

Control Strategy of Photovoltaic DC Microgrid Based on Fuzzy EEMD

Chunhui LIANG*, Weihong REN, Peng CHENG, Chao DING

Abstract: In order to improve the accuracy of power time series regulation of DC microgrid photovoltaic power generation and its hybrid energy storage system, a set of empirical mode decomposition (EEMD) control strategy based on fuzzy algorithm optimization is proposed in this paper. Through EEMD decomposition of photovoltaic power data, a set of eigenmode component functions is obtained, the EEMD power decomposition method is designed, and the EEMD optimization fuzzy control strategy is established. Finally, the effectiveness and accuracy of the controller are verified by simulation experiments. The results show that compared with the ordinary EEMD power decomposition control method, the proposed method can achieve better control effect under different power fluctuation characteristics, improve the strong randomness and fluctuation of distributed generation fluctuation, and has strong applicability.

Keywords: EEMD; DC microgrid; fuzzy control; power fluctuations

1 INTRODUCTION

In recent years, with the rapid development of global photovoltaic industry, the safe and reliable operation of photovoltaic power generation and its energy storage system is closely related to the safety and economy of power grid. Photovoltaic power is greatly affected by weather and other factors, and has strong fluctuation and intermittency, which brings great challenges to the safe and stable operation of power grid [1]. The persistence and stability of photovoltaic power generation and the stable operation of DC microgrid provide strong support for maintaining the stable operation of large power grid. A good coordinated control strategy cannot only reduce the uncertainty of input grid power, ensure the safe and stable operation of the power system, but also effectively improve the absorption capacity of photovoltaic power generation [2, 3].

Hybrid energy storage has been studied in microgrid for a long time. The hybrid energy storage system of supercapacitor and battery bears the pulse power output by the photovoltaic system, which can significantly reduce the number of batteries, prolong the battery life, and greatly reduce the construction cost [4]. Manandhar et al. proposed a power distribution method based on LPF (low-pass filter algorithm), which solved the problem of power supply and demand imbalance in the system by controlling the low-pass filter. The current feedback signal and compensation factor are added to LPF to reduce the dynamic response of the system. The control strategy can effectively utilize the supercapacitor and prolong the life of the battery [5]. The status information of photovoltaic power generation system is contained in the power signal, and the power signal can be simulated as vibration signal, which can be effectively regulated by analyzing the vibration signal of power fluctuation. Wavelet transform, Hilbert-Huang transform, Empirical Mode Decomposition (EMD) and other time-frequency analysis methods are commonly used to process such signals [6]. In Zhu et al. [7], empirical Mode Decomposition (EMD) method was used to decompose historical data of photovoltaic power, and then input to LSTM network for photovoltaic power prediction, but the influence of mode aliasing phenomenon that may occur in EMD was not considered. In practical application, the effect of wavelet transform is related to the selected

wavelet basis function and the number of decomposition layers, so the generalization is poor, and modal aliasing exists in EMD decomposition. Jiang et al. found that the Ensemble Empirical Mode Decomposition (EEMD) method can improve the anti-aliasing ability of the signal by adding gaussian white noise to the original signal to form a new signal and then decompose it [8]. In view of the battery and super capacitor hybrid energy storage system, multi-hysteresis current control based on power tracking is proposed as the control strategy of battery in Li et al. [9], which improves the problem of frequent switch of battery in charge and discharge state and improves its service life. However, there is no energy management for HESS under grid-connected condition. In Zhang [10], a method combining energy equalization, hill-climbing power and filtering, and empirical mode decomposition is proposed to realize that energy-type energy storage is responsible for the low-frequency part of the power, and power-type energy storage is responsible for the high-frequency part of the power. In literature [11, 12], it is proposed to add fuzzy control algorithm into photovoltaic HESS to complete the real-time regulation of charge state of energy storage equipment. Fuzzy control in this kind of method also adopts experience value and lacks online self-learning or self-adjustment function, which is time-consuming and laborious, so the adjustment of membership function and fuzzy rules becomes a difficult problem in the fuzzy control process [13]. In recent years, many researches have been carried out on photovoltaic DC microgrid and power stability coordination control. Aiming to solve the problem of voltage fluctuation of critical load caused by lack of control when an unplanned island occurs in a microgrid, Wang et al. proposed a voltage stabilizing control strategy of critical load based on electric spring [14]. In order to improve the bus voltage robustness of distributed multi-source DC microgrid, Mao et al. proposed cascade control method based on nonlinear virtual inertia and adaptive backstepping sliding mode [15]. Magaldi et al. proposed Passivity-based nonlinear control for an isolated microgrid system [16].

