



# Research on Charge and Discharge Control Strategy of Supercapacitor

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**Abstract.** This paper introduced four common methods to improve the voltage balance of supercapacitor. Because of the advantages of high efficiency and high speed, the flyover capacitor method is selected to solve the problem of different charging and discharging speed of supercapacitor caused by different parameters of supercapacitor. In order to further improve the efficiency of the supercapacitor charging and discharging control system, a fuzzy control algorithm is designed based on the balance strategy of the flyover capacitor to further improve the efficiency of the supercapacitor charging and discharging control system. Finally, the validity of the design is verified by PSIM simulation software.

**Keywords:** Supercapacitor · Charge and discharge control · Flyover capacitor method

## 1 Introduction

With the development of society and the progress of science and technology, the electronic industry urgently needs high-performance, lightweight, environmental protection energy storage devices to achieve sustainable renewable energy [1]. For the utilization of renewable energy, supercapacitor has become one of the most promising candidate power sources because of its fast charging ability, high power density and good cycle performance [2]. However, in practical applications, the voltage of single supercapacitor is only 1 V–4 V, so multiple supercapacitor units need to be used in series [3]. In the process of series use, because the parameters of each single supercapacitor are different, it is very easy to cause the voltage imbalance at both ends of the supercapacitor in the process of charging and discharging, which affects the service life of the supercapacitor [4]. Therefore, in order to reduce the damage of supercapacitor during charging and discharging and prolong its service life, it is an urgent problem to study and solve the voltage balance setting of series supercapacitor during charging and discharging.

This paper introduced four common methods to improve the voltage balance of supercapacitor, and designs the charging and discharging control system of supercapacitor by using the flyover capacitor method. In order to further improve the efficiency

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of the supercapacitor charging and discharging control system, a fuzzy control algorithm is designed based on the flyover capacitor equalization technology to improve the efficiency of the supercapacitor charging and discharging control system.

## 2 Common Equalization Techniques

### 2.1 Parallel Resistance Method

According to the characteristics of each supercapacitor in series and the charging current, the parallel resistance method selects the appropriate resistance to parallel with each supercapacitor, so as to realize the consumption of excess energy on the supercapacitor unit [5]. The principle is shown in Fig. 1.

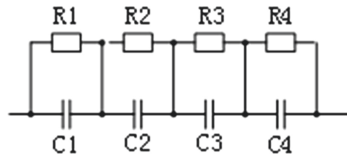


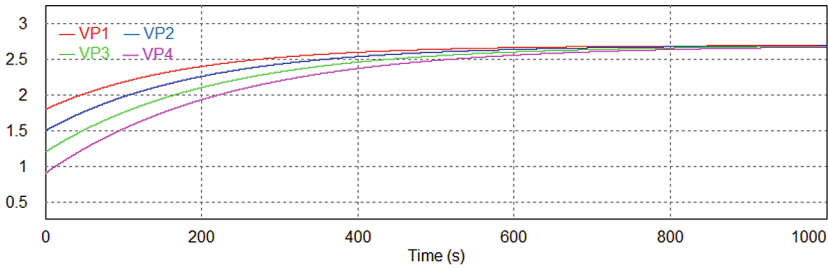
Fig. 1. Schematic diagram of the principle of parallel resistance method

When charging the supercapacitors C1, C2, C3 and C4 in the figure, the resistors R1, R2, R3 and R4 in parallel with each supercapacitor are discharging. The supercapacitor with high voltage has faster discharging speed than that with low voltage. Thus, in the process of charging and discharging the supercapacitor bank, the balanced protection of the supercapacitor unit is realized. The selection principle of resistance is to ensure that when the single super capacitor reaches the rated voltage, the current flowing through the parallel resistance is equal to the constant current, and the single super capacitor is not charging, so the super capacitor will not overcharge, so as to achieve the effect of equalization and protection. It can be seen from the schematic diagram that the circuit structure of parallel resistance is simple, no control module is needed, and the cost is low. However, this method is only suitable for low power applications because of its serious heating and high loss in the charging process.

