Hybrid energy storage system of storage battery / super capacitor for mine electric locomotive

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Abstract. At present, mining electric locomotive with lead-acid battery energy storage, when accelerating or braking, the battery bank (BT bank) in a short period of time is difficult to discharge large power and absorb feedback power, which affects the running efficiency and cruise mileage of electric locomotive. In view of the above problems, the hybrid energy storage system of storage battery and super capacitor is applied to the motor of mine car, and the complementary power distribution scheme of static power output by storage battery and dynamic power output by super capacitor is proposed. In order to realize the power sharing of the two energy storage devices, a bi-directional three-level DC/DC converter is proposed to realize the current and power control of the SC bank. The analysis and experiment show that the HESS can not only output large current and improve the acceleration performance of electric locomotive, but also can save electric energy and improve the running efficiency and cruise mileage of electric locomotive.

1. Introduction
At present, lead-acid batteries are used to store energy in mine electric locomotive. When the locomotive accelerates or brakes, the battery bank cannot discharge and absorb feedbacks in a large capacity in a short time, which affects the running efficiency and cruise mileage of electric locomotive [1]. The running process of electric locomotive can be divided into four states: starting, accelerating or climbing, decelerating or descending, and braking or stopping. The power demand of electric locomotive under these four operating states varies greatly [2]. If only a battery energy storage device is used to drive electric locomotive, is bound to achieve peak power demand and increase the capacity of the battery, and caused great waste [3].

As the lead-acid battery of electric locomotive is difficult to achieve the absorption of feedback pulsating energy, its efficiency is very low. Frequent and excessive charging will damage the battery, affect the power density and cycle life of the battery, and limit the improvement of energy recovery efficiency [4, 5]. Therefore, it is an urgent need to study a new energy storage system which can meet the rapid charge and discharge of electric locomotive. Compared with lead-acid battery, super capacitor (SC) has the advantages of high power density, long cycle life, high recovery efficiency of renewable energy, but low storage density of total energy. Because the two kinds of energy storage devices are complementary, the energy storage system of electric locomotive can be transformed into hybrid energy storage system (Hess) which is composed of battery and super capacitor, which will bring great performance improvement to the energy storage system of electric locomotive.
There are many researches on the application of hybrid energy storage system based on super capacitor in tram and electric vehicle [4, 5], but there is no report on the application of hybrid energy storage system in mine electric vehicle. In References [6, 7], a hybrid energy storage system based on lithium battery and super capacitor is proposed for tram. The loss model and system efficiency optimization of hybrid energy storage system are mainly discussed. The hybrid energy storage system of tram introduced in Reference [7] mainly analyzes the energy management strategy and capacity allocation, but does not study the power allocation of the energy storage system. In Reference [8], a hybrid energy storage system of low-speed electric vehicle super capacitor and lithium iron phosphate battery is designed. The scheme of active parallel hybrid energy storage system is adopted, and the efficiency of the hybrid energy storage system is mainly analyzed. In Reference [9], the hybrid energy storage system of battery and super capacitor connected to DC bus through bi-directional half bridge converter is presented. The detection method of high frequency component of load power is mainly analyzed.

Different from the above literature, this paper proposes to add super capacitor to the hybrid energy storage system of mine electric locomotive based on the traditional lead-acid battery electric locomotive. Firstly, the paper presents the circuit topology of mixed energy storage of mine electric locomotive. According to the Hess topology, three-level bi-directional DC / DC converter is used; the power distribution of two kinds of energy storage devices adopts the control of output current of SC bank and the active control of output power of SC bank, while the output power of BT bank is in passive control. By measuring the performance parameters of the electric locomotive in different working modes, the hybrid energy storage scheme and power distribution control strategy are verified.

