirectional DC/DC converter feedback control block diagram.

### 4. Simulation analysis

Based on the above analysis of the new battery-super capacitor hybrid power scheme proposed in this paper, the simulation model of the driving control system is built under the environment of MATLAB/Simulink. Among them, the switching frequency of DC/DC and DC/AC converters is 20 kHz, the rated voltage of storage battery is 220 V, the rated voltage and initial voltage of supercapacitor is 300V and 270V respectively, which is formed by series connection of 100*2F single capacitors. In this paper, a fast simulation is used with a time of 10 seconds.

When mining locomotive starts, accelerates or runs at uniform speed, the battery-super capacitor hybrid power system outputs electric energy. After boosting by bi-directional DC/DC converter, it is converted by three-phase converter to produce AC voltage-driven permanent magnet synchronous motor. Among them, the power required for start-up and acceleration is provided by supercapacitors, and the power required for uniform operation is provided by batteries. When the locomotive decelerates or brakes, the motor is used as a generator, and the energy generated is fed back to the power supply to prolong the running time of the locomotive, forming a waveform as shown in Figure 5.

Figure 5 shows that the electric locomotive starts in 0-1.3 seconds, accelerates in 5.8-6.3 seconds, and the electric energy is supplied by the supercapacitor. The electric quantity and voltage of the electric locomotive decrease. Because the storage battery does not provide electric energy in this stage, the electric quantity remains unchanged, the acceleration time of the electric locomotive is shorter, and the driving performance is obviously improved. Within 1.3-2.8s, 3.3-5.8s and 6.3-8.8s, the electric locomotive runs smoothly. At this time, the electric energy is supplied only by the storage battery, and its electric quantity decreases, while the supercapacitor does not provide electric energy, its electric quantity remains unchanged. Within 2.8-3.3 s and 8.8-10 s, the locomotive decelerates and brakes respectively. Permanent magnet synchronous motor (PMSM) acts as generator to generate feedback
electric energy, charges the supercapacitor, and the supercapacitor power increases. Because the supercapacitor is not full, it does not charge the battery, so the battery power remains unchanged.

![Figure 5. Simulation experimental waveform of HES.](image)

5. Conclusions
In this paper, a new type of battery-supercapacitor hybrid power control scheme for the MEL is proposed. A multi-input DC/DC converter is used to control the output of battery-supercapacitor hybrid power under different working conditions of the locomotive, and a series circuit of multi-input DC/DC converter and three-phase converter is used to replace the traditional phase-controlled rectifier circuit to control the bidirectional power of the MEL. The circuit topology of the scheme is theoretically analyzed and simulated to verify the feasibility of the scheme. According to the simulation results, it is concluded that the supercapacitor can play a good role in driving and energy feedback of the MEL.

Acknowledgement
This work is supported by NSFC-Shanxi Coal-based Low Carbon Joint Fund, Project No. U1610120.

References
[1] Gao L J, Dougal R A and Liu S Y 2005 Power enhancement of an actively controlled battery/ultracapacitor hybrid Transactions Power Electronics 20 pp 236-243
[2] Gao Z 2014 Application of super capacitor-battery hybrid energy storage system Tianjin University
[3] Chen G P 2014 Research on Hybrid energy storage system of electric vehicle based on fuzzy control Tianjin University of Technology
[4] Zhang D H, Wang J W and Liu K P 2012 Study on control strategy optimization of HEV on-board composite power supply system Power technology 36 pp 650-654
[5] Mao J M and Wang J Y 2015 Application of super capacitor in dual-power electric vehicle. *Modern Electronic Technology* **38** pp 144-147

[6] Cao B G and Cao J B 2008 Application of supercapacitors in electric vehicles *Journal of Xi’an Jiao tong University* **11** pp 1317-1322

[7] He J J, Hu K W, Chang-Ming Liaw 2015 On a battery/supercapacitor powered SRM drive for EV with integrated on-board charger *ICIT March 17-19* pp 2667-2672

[8] Wang D P 2013 Research on control technology of deep hybrid electric vehicle system *Nanjing: Nanjing University of Aeronautics and Astronautics*

[9] Wu X 2016 Research on control technology of rotary driving system of hybrid excavator. *HuNan University*

[10] Chen Q S, Qiu B and Xie Q C 2005 Fuel cell electric vehicle *Beijing Tsinghua University Press*