Research on Capacity Allocation and Control of Elevator Hybrid Energy Storage Device

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Abstract

The betterment of economic and energy recovery efficiency of an elevator energy storage device is considered a big challenge. To serve this purpose, this paper proposes a capacity allocation method and an energy control strategy of elevator hybrid energy storage device (HESD) based on supercapacitor and battery. By analysing the cost for HESD and calculating battery life with rain flow counting method, a capacity allocation scheme with the minimum daily average cost as the objective function is established. The working area of HESD is partitioned according to the state of charge (SOC) value, and the energy control state machine of HESD. The SOC and the DC bus voltage as the transition boundary is constructed to realize the reasonable energy control. The case analysis and experimental results show that the average daily cost of HESD is 54.65%, which is lower than single energy storage system. The energy saving efficiency of HESD is 15.2%, and this is higher than using only the supercapacitor, which improves the economy and energy saving efficiency of the elevator.

Keywords: elevator energy saving, hybrid energy storage system, rain flow counting method, capacity configuration

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1. Introduction

Nowadays, elevators are commonly used to transport people in buildings and consume a high proportion of electricity. Especially in mid-rise and high-rise residential buildings, elevators consume bulk of energy, which is about 50 % [1]. Thus, it is important to improve the energy efficiency of elevators.

At present, there are mainly two ways to save energy in elevators. One method is recycling the regenerative energy to the grid. By utilizing elevators' operation characteristics and weight difference between cabin and counterweight, the elevator gravitational potential energy can be transformed into electrical energy and then fed back into grid [2-4]. However, there are some repercussions in the grid-connection of regenerative energy [5-7].

The other method is DC energy storage, which mounts the energy storage device (ESD) on the DC bus through a bidirectional DC/DC converter to realize the storage and utilization of the elevator energy [8-10]. An elevator regeneration energy saving strategy based on batteries was proposed in [9]. With the rise of supercapacitor technology, the application of supercapacitor energy storage of elevator has become an emerging topic in research [10-12]. In [10], a supercapacitor-based energy management method is designed by adjusting the elevator cabin speed. In [11], a fuzzy logic controller was proposed to control the power flow of supply and the supercapacitor of elevator. In [12], a multichannel buck-boost converter was used to develop a supercapacitor based energy storage system, which reduces elevator’s energy consumption and provides passenger rescue services.

In recent years, the hybrid energy storage device (HESD) based on supercapacitor and battery has been applied to many fields, such as renewable energy, power system, electric vehicle and electric boat [13-16]. The supercapacitor has the advantages of long life, fast dynamic response and high power density [14, 17, 18], and the battery has higher energy density [19, 20]. The HESD combines the supercapacitor and battery together and makes use of their complementary advantages [14]. However, there are not many reports on the HESD application in elevators.

In this paper, we take the elevator HESD based on supercapacitor and battery as the research object and establish the capacity allocation method with the minimum daily average cost as the objective function to improve the economy of the HESD. Also, the energy control state machine of the HESD is established by utilizing the complementary characteristics of the supercapacitor and the battery, which realize the reasonable energy control and improve the energy saving efficiency.

2. Hybrid Energy Storage Device of Elevator

The structure of elevator HESD is shown in Figure 1. The HESD is composed of a supercapacitor, a battery, and two bidirectional DC/DC converters. This structure fully utilizes the complementary characteristics of the supercapacitor and battery. The supercapacitor has high power density and low energy density. Whereas, the battery has low power density and high energy density. The supercapacitor and the battery are both connected to the DC bus of the elevator inverter through the bidirectional DC/DC converters. With this arrangement, energy regenerated by the elevator is absorbed by supercapacitor and some part of it can be provided to the elevator. In this way, the energy saving efficiency of the elevator is improved.

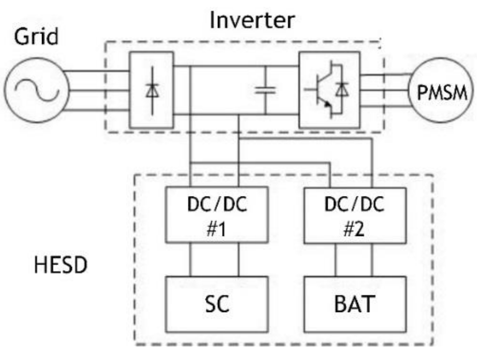

Figure 1. HESD of elevator

3. Capacity Allocation

In order to reduce the cost of the HESD, a capacity allocation optimization model of the HESD is established in this section. With the minimum daily average cost as the objective function, the capacities of the battery and the supercapacitor are reasonably allocated.