2. Hybrid energy storage scheme of electric locomotive

Lead-acid battery energy density than the SCs is big, but the power density is relatively small; SCs instantaneous output power density is greater than the battery. Based on the complementarities of the two energy storage devices, an electric locomotive HESS with high specific energy and high specific power requirements can be formed [10, 11]. In this paper, the electric locomotive hybrid energy storage and motor drive system structure as shown in Figure 1. The SC Bank is connected to DC bus via bidirectional DC/DC converter, as in the traditional electric locomotive, the battery is directly connected with the DC bus to provide voltage support for the DC bus. The DC bus voltage is converted by boost converter and three-phase inverter respectively to supply power to the two motors.

![Figure 1. Structure diagram of our HESS and motor drive system of electric locomotive.](image)

The driver operating lever sets the locomotive speed value (Vreq), and the locomotive transmission system calculates the total power demand (Preq) and the motor setting speed (ωreq). The locomotive controller controls the two types of energy storage devices to distribute the power output according to the setting total power and motor speed. The charging and discharging power of SC bank is controlled.
by a bidirectional DC/DC converter, which controls both the discharging power of SC bank and the regenerative feedback power of the motor braking. It is an active control. The discharge power ($P_{bdis}$) of BT bank is the difference between the total power ($P_{req}$) and the power of SC bank, which is a passive control.

In the Hess topological structure described in Figure 1, when the electric locomotive is running at constant speed, the electric power is mainly output by BT bank; when the electric locomotive is in acceleration or uphill state, the output power of BT bank at this time is not enough to meet the dynamic power demand of the motor, which is supplemented by the power of SC bank into action state; when the locomotive is in deceleration or downhill state, the motor works in regenerative power generation mode, the feedback energy generated is first transmitted to DC bus, and then charged to SC bank through bidirectional DC / DC converter. During the driving cycle of the electric locomotive, the complementary characteristics of SC bank and BT bank are fully utilized, so that the electric locomotive can output more dynamic power when needed, and further improve the heavy load starting and acceleration performance of the electric locomotive.

In the proposed hybrid energy storage system of electric locomotive, in order to make two kinds of energy storage devices output electric energy reasonably, it is necessary to optimize the power distribution control. In the hybrid energy storage system as shown in Figure 1, the connection of the battery group is the same, but the super capacitor group is connected to the DC bus through the bidirectional DC / DC converter. Because the response speed of super capacitor is faster, the power distribution control is realized by controlling the charge and discharge current of super capacitor. This means that the power distribution of the two energy storage devices depends on the power demand of the load and the output current of the super capacitor, while the output power of the battery is under passive control. Due to the high power of the electric locomotive, the supercapacitor is divided into two groups of SC1 and SC2, so the bidirectional DC / DC converter is proposed to adopt the three-level half bridge topology [11, 12]. Performance parameters and variables are shown in Table 1.

| Variable (unit) | Interpretation | Variable (unit) | Interpretation |
|----------------|----------------|----------------|----------------|
| $P_{req}$ (W)  | Total locomotive demand power | $u_0$ (V) | The control voltage calculated by the current controller |
| $P_{cmaxchg}$ (W) | SC Bank maximum charging power | $u_{AB}$ (V) | The voltage between point A and point B of three-level converter |
| $P_{cmaxdis}$ (W) | SC Bank maximum discharge power | $u_{CO}$ (V) | The output voltage of three-level converter |
| $P_{clim}$ (W) | SC Bank minimum power control value | $i_{co}$ (A) | The output current of three-level converter |
| $P_{mr}$ (W) | The rated total power of the motor | $i_{BT, out}$ (A) | The output current of the BT Bank |
| $P_{bdis}$ (W) | BT Bank discharge power | $i_{SC, out}$ (A) | The detection value of SC Bank's output current on the load side |
| $U_{SC}$ (V) | SC Bank voltage, $U_{SC}=U_{SC1}=U_{SC2}$ | $i_{SC, ref}$ (A) | Reference value of SC Bank's output current on the load side |
| $U_{BT}$ (V) | The voltage of BT Bank | $i_{Load}$ (A) | The total demand current calculated from the total load power |
| $U_{cap}$ (V) | The reference voltage of SC Bank | $d$ | Pulse duty ratio of switching devices, $d=d_1=d_2$ |
| $U_{cmax}$ (V) | The maximum voltage of SC Bank | | |

Table 1. Performance parameters and variables.
2.1. Three-level DC/DC converter

The circuit structure of the three-level bi-directional DC/DC converter is shown in Figure 2.

