Fuzzy Control for Hybrid Energy Storage System of Microgrid with Pulse Load

Meng Shi, Jinquan Wang, Yibin Yang and Kefeng Huang

ABSTRACT

The working pattern of pulsed load takes on the feature of impact, periodicity and continuity, and it brings great challenges to microgrid. To improve the dynamic performance for independent microgrid and ensure the reliability and stability of the system, this paper proposes a fuzzy control charging and discharging power correction method based on the hybrid energy storage system (HESS) with pulse load independent microgrid, and based on the state of charge (SOC) of supercapacitor. The charging and discharging power allocation strategy is verified by simulation to optimize the energy supply of HESS under the control strategy. The simulation shows that the control strategy can effectively suppress the power fluctuation caused by the pulse load, avoid overcharge and discharge of the energy storage medium, and improve the power quality of the power supply system.¹

KEYWORDS

Hess; Fuzzy Control Method, Virtual Impedance; Power Correcting; Power Distribution.

INTRODUCTION

With the rapid development and numerous applications of power electronic converter technology, new types of equipment represented by phased array radars continue to emerge. This type of equipment has a low average power load and a high peak value [1], short cycle, strong shock, and strong pulse characteristics. It is a

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typical pulse load. To maintain the reliability, stability, and economy of an independent microgrid system, the use of an energy storage system for power stabilization is one of the effective means.

Nowadays, energy storage devices can be classified into two types: energy type and power type [2, 3]. Energy type energy storage devices represented by batteries have large energy densities and many stored energy, and supercapacitors represent power type energy storage devices. High power density and fast response [4]. In order to make the energy storage system have the dual advantages of energy and power, this paper applies HESS to reduce the fluctuation on the microgrid bus voltage.

In the research of HESS, the problem of power distribution among different energy storage media is one of the hot topics in recent years[5]. Based on the fuzzy control method, this paper performs "double optimizations" to HESS which is consisted of a battery and a supercapacitor. Firstly, according to the measured diesel generator set rectified output DC power, impulse load equivalent power and hybrid energy storage cell $SOC_H$, the fuzzy logic algorithm is used to optimize the charge and discharge power of HESS. Then, a power distribution algorithm is established between the supercapacitor and the battery on the basis of the SOC of supercapacitor, and to optimize the energy storage of the battery. Finally, the proposed method is verified by Matlab/SIMULINK simulation software.

**STRUCTURE OF MICROGRID WITH HESS**

This paper focuses on the control optimization of HESS consisting of a battery and a supercapacitor in microgrid with pulse load. The structure of the system is shown in Figure 1.

![Figure 1. Block diagram of microgrid with HESS.](image-url)
In Figure 1, the diesel generator set is controlled by C through a controllable rectification to supply power to the pulse load. The output voltage is ud0, and the load current is idc. The DC switch S is a pulse load that is composed of a pulse switch and a resistor load. HESS which is consisting of a supercapacitor and a lithium iron phosphate battery is connected to the DC bus, and the bus voltage fluctuation caused by the pulsed load operation is suppressed, and the waveform distortion of the AC current and voltage before the rectifier is reduced, improve the quality of AC power supply and working conditions of diesel generators.

According to the operating characteristics of the system, the entire system can be divided into three power modules: hybrid storage charge and discharge power PH(t), diesel generator set supply DC power Pdc(t), pulse load equivalent power Pload; where HESS charger The discharge power includes the supercapacitor charging and discharging power PS(t) and the battery charging and discharging power PB(t).

Ignoring the energy loss of the line and equipment in the system operation, the law of conservation of energy, the available power of each part satisfies the following relationship:

\[
\begin{align*}
P_H(t) + P_{dc}(t) &= P_{load} \\
PB(t) + PS(t) &= PH(t)
\end{align*}
\]

(1)

POWER CORRECTION BASED ON FUZZY CONTROL METHOD

Acquisition for Reference: SOC_H

According to the state of charge of the hybrid battery and the supercapacitor, SOCH of HESS can be calculated by Equation (2), where SOCB(t) and CB are the charge and rating of the battery in HESS, respectively; SOCS(t) and CS are the charge and rating of the supercapacitor in HESS:

\[
SOC_H = \frac{SOC_B(t) \cdot C_B + SOC_S(t) \cdot C_S}{C_B + C_S}
\]

(2)

Figure 2. The state of charge of HESS.
The key role of HESS in an independent microgrid is that it supplements or absorbs system energy by continuously charging and discharging to ensure that the system is in a power balanced state as a whole. Therefore, the charge of HESS is closer to half of the saturation capacity, and its performance is better. On the contrary, the closer the charge is to the air power or saturation, the worse the performance is. This paper divides HESS from empty power to saturation into seven states as shown in Figure 2.