3.1 Objective function

The capacity allocation optimization model of the HESD's objective function is established as follow:

$$C_{cost} = \min(C_{SC} + C_{bat} + C_{DC1} + C_{DC2}) \quad (1)$$

where C_{sc}, C_{bat}, C_{DC1}, C_{DC2}, C_{cost} represent the daily average costs of supercapacitor, battery, DC/DC converter #1, DC/DC converter #2 and total cost respectively.

The daily average costs include initial costs and maintenance costs, which can be represented as follow:

$$\begin{cases} C_{sc} = \dfrac{C_{E,sc}E_{sc}(1+\lambda_{sc})}{T_{day,sc}} \\ C_{bat} = \dfrac{C_{E,bat}E_{bat}(1+\lambda_{bat})}{T_{day,bat}} \\ C_{DC1} = \dfrac{C_{P,DC}P_{DC1}}{T_{day,DC}} \\ C_{DC2} = \dfrac{C_{P,DC}P_{DC2}}{T_{day,DC}} \end{cases} \quad (2)$$

where $C_{E,sc}$, $C_{E,bat}$ are the unit capacity costs of supercapacitor and battery respectively; E_{sc} and E_{bat} are the rated capacities of supercapacitor and battery respectively; λ_{sc} and λ_{bat} are the maintenance cost coefficients of supercapacitor and battery respectively; $C_{P,DC}$ are unit power cost of DC/DC converter; P_{DC1} and P_{DC2} are the rated transmission power values of DC/DC converter #1 and DC/DC converter #2 respectively; $T_{day,sc}$, $T_{day,bat}$, $T_{day,DC}$ are respectively the life of supercapacitor, battery and converter.

3.2 Energy storage device life

The life of supercapacitor is generally more than 10 years, and its cycle life is as high as 0.5 to 1 million times. The life of the bidirectional DC/DC converter is mainly affected by thermal mechanical stress, and its cycle life can generally reach 1 million times. Therefore, $T_{day,sc}$ and $T_{day,DC}$ are both set to 10 years in this paper.

Compared to supercapacitor and bidirectional DC/DC converter, the life of battery is short. In this paper, we analyse the life of battery based on the impact of depth of discharge (DoD). It is known that the life of lead-acid battery used in this paper is as shown in the following equation:

$$T_{bc}(d) = -3278d^4 - 5d^3 + 12823d^2 - 14122d + 5112 \quad (3)$$

where d is the battery's depth of discharge.

Due to the irregularity of the elevator operation, the DoD of the battery is constantly changing. Therefore, we use rain flow counting method to obtain the number of charge and discharge cycles and the corresponding DoD of the battery in one day [21, 22]. And the battery life loss per day can be obtained by using the following equation:

$$L_{loss,bat} = \sum_{i=1}^{m} \frac{N_{bc}(d_i)}{T_{bc}(d_i)} \quad (4)$$

where m is the number of different DoD obtained by the rain flow counting method, $N_{bc}(d_i)$ indicates the number of times the DoD is d_i, $T_{bc}(d_i)$ represents the life when the DoD is d_i.

Therefore, the life of the battery is:

$$T_{day,bat} = \frac{1}{L_{loss,bat}} \quad (5)$$

3.3 Constraints

To allocate the capacity of HESD, the following constraints should be considered:

- *Energy conservation*: The sum of battery and supercapacitor's power should be the same as the elevator's power shortage.
- *SOC constraint*: In order to prevent over charging or over discharging of the HESD and prolonging the service life, it is necessary to set the upper and lower limits of the SOC of battery and supercapacitor. Besides, it is also necessary to consider the cooperation problem between the bidirectional DC/DC converter and the energy storage system when setting the SOC range value.
- *Power contraint*: The input and output power of the battery and supercapacitor should not be greater than the rated power of its own and bidirectional DC/DC converter.