The three-level converter is composed of two traditional half bridge converters in series. The super capacitor bank is divided into two parts with equal capacity, SC1 and SC2. The output side is led from A and B points. The output voltage and current are UCO and ICO respectively after connecting the inductance L. the battery voltage UBT keeps the support of DC bus voltage.

![Circuit structure and control scheme for bi-directional DC/DC converter.](image)

**Figure 2.** Circuit structure and control scheme for bi-directional DC/DC converter.

The control pulses of the four switching devices of the three-level converter are SW1A and SW1B, SW2A and SW2B respectively, and their waveforms are shown in Figure 3(a). The SW1A and SW1B, SW2A and SW2B are in contrast to each other in pulse phase, while the phase difference between SW1A and SW2B is 90°. The three-level converter has four working states in one working week, as shown in Table 2. The waveforms of output voltage $u_{AB}$ and output current $i_{co}$ of the three-level converter are shown in Figure 3(b). The $u_{AB}$ presents three level states: 0, $U_{SC1}$ ($U_{SC2}$), and $U_{SC1} + U_{SC2}$.

**Table 2.** Different working conditions of three-level converter.

|      | SW2A | SW2B | SW1B | SW1A | $u_{AB}$ |
|------|------|------|------|------|----------|
| Stage 1 | 0    | 1    | 0    | 1    | $U_{SC2}$ |
| Stage 2 | 1    | 0    | 1    | 0    | $U_{SC1}$ |
| Stage 3 | 0    | 1    | 1    | 0    | 0        |
| Stage 4 | 1    | 0    | 0    | 1    | $U_{SC1} + U_{SC2}$ |

Note: "1" indicates that the device is in turn-on state, and "0" indicates that the device is in turn-off state.

![Working waveform of three-level converter.](image)

**Figure 3.** Working waveform of three-level converter.
2.2. Power distribution control strategy of the HESS

The general principle of the HESS power distribution control strategy is as follows: the SC bank shares the dynamic change part of locomotive power, the BT bank only shares the static part of power, reduces the discharge current of the BT bank, and fully recovers the regenerative energy of locomotive generation braking [13]. The specific control strategy is as follows: when the locomotive speed is zero or low, the control the SC bank energy is at a high level to prepare sufficient energy for the subsequent locomotive acceleration. Under the locomotive condition of medium speed, the SC bank energy is controlled in the state of medium voltage to ensure that it can not only accelerate discharge but also absorb renewable energy when locomotive decelerating. When the locomotive reaches or approaches the maximum speed, the SC bank is controlled to be near the minimum operating voltage, ready to receive the regenerative energy when the locomotive braking.

According to the relationship between the actual voltage and nominal voltage of the super capacitor, the total demand power of the locomotive and the calculated value of the maximum charge and discharge power, a power distribution control strategy is established to complete the distribution of the demand power of the super capacitor under different operating conditions of the locomotive. The power distribution method is shown in Figure 4. In Figure 4, \( P_{\text{req}} \) is the total demand power (W); \( P_{\text{creq}} \) is the output power of the super capacitor (W); \( P_{\text{cmaxchg}} \) is the calculation value of the maximum charging power of the super capacitor (W); \( P_{\text{cmaxdis}} \) is the calculation value of the maximum discharging power of the super capacitor (W); \( P_{\text{clim}} \) is the lowest control value of the working power of the super capacitor (W), \( P_{\text{clim}} = P_{\text{req}} \cdot 0.3 \cdot P_{\text{MR}} \) and PMR is the rated power of the motor.