The supercapacitor of 4 rated voltages is 2.7 V, capacitance values of 200 F, 220 F, 240 F, 260 F and initial voltage of 1.8 V, 1.5 V, 1.2 V, 0.9 V are connected in series under the condition of constant current of 3 A, and the blocking value of parallel resistance is 0.9  $\Omega$ . After 1000 s, the simulation results are shown in Fig. 2. It can be seen from the figure that the voltage of supercapacitors is rising and gradually approaching during the charging process, and the charging rate is gradually decreasing. Finally, the voltage of each supercapacitor reaches the rated voltage of 2.7 V.

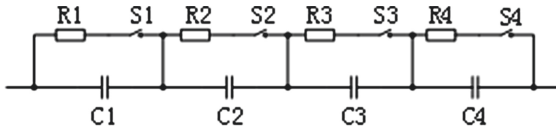
### 2.2 Switch Resistance Method

The switch resistance method is based on the parallel resistance and a switch connected in series with the parallel resistance [6]. The parallel switch works when the super



**Fig. 2.** Simulation effect of parallel resistance

capacitor is charging, and the voltage collected by the voltage sensor is equal to the reference voltage of the pre-set super capacitor rated voltage, the switch is turned on, so that the current flows through the resistor and the switch, and then reaches the super capacitor. The schematic diagram of the equilibrium state of the capacitor is shown in Fig. 3. The value of the resistance of the parallel resistance should be the current flowing of the resistor when the supercapacitor monomer is charged to the rated voltage, and the supercapacitor monomer is not continued, so that there is no overvoltage.



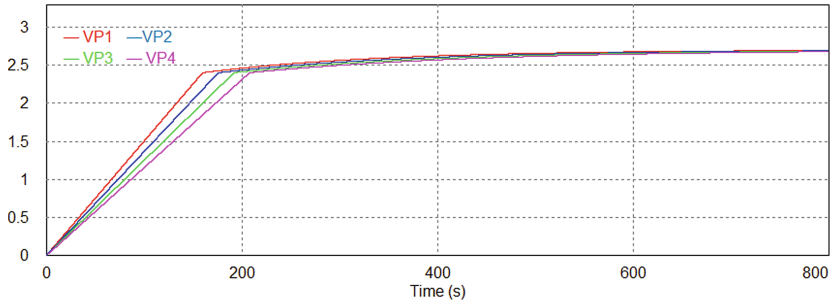
**Fig. 3.** Schematic diagram of switch resistance

The supercapacitor of 4 rated voltages is 2.7 V, and the capacitance values are 200 F, 220 F, 240 F, 260 F, in the case where the constant current is 3 A. The initial voltage value is set to 0 V, the reference voltage is set. For 2.4 V, the parallel resistance tissue is selected 0.9  $\Omega$  for simulation, and the simulation time is 800 s, the result is shown in Fig. 4. It can be seen from Fig. 3 that the switch resistance method is more flexible than the parallel resistance method. When the switch is disconnected at the beginning of charging, the parallel resistance can't be shunted, and the loss is lower than that of the parallel resistance method. However, when the reference voltage is reached, the switch turns on, and the rising rate of supercapacitor voltage gradually decreases significantly, and gradually approaches the rated voltage. In this process, there is still energy loss, at the same time, the structure of the circuit is also complex.

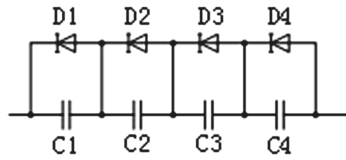
### 2.3 Voltage Stabilizing Diode Method

The voltage stabilizing diode method is a diode which replaces the parallel resistance in the parallel resistance method into a diode of the breakdown voltage equal to the rated voltage, which is shown in Fig. 5.

When charging the supercapacitor C1, C2, C3 and C4, if C2 reaches the rated voltage, the voltage stabilizing diode D2 associated with the inverse is reverse, and the current



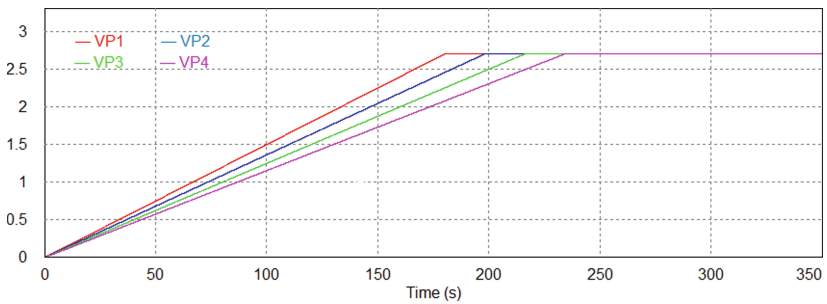
**Fig. 4.** Simulation effect of switch resistance