Hence, the constraints can be written as:

$$\begin{cases} P_{bat}(t) + P_{SC}(t) = P_{ele}(t) \\ SOC_{SC\_min} \leq SOC_{SC}(t) \leq SOC_{SC\_max} \\ SOC_{bat\_min} \leq SOC_{bat}(t) \leq SOC_{bat\_max} \\ -P_{SC} \leq P_{SC}(t) \leq P_{SC} \\ -P_{bat} \leq P_{bat}(t) \leq P_{bat} \end{cases} \quad (6)$$

where $P_{sc}(t)$, $P_{bat}(t)$ and $P_{ele}(t)$ are the powers of supercapacitor, battery and elevator respectively, P_{sc}, P_{bat} and P_{DC} are the rated powers of supercapacitor, battery and DC/DC converter respectively.

4. Energy Control

To utilize the elevator's regenerative energy, the energy flow of the HESD should be controlled properly.

Because of the large power density and rapid response, supercapacitor is prior used to charge and discharge. Because of the characteristics of high energy density, the battery is used to compensate for the lack of charge and discharge energy.

Assume that the supercapacitor's SOC upper limit is SOC_{sc_up}, the lower limit is SOC_{sc_down}, the DC bus voltage is u_{dc}, the DC bus voltage fluctuation upper limit is u_{dc_max}, and the DC bus voltage fluctuation lower limit is u_{dc_min}. According to the SOC values, we partition the operation areas of supercapacitor and battery, as shown in Figure 2.

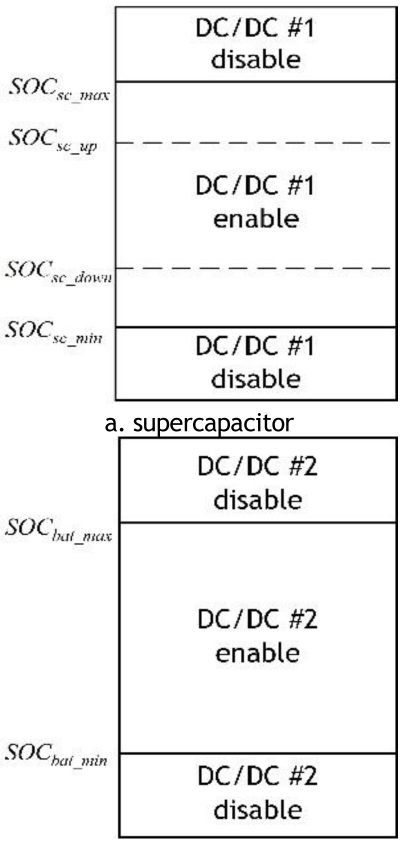

Figure 2. SOC partition of HESD

Also, we propose the HESD's energy control state machine, which is shown in Figure 3.

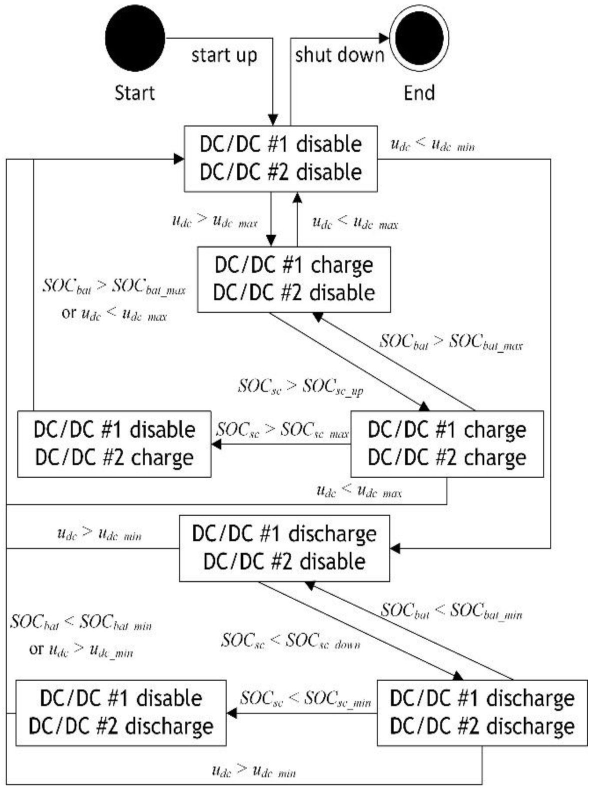

Figure 3. State machine of HESD's energy control

It can be seen from Figure 2 and Figure 3 that the HESD's energy control is mainly composed of charge and discharge states.