**Correction of Charge and Discharge Power of HESS**

If the state of charge of HESS is not considered, the power fluctuation quantity $P_H(t)$ is directly calculated based on the rectified output DC power $P_{dc}(t)$ and the load equivalent power $P_{load}$, and HESS is forcibly used to release or absorb energy. It is extremely easy to overcharge or over-discharge HESS. In this regard, this paper uses the fuzzy control method to correct the charging and discharging power of HESS.

As shown in Figure 3, the state of charge $SOC_H$ of HESS and the charging and discharging reference power $P_H$ are taken into consideration as the input amount of the fuzzy control method at the same time. After the fuzzy control, the $\Delta P_H$ is obtained and then the reference value $P_H$ is corrected and a mixed storage is obtained. The system can charge and discharge power $P_e$.

![Figure 3. Correction control chart of charge and discharge power of HESS.](image)

![Figure 4. 2 Input-1 output fuzzy control method structure.](image)
As shown in Figure 4, this paper adopts a 2-input (SOCH, PH)-1 output (ΔPH) fuzzy control method. The range of SOCH is [0, 1]; the membership functions of the two input variables contain seven fuzzy subsets: negative maximum (NB), negative median (NM), negative minimum (NS), zero (ZO), positive minimum (PS), positive intermediate (PM), and positive maximum (PB).

The basis for determining the rules is as follows: If the power fluctuation PH (t) is positive, the independent microgrid requires HESS to discharge to the bus to supplement the load power demand, and the supplementary value must refer to the charge of HESS itself. When the SOCH value is large, it discharges more, when it is medium, it discharges little, and when it does not discharge for hours. Referring to the seven states of the two input quantities, the fuzzy control method logic is shown in Table I.

### TABLE I. FUZZY CONTROL METHOD LOGIC TABLE.

<table>
<thead>
<tr>
<th>Power fluctuation</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>ZO</td>
<td>ZO</td>
<td>ZO</td>
<td>ZO</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
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<td>NM</td>
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<td>ZO</td>
<td>ZO</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
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<tr>
<td>NS</td>
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<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
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<tr>
<td>ZO</td>
<td>NM</td>
<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PM</td>
<td>PM</td>
</tr>
<tr>
<td>PS</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PM</td>
<td>PM</td>
</tr>
<tr>
<td>PM</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>ZO</td>
<td>ZO</td>
<td>ZO</td>
<td>ZO</td>
</tr>
<tr>
<td>PB</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>ZO</td>
<td>ZO</td>
<td>ZO</td>
<td>ZO</td>
</tr>
</tbody>
</table>

### DISTRIBUTION OF CHARGE/DISCHARGE POWER OF HESS

When charge/discharge power Pe is allocated to supercapacitors and storage batteries, the operating characteristics of the two types of energy storage media must be considered, and the power changes slowly and rapidly. The components are allocated to the battery, and the supercapacitor. The traditional distribution method has a simple principle, but its optimal filter time constant will change with the parameters of each module of the microgrid system. It is difficult to find the calculation rule, and the filtering effect is not ideal. Compared with the traditional filtering method, a power optimization control method based on SOC of supercapacitor is proposed. When the system is running, the state-of-charge SOCS of the supercapacitor is only related to the capacitor voltage. The calculation is convenient and does not jump, so it is used as an independent variable of the power distribution function. To simplify the calculation, the correlation coefficient between the battery-distribution power PBe and the supercapacitor real-time state of charge SOCS is -1. That is, when the SOCS is close to the maximum value SOCSmax, the closer PBeis to the negative maximum value PBemax, the greater the charging power of the battery is, the stronger the supercapacitor discharges; when the SOCS is close to the minimum value, the PBe is closer to the positive maximum.
value \( P_{Bemin} \), the discharging electric power of the battery. The larger the supercapacitor is forced to charge, and its linear power distribution function image and formula are respectively shown in Figure 5 and Equation (3).

\[
P_{Be} = \frac{-2P_{Bemax}}{SOC_{Sm} - SOC_{Smin}} (SOC_S - \frac{SOC_{Smax} + SOC_{Smin}}{2})
\]  

(3)

The power \( P_{Se} \) assigned to the supercapacitor is:

\[
P_{Se} = P_e - P_{Be}
\]  

(4)

According to equation (4), the supercapacitor distribution power \( P_{Se} \) is obtained, and the current reference signal of the supercapacitor is compared with the front-end voltage \( u_S \), and the real-time current measurement value is fed back as the difference, and then the supercapacitor is actually put into operation mode through the PI regulator. The PWM signal, the control block diagram shown in Figure 6.

![Figure 5. Power distribution function of HESS.](image)

![Figure 6. Supercapacitor PWM signal schematic.](image)
Reference to the principle of supercapacitor PWM signal generation control method can be battery PWM signal, but it is worth noting that the battery also need to consider the indicator: the state of power (SOP)\cite{8}, in order to avoid over discharge of the battery, generally add SOP limit processing.