**Fig. 5.** Schematic diagram of Zener diode

flows through D2, thereby consuming the excess energy, and stopping charging the supercapacitor C2 to achieve the effect of voltage equalization. As can be seen from the schematic, the circuit of this method is simple and the cost is low, but there is also a phenomenon of energy loss and fever. If heating is serious, the parameters of the diode will be affected, or even damaged.

Connect four supercapacitors with a rated voltage of 2.7 V and capacitance values of 200 F, 220 F, 240 F, and 260 F in series with a constant current of 3 A. The initial voltage value is set to 0 V. The breakdown voltage is set to 2.7 V, and the result is shown in Fig. 6 after the simulation for 350 s. It can be seen from the figure, when the constant current is charged, the voltage of each supercapacitor presented a linear upward trend. When a supercapacitor reached the rated voltage of 2.7 V, the voltage didn't rise and remained unchanged at the rated voltage of 2.7 V, and there will be no overshooting.



**Fig. 6.** Simulation effect of Zener diode

### 2.4 Flyover Capacitor Method

The flyover capacitor method is to detect the supercapacitor with the highest voltage and the lowest voltage through the voltage detection module, and then control the opening and closing of each switch through the control circuit to transfer the energy of the supercapacitor with the highest voltage to the capacitor with the lowest voltage through an ordinary capacitor as an intermediate energy storage device, so as to realize the energy transfer between the high and low capacitors, realize the function of voltage balance [8]. The schematic diagram is shown in Fig. 7.

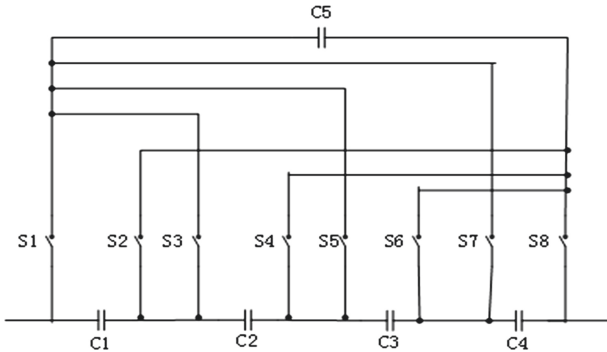


Fig. 7. Schematic diagram of flyover capacitor

Suppose that in the schematic diagram, the voltage detection module detects that the voltage of C1 is the highest and that of C3 is the lowest, the energy of the C1 having a high voltage is required to transfer the C3 of the lowest voltage. By controlling the switch network, S1 and S2 are closed, so that C1 with the highest voltage charges the intermediate energy storage device C. when the voltage of C is equal to that of C1, S1 and S2 are opened, S5 and S6 are closed, so that C charges C3 until the voltage of C3 is equal to that of C, and S5 and S6 are opened, The detection circuit re detects the supercapacitor with the highest and lowest voltage, and repeats the above process until the voltage reaches the equilibrium state. It is assumed that in the schematic.

Four supercapacitors with rated voltage of 2.7 V and capacitance values of 200 F, 220 F, 240 F and 260 F are connected in series under the condition of constant current of 3 A. the initial voltage value is set to 0 V and the capacity of flyover capacitor is set to 1 MF. The simulation effect after 60s is shown in Fig. 8. The voltage value of each capacitor is balanced and the effect of voltage balance is achieved.