- *Charge state*: The elevator is in the state of power generation when falling in heavy load or rising in light load. The regenerative energy is fed back to the DC bus, causing u_{dc} to rise. In this state, the regenerative energy should be absorbed by the HESD. When u_{dc} exceeds u_{dc_max}, the bidirectional DC/DC converter 1 charges the supercapacitor to stabilize the u_{dc} and the SOC_{sc} gradually rises. If SOC_{sc} reaches SOC_{sc_up} and u_{dc} is still greater than u_{dc_max}, that is, the elevator is still in the power generation state, the bidirectional DC/DC converter 2 charges the battery and the SOC_{bat} gradually rises. If u_{dc} is still greater than u_{dc_max} after SOC_{sc} reaches SOC_{sc_max} or SOC_{bat} reaches SOC_{bat_max}, which means that the regenerative energy exceeds the energy recovery capability of the supercapacitor or battery, the bidirectional DC/DC converter 1 or the bidirectional DC/DC converter 2 should stop working to prevent over charge.

- *Discharge state*: The elevator is in the power consumption state when rising in heavy load or falling in light load, causing the u_{dc} to drop. In this state, the HESD should compensate for the lack of energy. When u_{dc} is less than u_{dc_min}, the supercapacitor discharges to the DC bus through the bidirectional DC/DC converter 1 to stabilize the u_{dc} and the SOC_{sc} gradually decreases. If SOC_{sc} reaches SOC_{sc_down} and u_{dc} is still less than u_{dc_min}, that is, the elevator is still in the power consumption state, the battery is discharged to the DC bus through the bidirectional DC/DC converter 2 and the SOC_{bat} gradually decreases. If u_{dc} is still less than u_{dc_min} after SOC_{sc} reaches SOC_{sc_min} or SOC_{bat} reaches SOC_{bat_min}, then bidirectional DC/DC converter 1 or bidirectional DC/DC converter 2 should stop working to prevent over discharge.

5. Case Study

In this section, a case study is conducted to verify the HESD's capacity allocation optimization model.

5.1 Parameters

The major parameters of elevator in this case is shown in Table 1.

Table 1. Major parameters of the elevator

Parameter	Value
Number of floors	15
Height/m	60
Balance factor	0.5
Rated load/kg	1000
Rated power/kW	13.6

According to the single-day elevator traffic curve of a building [23], it can be seen that the traffic flow into the hallway peaks in the morning and at noon, and conversely, the traffic flow out of the hallway peaks at noon and night. Thus, it can be considered that a lot of heavy load rise operations and light load fall operations occur during 7:00-8:00 and 12:30-13:00. A large number of heavy load fall and light load rise operations occur during 11:30-12:00 and 17:00-18:00. And at other times, the elevator basically operates in light load condition. Therefore, the operating conditions of the elevator can be estimated in this case study, which are shown in Table 2.

Table 2. Elevator operating conditions

Time	Heavy load rise /light load fall (times)	Heavy load fall /light load rise (times)
7:00-8:00	15	0
11:30-12:00	0	10
12:30-13:00	10	0
17:00-18:00	0	15
Other	50	50

In one elevator operation cycle(fall and rise), the energy recovered by the HESD is mainly the change value of the potential energy. When the elevator's rising distance is h, the change value of potential energy is:

$$W = (M + m_1 - m_2)gh \tag{7}$$

where M is the elevator's load weight, m_1 is the elevator's cabin weight, m_2 is the elevator's counterweight.

If W>0, the elevator's traction machine is in the power consumption state. If W<0, the elevator's traction machine is in the power generation state. The difference between m_1 and m_2 can be derived from the balance factor and the elevator's rated load, which is:

$$m_1 - m_2 = -km_N \tag{8}$$

where k is the balance factor and m_N is the rated load.