\[
\begin{align*}
P_{\text{req}} & > 0 \\
& \begin{cases}
N & \text{if } U_{\text{SC}} > U_{\text{cap}} \\
Y & \text{if } U_{\text{SC}} \geq U_{\text{cap}}
\end{cases}
\end{align*}
\]

\[
\begin{align*}
P_{\text{creq}} & = P_{\text{cmaxchg}} \\
P_{\text{creq}} & = P_{\text{req}} \\
P_{\text{creq}} & = P_{\text{cmaxdis}} \\
P_{\text{creq}} & = P_{\text{clim}}
\end{align*}
\]

**Figure 4.** The SC bank power control flow chart.

1. If the total demand power of the locomotive is greater than 0 \((P_{\text{req}} > 0)\), and the SC bank voltage is greater than its reference voltage \((U_{\text{SC}} > U_{\text{cap}})\), it means that the locomotive motor is in normal running state, while the SC bank is in the state of discharge. As long as the output power \(P_{\text{creq}}\) is not greater than \(P_{\text{req}}\), the SC bank can always output power by the maximum \(P_{\text{cmaxdis}}\); If the output power \(P_{\text{creq}}\) is greater than \(P_{\text{req}}\), it is adjusted to be equal to \(P_{\text{req}}\).

2. If \(P_{\text{req}} > 0\), \(U_{\text{SC}} \leq U_{\text{cap}}\), it means that the SC bank voltage has been lower than its reference voltage, it indicates that the terminal voltage has been lower than the nominal voltage \(U_{\text{cap}}\), and the power reserve of the supercapacitor is too small. The output power of the supercapacitor should be reduced to the lowest control value \(P_{\text{clim}}\).

3. If \(P_{\text{req}} \leq 0\), it means that the locomotive is decelerating or braking, and the locomotive motor is in power generation state at this time, the SC bank is charged to absorb the power generated by regeneration. If only the charging power \(P_{\text{creq}}\) is not greater than total demand power \(P_{\text{req}}\), the maximum charging power \(P_{\text{cmaxchg}}\) can be charged all the time. If \(P_{\text{req}} \leq P_{\text{cmaxchg}}\), the charging power of the SC bank \(P_{\text{creq}} = P_{\text{req}}\).

The total power required of mining electric locomotive \(P_{\text{req}}\) is equal to the sum of the output power of SC bank and BT bank. The \(P_{\text{req}}\) should be decoupling into high frequency and low frequency parts,
be shared between two storage devices. The high frequency power can be provided by the SC bank and the smooth power will be from the BT bank.

By measuring the load current signal, and using the high frequency part of the load current as the current reference of the convert, the power from the BT bank will be passively controlled. When regenerative breaking of locomotive, the charge current is set as the reference to the SC bank interface converter. When charged by instantaneous current, the efficiency of the SC bank with converter is higher than BT bank. Current reference of the SC bank $i_{SC,Ref}$ can be expressed approximately as

$$i_{SC,Ref} = \frac{P_{SC,Ref}}{U_{BT}}$$  \hspace{1cm} (1)

The power sharing control of the SC bank is realized by controlling the output current $i_{SC, out}$ of the three-level converter (see Figure 2). The current controller is a PI regulator, which is designed as a typical linear controller. Its control block diagram is shown in Figure 5. The error signal between the SC bank's current reference value $i_{SC,Ref}$ and the measured current $i_{SC, out}$ is taken as the input of PI regulator, and the dynamic component of output voltage of three-level converter can be calculated through PI regulator. Finally, the duty cycle $d$ of the three-level converter's PWM control pulse is calculated from Equation (2). System open-loop transfer function is constants as following.

$$d = \frac{u_o + U_{CO}}{U_{SC1} + U_{SC2}}$$  \hspace{1cm} (2)

$$\frac{i_{SC, out}(s)}{i_{SC,Ref}(s)} = \frac{K_p K_i s + 1}{K_i s (L_{CO} + R_{LCO} s)}$$  \hspace{1cm} (3)