This section is based on the power optimization allocation method of HESS and the correction of the electric power by the fuzzy control method. The optimized control principle of the independent microgrid HESS under the pulse load is shown in Figure 7.

**SIMULATION AND RESULTS ANALYSIS**

**Simulation System**

In order to verify the correctness and feasibility of the "dual optimization" control strategy of HESS, the simulation study was carried out using Matlab/SIMULINK software. The system consists of a diesel generator set, a lithium iron phosphate battery, supercapacitor, HESS, and a pulsed load.

The control method of the battery is shown in Figure 8. The current tracking control method is used to control the constant voltage and current limit. $i_{L\text{ref}}$ is the reference value of the inductor current; $G_m(s)$ is the transfer function of PWM; $G_{boid}(s)$ is the transfer function of the control signal of the inductor current signal; $H(s)$ is the sampling link of the inductor current; $G_{boid1}(s)$ and $G_{boid2}(s)$ is the correction function of the current loop when discharging and charging, respectively, to improve system stability.

The supercapacitor stabilizes the high-frequency power fluctuations in HESS. In this paper, it is designed to select the current control during the charging process. In order to avoid the time-lag and sampling distortion, the supercapacitor adopts a double-loop control strategy. The control principle diagram is shown in Figure 9.
The main parameters are set as follows: diesel generator set power 30 kW, pulse load peak power 30 kW, period 56 ms, duty cycle 50%, and the pulsed load equivalent power is 32.19 kW. The equivalent power of the pulsed load is greater than that of the diesel generator set and must be compensated by the energy storage system. The parameters of HESS are set to: DC bus voltage 500 V, lithium iron phosphate battery 7.26 kW/10.13 kWh, supercapacitor 5.06 kW/2.17 kWh.

Results Analysis

DC BUS VOLTAGE

Figure 8. Charge/discharge control strategy of battery.

Figure 9. Charging/discharging control strategy of supercapacitor.

Figure 10. Comparison for simulation waveform of diesel generator.
The DC bus voltage simulation waveform is shown in Figure 10. Analysis can be obtained: Before HESS is put into operation, the DC bus voltage fluctuates greatly. The maximum voltage can reach 600 V, the minimum value is about 380 V, and the amplitude difference is as high as 220 V; at the 2nd second, When the system is put into operation, the amplitude oscillation of the voltage is greatly reduced, fluctuating from 530 V to 450 V, and the amplitude difference is reduced to 80 V. HESS mainly plays a role in peak load shifting. When the peak power of the pulsed load suddenly changes, the diesel generator set and HESS collectively supply power to the load. After the pulse is completed, the diesel generator set charges HESS. System output characteristics.

COMPARISON OF TOTAL HARMONICS

The comparison of the system harmonic content before and after the compensation of HESS is shown in Figure 11. Before compensation system of Figure 11(a) was added, the harmonic distortion ratio (THD) of the system was as high as 37.6%, and the energy storage compensation After the addition, the distortion rate of Figure 11(b) dropped to 28.16%, and 6k±1 harmonics were suppressed to some extent. Based on the simulation results, the DC voltage fluctuation rate δu and the AC frequency fluctuation rate δf before and after HESS is added can be obtained through calculation. Table II shows the comparison results. Based on the new control strategy proposed in this paper, the voltage fluctuation rate, the AC frequency fluctuation rate, and the harmonic distortion rate are greatly reduced, and the system performance is improved to achieve the optimization goal.

![Figure 11](image_url)

(a) Before HESS compensates (b) After compensation of HESS

Figure 11. Total harmonic content before and after compensation of energy storage system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>δf /%</th>
<th>δu /%</th>
<th>THD /%</th>
</tr>
</thead>
<tbody>
<tr>
<td>without HESS</td>
<td>6.56</td>
<td>26.08</td>
<td>37.60</td>
</tr>
<tr>
<td>with HESS</td>
<td>3.41</td>
<td>14.46</td>
<td>28.16</td>
</tr>
</tbody>
</table>

TABLE II. COMPARISON BETWEEN SYSTEM INDICATORS OF HESS.
CONCLUSIONS

This paper proposed a “double optimization” control for HESS which is composed of a battery and a supercapacitor in microgrid with pulse load. Firstly, the fluctuating power is calculated from the rectified DC power and the equivalent power of the pulsed load, and it constitutes 2 inputs with the SOC of HESS. The fuzzy logic algorithm is used to modify the charging and discharging power of HESS; secondly, the supercapacitor SOCH is used as the battery power distribution. Based on this, the battery power distribution formula was deduced and the distribution method of the charge and discharge power of HESS was optimized. Simulation results by Matlab/Simulink show that the power optimization control strategy proposed in this paper can effectively reduce the power fluctuations of the diesel generator set with pulsed load operation, improve the power quality of the system, reduce the charge and discharge power peaks of the battery and the supercapacitor, and improve the storage capacity. The life of equipment can realize the optimal control for HESS of microgrid with pulse load.

REFERENCES