According to the parameters of the elevator and traction machine in this case, W equals to 83 Wh if the elevator rises in the heaviest load and falls without load in one cycle, and W equals to -83 Wh if the elevator rises without load and falls in the heaviest load in one cycle.

The HESD is composed of a lead-acid battery, a supercapacitor and two bidirectional DC/DC converters, whose unit prices are listed in Table 3.

Table 3. Prices of HESD components

Time	Price of power (CNY/kW)	Price of capacity (CNY /kWh)	Maintenance price (CNY /kWh^2)
Battery	-	800	0.05
Supercapacitor	-	27000	0.05
DC/DC	500	-	-

5.2 Results and analysis

To meet the power constraint, the rated power of the supercapacitor should be greater than the rated power of the elevator traction machine with a certain margin. And the rated power of the battery should be greater than the maximum regenerative power of the elevator traction machine with a certain margin. Thus, the rated powers of the supercapacitor and the battery are set to 16 kW and 8 kW respectively.

To meet the SOC constraint and recover all the regenerative energy at night peak, the total capacity of the super capacitor and battery need to be greater than 2.5 kWh.

Since the energy density of the battery is large, its capacity is set to 2.5 kWh. Taking the supercapacitor's capacity as a variable and combining the constraints, the optimization of minimum daily average cost is performed. And the daily average cost curve is shown in Figure 4.

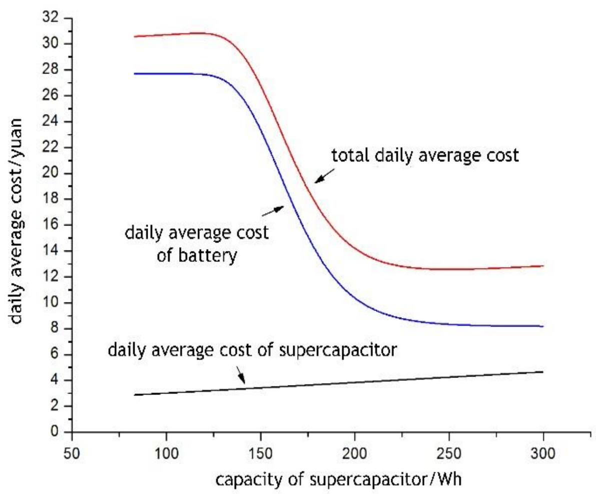

Figure 4. Daily average cost changing curve

As can be seen from Figure 4, the battery's average daily cost decreases as the capacity of the supercapacitor increases. If the supercapacitor's capacity exceeds 200 Wh, the daily average cost of the battery decreases at a slower rate. The total daily average cost of the hybrid energy storage system reaches a minimum when the supercapacitor's capacity is around 250 Wh, which is 12.58 RMB.

The life and average daily cost of HESD with optimized capacity allocation and the system using only battery or supercapacitor are shown in Table 4.

Table 4. Optimization results

Parameter	Battery	Super-capacitor	HESD	
			Battery	Super-capacitor
Rated power/kW	16	16	8	16
Rated capacity/kWh	2.5	2.5	2.5	0.25
Life/year	0.24	10	1.29	10
Average daily cost/yuan	27.74	23.68	12.58	

Among them, the rated power and rated capacity of the energy storage system using only battery and supercapacitor are set to 16 kW and 2.5 kWh, respectively.

It can be seen from Table 4 that when only the battery is used, the cycle life is greatly reduced due to frequent charging and discharging of the battery. And the battery can only be used for 0.24 years, resulting in a great increase in the average daily cost of ESD. When only the supercapacitor is used, the daily average cost is still high due to the high unit price of the supercapacitor. When both battery and supercapacitor are used, the battery ensures the energy's storage and utilization because of its advantages of high energy density while the supercapacitor withstands the losses of frequent charging and discharging. These complementary characteristics improve the life of the battery and reduce the average cost of the ESD by 54.65%, which greatly improves the economy of the ESD.

6. Experiment

In order to compare the practical application effects of different types of elevator ESDs, the prototype is designed for experimental verification.

The HESD is shown in Figure 5.