Where, $K_p, K_i$ are the proportional and integral coefficient; $R_{LCO}, L_{CO}$ are the resistance and inductance in the control system.

\[\text{Figure 5. Current control block diagram of three-level controller.}\]

3. Experimental results and discussions
The parameters of the experimental system are shown in Table 3.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Parameter} & \textbf{Value} \\
\hline
In wheel motor Power & 3kW×2 \\
\hline
DC bus voltage & 96V \\
\hline
Battery rating voltage & 96V \\
\hline
Super capacitor capacitance & 190F×2 \\
\hline
Super capacitor rating voltage & 96V×2 \\
\hline
IGBT module maximum rate & 600V/150A \\
\hline
\end{tabular}
\caption{Experimental parameters of the HESS.}
\end{table}

The experimental system simulated three working modes of electric locomotive respectively: constant speed forward, acceleration or uphill, deceleration or downhill. The experimental test of the HESS power sharing is conducted, the records in Figure 6 is that there are three current waveforms of the BT bank $i_{BT}$, the SC bank $i_{SC}$ and the load $i_{Load}$ in different working modes.

Figure 6(a) showed that the locomotive was working constant speed state, during this period, the average output current of the SC bank was nearly close to zero, and the load current is all provided by
the BT Bank. The current waveform in Figure 6(b) is that the locomotive is working accelerated state, the load current $i_{\text{load}}=52A$, $i_{\text{SC}}=43A$, $i_{\text{BT}}=8A$, $i_{\text{SC}} > i_{\text{Load}}$. During this period, the load requires large dynamic power, which is mainly supplied by the SC bank. Figure 6(c) showed the current waveform during the locomotive deceleration. During deceleration period, $i_{\text{SC}}=-41A$, $i_{\text{Load}}=-48A$, $i_{\text{BT}}=-7A$, indicating that the locomotive is in generation baking state, the SC bank and the BT bank are in the charging state, and the regenerative energy generated by the load is mainly absorbed by the SC bank.

![Figure 6. The current waveform in different working stage.](image)

![Figure 7. Power sharing curve of the HESS.](image)

Figure 7 is the power output curve of the HESS. The dotted line in Figure 7 is the total demand power of the electric locomotive; the other two solid lines are the output power curves of the SC bank and the BT bank. The scenario in Figure 7 is that the load power demand rises rapidly during 0-2s. During the interval, the output power of SC bank is greater than that of the BT bank, and the power curves of both shows an upward trend. During the interval of $t = 2$–5s, the locomotive enters a stable working state, the SC bank power curve shows a downward trend, the BT bank power curve shows an upward trend. During this interval, the BT bank supplies the main power output. During the interval of $t = 5$–10s, the electric locomotive is in deceleration and braking state, the output power of the BT bank continues to decrease. At this time, the locomotive is working in state of regenerative generation braking, and the renewable energy generated is absorbed by the SC bank, so the power curve of the SC
bank is negative during this period. In the whole working cycle, the algebraic sum for the output power of the BT bank and the SC bank is equal to the demand power of electric locomotive.

4. Conclusions
In this paper, a novel type of HESS is proposed, which is suitable for mine electric locomotive. The circuit structure of hybrid energy storage system with super capacitor and battery is designed. A bidirectional three-level DC/DC converter is proposed to realize the output power distribution of the HESS. For the aspect of control of the HESS, it is proposed to actively control the output power of the SC bank by controlling the output current of the SC bank, and the output power of the BT bank is passively controlled. The analysis and experimental results show that this control method can realize the power sharing of the BT bank and the SC bank of the locomotive in different working modes, satisfies the load peak power demand of the locomotive, and prolong the cruise mileage of the locomotive. It provides technical support for the research and development of new battery electric vehicle.

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