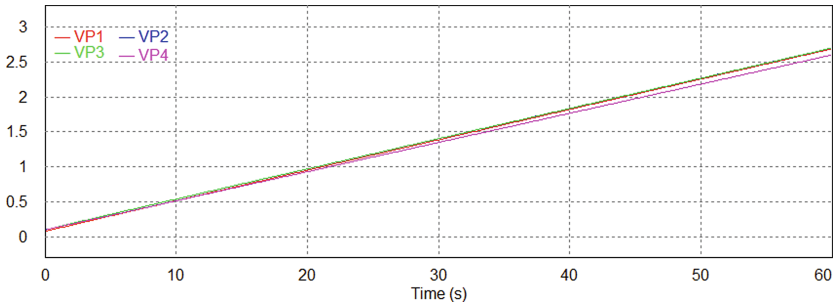


Fig. 8. Simulation diagram of flyover capacitance

### 3 The Choice of Equalization Technology

Through the above analysis, it can be clearly seen that the advantages of direct parallel resistance method, switching resistance method and voltage stabilized diode method are relatively simple structure and relatively low cost, but they have the disadvantages of large energy loss and serious heating, which makes the above schemes have great limitations. The flyover capacitor method has advantages over the above methods in balancing speed and efficiency, so the flyover capacitor method is used as the system balancing strategy in this design. In this design, the flyover capacitor equalization technology is used to realize the energy transfer between supercapacitor and flyover capacitor. In order to improve the rate of charging and discharging in the process of energy transfer,

The switch in Fig. 7 is changed to a series of MOS transistors that can be bidirectional on and bidirectional off. One switch is replaced by every two MOS transistors, and each conduction path contains four MOS transistors. The obtained balanced topology is shown in Fig. 9. In the process of principle analysis, it is assumed that the supply voltage is basically unchanged in a switching cycle, and the parasitic parameters of components and circuits are ignored.

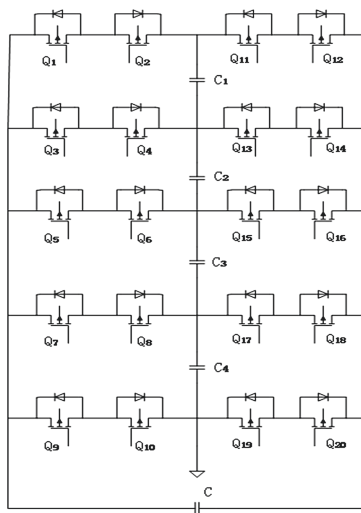


Fig. 9. Equilibrium topology

In this topology, assuming that the power of C1 is transferred to C3, the equalization process consists of two stages, C1 discharge and C3 charging, and the switch tube has different conduction states. Let the switching cycle of MOS transistor be T and the duty cycle be D.

In [0, DT] time, when C1 charges the flyover capacitor C, the switches Q<sub>11</sub>, Q<sub>12</sub>, Q<sub>3</sub> and Q<sub>4</sub> turn on, C1 transfers energy to the flyover capacitor C through the MOS tube, and the current of the flyover capacitor increases linearly. According to the hypothesis, the discharge current  $i_{c1}$  of C1 and the variation of flyover capacitor current  $\Delta i_c$  can be obtained.

$$i_{c1}(t) = i_C(t) = \frac{1}{C} \int_0^t v_C dt + i_C(0) = \frac{V_{C1}}{C} t + i_C(0) \quad (1)$$

$$\Delta i_C = i_C(DT) - i_C(T) = \frac{V_{C1}(D)}{Cf} \quad (2)$$

In [DT, t] time, when the flyover capacitor charges C3, the switches Q<sub>17</sub>, Q<sub>18</sub>, Q<sub>5</sub> and Q<sub>6</sub> are on, and the energy in the flyover capacitor is released to C3. The voltage at both ends of the flyover capacitor is equal to the voltage at both ends of C3. It can be concluded that the discharge current of the flyover capacitor is C3, and the changes of the charging current and the flyover capacitor current are as follows:

$$i_{C3}(t) = i_C(t) = \frac{1}{C} \int_{DT}^t v_C dt + i_C(DT) = -\frac{V_{C3}}{C}(t - DT) + \frac{V_{C1}D}{Cf} + i_C(0) \quad (3)$$

$$\Delta i_C = i_C(DT) - i_C(T) = \frac{V_{C3}(1 - D)}{Cf} \quad (4)$$

## 4 Design of Fuzzy Control Algorithm

Due to the different decay rate of the chemical characteristics of each supercapacitor, there are differences between them, which makes it difficult to get the voltage, current and other parameters of each supercapacitor. In order to improve the balance performance of the system, this paper not only designs the hardware circuit, but also adds the algorithm design from the software aspect. Through the modal analysis of the equalization technology in the previous section, it is concluded that the duty ratio of the switch tube plays an important role in the equalization charging and discharging process of the system. In view of the uncertainty of the system and the nonlinear characteristics of the complexity, this paper selects the fuzzy control algorithm as the control core to optimize the charging and discharging equalization of the super capacitor.