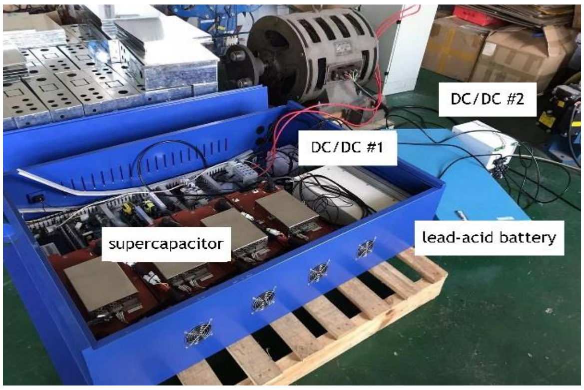

Figure 5. Hybrid energy storage device

For the supercapacitor, the capacity is 40 F and the rated voltage is 196 V. For lead-acid battery, the capacity is 17 Ah and the rated voltage is 196 V. The rated powers of supercapacitor's and battery's bidirectional DC/DC converter are 16 kW and 8 kW, respectively. The major parameters of the experimental elevator are the same as mentioned in Table 1 and the floor number of building for experiment is 2. The experimental elevator traction machine is shown in Figure 6.

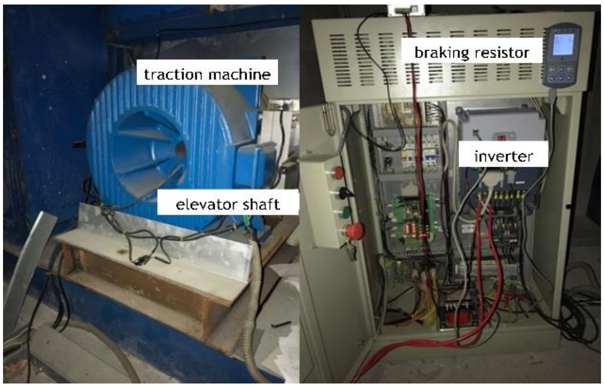

Figure 6. Elevator traction machine

In the case of no load, we compare the energy consumptions in the conditions of using no ESD, supercapacitor and HESD.

The grid side voltage and current are measured, and the power consumptions of the elevator in three cases are calculated, and results are shown as Figure 7.

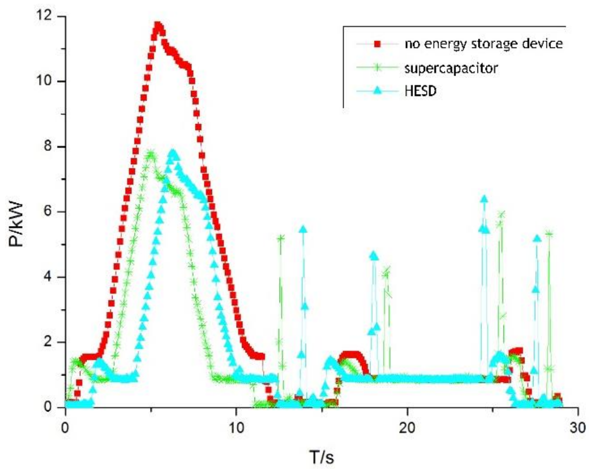

Figure 7. Power consumptions of no ESD, supercapacitor and HESD

It can be seen from Figure 7 that, at the beginning, the elevator falls and consumes energy. The maximum power provided by the grid is about 12 kW if no ESD is used, while the power is about 8 kW if HESD or supercapacitor is used. And then the elevator rises, and the powers provided by the gird are about 1 kW in all three conditions. However, in the condition of using supercapacitor and HESD, the energy regenerated by the elevator is saved by supercapacitor and HESD instead of being consumed by braking resistor.

Under different load conditions, the energy consumptions of the three cases are respectively measured. The total energy consumptions are also calculated. And the results are shown in Table 5.

Table 5. Energy consumption of elevator

Load	ESD	Energy consumption (Wh)	Energy saving efficiency (%)
0%	No	21.87	-
	Supercapacitor	15.57	28.8
	HESD	15.37	29.7

Load	ESD	Energy consumption (Wh)	Energy saving efficiency (%)
25%	No	14.14	-
	Supercapacitor	12.34	12.8
	HESD	12.16	14.0
50%	No	11.71	-
	Supercapacitor	11.37	2.8
	HESD	11.52	1.6
75%	No	19.81	-
	Supercapacitor	15.66	21.0
	HESD	14.62	26.2
100%	No	25.27	-
	Supercapacitor	19.48	22.9
	HESD	17.97	28.9
Total	No	92.80	-
	Supercapacitor	74.43	19.8
	HESD	71.64	22.8

It can be seen from Table 5 that the energy saving efficiency of the elevator using HESD reaches 22.8 %. Compared with the elevator using only the supercapacitor, the energy saving effect is improved by 15.2 %, which means that the HESD has better energy saving efficiency.

7. Conclusion

Taking the elevator HESD based on supercapacitor and battery as the research object, this paper has proposed a capacity allocation method and an energy control strategy of the HESD. By analysing the cost of the components and calculating the battery's life using the rain flow counting method, a capacity allocation scheme of HESD with the minimum daily average cost as the objective function is established. Utilizing the complementary characteristics of supercapacitor and battery, the SOC of the HESD is partitioned and the state transition boundary is set according to the SOC and DC bus voltage variation. Based on this, the energy control state machine of HESD is constructed, which realizes the reasonable control of HESD's energy. The analysis and experiment are conducted to verify the proposed method. The results show that the average energy cost of HESD is reduced by 54.65 %, and the energy saving efficiency of the elevator using HESD is increased by 15.2 % compared with the elevator using only the supercapacitor. Thus, the economy and energy saving efficiency of the elevator are greatly improved.

8. Bibliographic References

[1] CHOU, S.Y., BUDHI, D.A., DEWABHARATA, A., ZULVIA, F.E., "Improving elevator dynamic control policies based on energy and demand visibility", In: 2018 3rd International Conference on Intelligent Green Building and Smart Grid (IGBSG 2018), Taiwan, China, 22-25 April 2018, USA: IEEE, 2018, pp. 1-4.

[2] LIN K.Y., LIAN K.Y., "Actual measurement on regenerative elevator drive and energy saving benefits", In: 2017 International Automatic Control Conference (CACS 2017), Taiwan, China, 12-15 Nov. 2017, USA: IEEE, 2017, pp. 1-5.

[3] HE, J., MAO, C., LU, J., YANG, J., "Design and Implementation of an Energy Feedback Digital Device Used in Elevator", *IEEE Transactions on Industrial Electronics*, 2011, vol. 58, no. 10, pp. 4636-4642, ISSN 1557-9948.

[4] XU, B., YANG, J., YANG, H., "Comparison of energy-saving on the speed control of the VVVF hydraulic elevator with and without the pressure accumulator", *Mechatronics*, 2005, vol. 15, no. 10, pp. 1159-1174, ISSN 0957-4158.

[5] LI, B., WAN, J., LI, M., GE, A., "Research on elevator drive device with super capacitor for energy storage", In: 2011 4th International Conference on Power Electronics Systems and Applications, 12 August 2011, Hong Kong, China, USA: IEEE, 2011, pp. 1-5.

[6] ETXEBERRIA-OTADUI, I., VISCARRET, U., CABALLERO, M., RUFER, A., BACHA, S., "New optimized PWM VSC control structures and strategies under unbalanced voltage transients", *IEEE Transactions on Industrial Electronics*, 2007, vol. 54, no. 5, pp. 2902-2914, ISSN 0278-0046.

[7] CHOI, W., LEE, W., HAN, D., SARLIOGLU, B., "New configuration of multifunctional grid-connected inverter to improve both current-based and voltage-based power quality", *IEEE Transactions on Industrial Electronics*, 2018, vol. 54, no. 6, pp. 6374-6382, ISSN 0093-9994.

[8] BILBAO, E., BARRADE, P., ETXEBERRIA-OTADUI, I., RUFER, A., LURI, S., GIL, I., "Optimal energy management strategy of an improved elevator with energy storage capacity based on dynamic programming", *IEEE Transactions on Industry Applications*, 2013, vol. 50, no. 2, pp. 1233-1244, ISSN 0093-9994.

[9] LIN S., SONG W., CHEN Y., LING L., FENG Z., "Study on the model of elevator regeneration energy and its energy storage control method", In: 2015 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE 2015), Offenburg, Germany, 20-23 Oct. 2015, USA: IEEE, 2016, pp. 125-128.