### 4.1 Design of Fuzzy Controller

This paper takes the collected current value and the pre-set deviation value and the current change rate as the input of the system's balanced fuzzy controller, and then calls the fuzzy control algorithm program, through the fuzzy controller processing, outputs

clear control amount and the time response current variation, and adjusts the output pulse width of the corresponding PWM signal through the control amount. The high and low of PWM signal is used to control the closing and opening of MOS transistor, so as to realize the voltage balance of supercapacitor in the process of charging and discharging.

The fuzzy controller is the core of the fuzzy control system in this system, so the design of the fuzzy controller in this system will be described from the three processes of fuzzification, fuzzy reasoning and clarity introduced in the second chapter.

**1. Fuzzification**

The fuzzy controller in this paper adopts the Mamdani type “double input single output” control structure, which has the advantages of less information, no overshoot, fast response and less errors, the deviation  $e$  and current change rate  $ec$  obtained by subtracting the set value 1.2 from the collected current  $i$  are used as input parameters, and the duty cycle  $D$  of MOS switch is output. In order to improve the accuracy of the control, the value of  $e$  is divided into seven fuzzy sub states in the universe  $[-6, 6]$ , and the language values are: NS, NM, NL, ZE, PS, PM, PL. Similarly, the fuzzy sub states of the current change rate  $ec$  and the duty cycle  $D$  value of MOS switches can also be divided into the above seven fuzzy sub states, and the fuzzy control rules of the system can be obtained as shown in Table 1.

**Table 1.** Fuzzy control rules

$\begin{matrix} D \\ e \\ ec \end{matrix}$	NS	NM	NL	ZE	PS	PM	PL
NS	NS	NS	NS	NS	NM	NL	ZE
NM	NS	NS	NM	NM	NL	ZE	ZE
NL	NS	NM	NM	NL	ZE	ZE	PS
ZO	NM	NL	NL	ZE	PS	PS	PM
PS	NL	ZE	ZE	PS	PM	PM	PL
PM	ZE	ZE	PS	PM	PM	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

**2. Fuzzy Inference**

According to the analysis, the fuzzy control rules in this paper can be expressed in the following form: if  $\{(e) = A_i \text{ and } (ec) = B_j\}$  then  $D = C_{ij}$ , ( $i, j = 1, 2, \dots, n$ ),  $A_i, B_j$  and  $C_{ij}$  are all fuzzy sets in their respective domains in the process of fuzzification.

Suppose that there are  $n$  fuzzy rules in a fuzzy controller, and each fuzzy rule in the fuzzy controller corresponds to a fuzzy relation  $R_i$ . Then the sum of the fuzzy relations  $R_j$  ( $j = 1, 2, \dots, N$ ) corresponding to the  $N$  fuzzy rules is the total fuzzy relation  $R$  of the fuzzy control system.

$$R = R_1 \cup R_2 \cup \dots \cup R_n = \bigcup_{i=1}^n R_i \tag{5}$$

Substituting  $R$  into approximate reasoning rule:

$$U^* = \left( \overset{\rightarrow^*}{A} \right)^T \circ R \tag{6}$$

The total output of approximate reasoning is:

$$U^* = \left( \overset{\rightarrow^*}{A} \right)^T \circ \bigcup_{j=1}^n R_j \tag{7}$$

Or

$$U^* = \prod_{j=1}^n \left( \left( \overset{\rightarrow^*}{A} \right)^T \circ R_j \right) = \prod_{j=1}^n U_j \tag{8}$$

In the above formula “ $\circ$ ” Represents the synthesis algorithm, and  $A^*$  is the input quantity matrix.

According to the above introduction, there are two calculation orders. Formula 7 calculates each  $R_j$  from 1 to N, and then calculates their union, it is calculated by substituting it into the synthesis rule. Then the formula (8) first calculates each  $U_j$  from 1 to N, then calculates their union, and substitute them into the synthesis rule.

Because in a certain sampling period, one input of the input controller can not activate all fuzzy relations at the same time, that is to say, it can't activate all fuzzy control rules [9]. Therefore, it is necessary to optimize the activation of fuzzy control rules, so this paper chooses formula (8) for fuzzy reasoning. In this way, in a certain sampling period, the activated fuzzy relations can be calculated first, and then their union can be calculated, which can greatly reduce the amount of calculation and improve the corresponding ability of the controller.

### 3. Clarify

In this paper, the weighted average method, which is convenient, intuitive and reasonable for calculation, is selected to carry out the deblurring calculation. The weighted average method, also known as the area center method, first calculates the integral of the membership function curve of the fuzzy set in the corresponding abscissa range, that is, the area surrounded by them, and calculates the abscissa value of the area center [10], this value is the accurate value after clear calculation. Let  $Z(u)$  be the membership function of fuzzy subset  $Z$  on the universe  $M$ , and  $u$  belongs to  $M$ . The abscissa of the center of the area is  $X$ , defined by:

$$X = df(u) = \frac{\int_M uz(u)du}{Z(u)du} \tag{9}$$

### 4.2 Simulation of Fuzzy Controller

In order to verify whether the fuzzy controller designed above meets the requirements of this design and whether it can achieve the objective of membership function optimization,

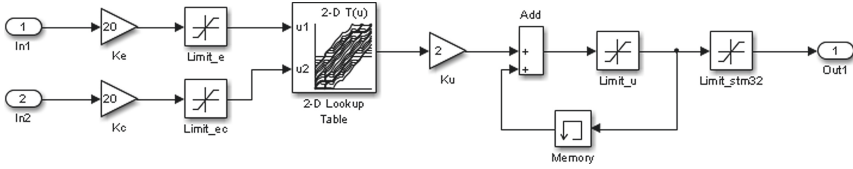


Fig. 10. Fuzzy control simulation block diagram

it is simulated by using Simulink. The simulation block diagram of fuzzy control is shown in Fig. 10.

Figure 11 shows the simulation effect of supercapacitor charge discharge balance under fuzzy algorithm. Compared with the equalization effect diagram of the supercapacitor without fuzzy control before (Fig. 8), in the process of charging and discharging, the battery pack with fuzzy control achieves the equalization effect in 40 s, while in Fig. 8, it takes 60 s for the supercapacitor to achieve the equalization effect without fuzzy control. Through the above analysis, it can be concluded that the charging time of supercapacitor can be optimized by using fuzzy control system. The comparison between this method and the previous charging and discharging strategy is shown in Table 2. It can be seen that the charging and discharging speed of this method is higher than that of other methods.

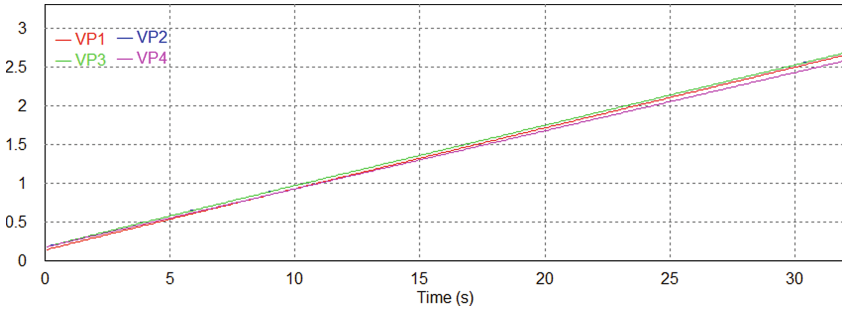


Fig. 11. Effect diagram of charge discharge equalization under fuzzy algorithm

Table 2. Time comparison of each charging strategy.

Charge discharge strategy	Time/s
Parallel resistance method	800
Switch resistance method	600
Voltage stabilizing diode method	350
Flyover capacitor method	60
Simulation of fuzzy controller	35

## 5 Conclude

This paper first introduced four common equalization technologies of supercapacitor. Through principle analysis and PSIM simulation comparison, it is found that the flying capacitor method has the advantages of high efficiency and fast speed. This method is used as the equalization technology of supercapacitor charge and discharge control. Secondly, in order to further improve the efficiency of the supercapacitor charging and discharging control system, a fuzzy control algorithm is designed based on the balance strategy of the flying capacitor to further improve the efficiency of the supercapacitor charging and discharging control system.

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