[10] JABBOUR, N., MADEMLIS, C., "Supercapacitor-Based Energy Recovery System with Improved Power Control and Energy Management for Elevator Applications", *IEEE Transactions on Power Electronics*, 2017, vol. 32, no. 12, pp. 9389-9399, ISSN 0885-8993.

[11] LI, Z., RUAN, Y., "A novel energy saving control system for elevator based on supercapacitor bank using fuzzy logic", In: 2008 International Conference on Electrical Machines and Systems, Wuhan, China, 17-20 Oct. 2008, USA: IEEE, 2009, pp 2717-2722.

[12] LURI, S., ETXEBERRIA-OTADUI, I., RUJAS, A., BILBAO, E., GONZALEZ, A., "Design of a supercapacitor based storage system for improved elevator applications", In: 2010 IEEE Energy Conversion Congress and Exposition, Atlanta, GA, USA, 12-16 Sept. 2010, USA: IEEE, 2010, pp 4534-4539.

[13] BELLACHE, K., CAMARA, M. B., DAKYO, B., "Transient power control for diesel-generator assistance in electric boat applications using supercapacitors and batteries", *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2018, vol. 6, no. 1, pp. 416-428, ISSN 2168-6777.

[14] AKRAM, U., KHALID, M., SHAFIQ, S., "An innovative hybrid wind-solar and battery-supercapacitor microgrid system—Development and optimization", *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2017, vol. 5, pp. 25897-25912, ISSN 2169-3536.

[15] ZHOU, T., SUN, W., "Optimization of battery–supercapacitor hybrid energy storage station in wind/solar generation system", *IEEE Transactions on Sustainable Energy*, 2014, vol. 5, no. 2, pp. 408-415, ISSN 1949-3029.

[16] KOUCHACHVILI, L., YAICI, W., ENTCHEV, E., "Hybrid battery/ supercapacitor energy storage system for the electric vehicles", *Journal of Power Sources*, 2018, vol. 374, no. 15, pp. 237-248, ISSN 0378-7753.

[17] ZHU, X., LI, X., SHEN, G., XU, D., "Design of the dynamic power compensation for PEMFC distributed power system", *IEEE Transactions on Industrial Electronics*, 2010, vol. 57, no. 6, pp. 1935-1944, ISSN 0278-0046.

[18] QU, L., QIAO, W., "Constant power control of DFIG wind turbines with supercapacitor energy storage", *IEEE Transactions on Industry Applications*, 2011, vol. 47, no. 1, pp. 359-367, ISSN 0093-9994.

[19] SONG, Z., HOU, J., HOFMANN, H. F., LIN, X., SUN, J., "Parameter Identification and Maximum Power Estimation of Battery/Supercapacitor Hybrid Energy Storage System Based on Cramer–Rao Bound Analysis", *IEEE Transactions on Power Electronics*, 2018, vol. 34, no. 5, pp. 4831-4843, ISSN 0885-8993.

[20] VENERI, O., CAPASSO, C., PATALANO, S., “Experimental investigation into the effectiveness of a super-capacitor based hybrid energy storage system for urban commercial vehicles”, *Applied Energy*, 2018, vol. 227, no. 1, pp. 312-323, ISSN 0306-2619.

[21] SCHALTZ, E., KHALIGH, A., RASMUSSEN, P., “Influence of battery/ultracapacitor energy-storage sizing on battery lifetime in a fuel cell hybrid electric vehicle”, *IEEE Transactions on Vehicular Technology*, 2009, vol. 58, no. 8, pp. 3882-3891, ISSN 0018-9545.

[22] BINDNER, H., CRONIN, T., LUNDSAGER, P., MANWELL, J. F., ABDULWAHID, U., BARING-GOULD, I., *Lifetime modelling of lead acid batteries*, 1st ed., vol. 2, Denmark: Risoe National Laboratory, 2005.

[23] JIANG, J.H., LIU, H.P., JIANG, Z.Z., WANG, W., “Supercapacitor selection and control strategy of energy storage elevator”, *Journal of Zhejiang University (Engineering Science)*, 2014, vol. 48, no. 4, pp. 610-615, ISSN 1008-973X.

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