In the face of complex nonlinear time series, a single control algorithm may not be able to achieve accurate control. The single fuzzy algorithm has poor dynamic control ability, and the single EEMD algorithm lacks high accuracy. For comprehensive learning of higher-order data

information, prediction accuracy is also difficult to improve. In this paper, the method of fuzzy optimization EEMD can give full play to the advantages of the two algorithms, make up for the defects of the single algorithm, and improve the control accuracy of the hybrid energy storage system.

The main structure of this paper is as follows: the first chapter introduces the current research status on this topic; the second chapter discusses the basic structure of microgrid and the related principles of distributed control;

the third chapter examines EEMD decomposition principle and power decomposition of DC microgrid hybrid energy storage system; the fourth chapter presents Coordinated control of EEMD Hybrid energy storage system based on fuzzy optimization; and the fifth chapter summarizes the article. The simulation results are compared with a single EMD example to verify that the proposed control strategy has better control ability in photovoltaic HESS coordinated control, and has certain practicability and precision.

The overall structure of the paper is shown in Fig. 1.

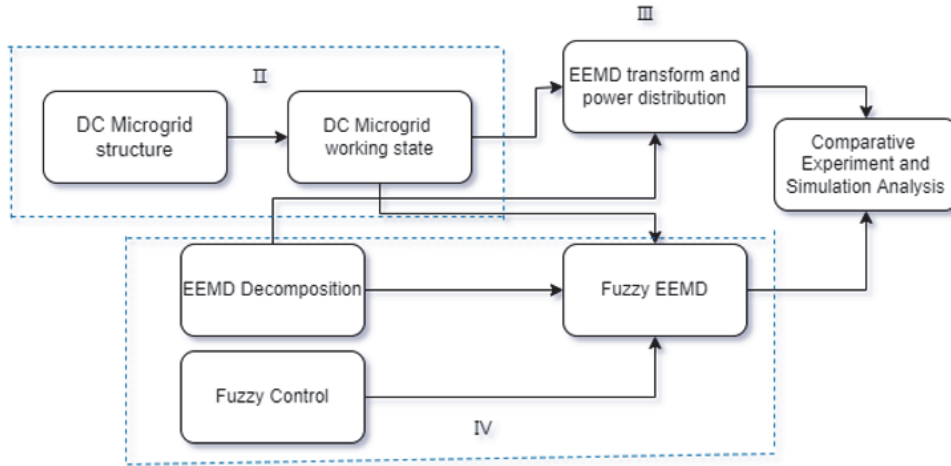


Figure 1 Paper structure chart

2 PV DC MICROGRID STRUCTURE AND BASIC WORKING PRINCIPLE

DC microgrid system generally includes distributed power supply, energy storage device, power electronic converter, DC load and other equipment [17, 18]. The DC microgrid system structure including photovoltaic array power generation and hybrid energy storage is shown in Fig. 2. Photovoltaic power generation and hybrid energy storage system are connected to the DC bus through DC/DC converter, and the DC bus is connected with DC load to realize the isolated operation of photovoltaic microgrid. The PHOTOVOLTAIC power generation unit transmits power to the DC bus through boost converter, and the energy storage power supply is connected to the DC bus through buck/ Boost bi-directional converter to transmit or absorb power.

The energy storage module in PV DC microgrid adopts hybrid energy storage mode. Due to the influence of light,

weather, load increase and switching off, the photovoltaic power generation system will have intermittent and random photovoltaic output. The combination of energy storage system and photovoltaic system can effectively reduce the intermittence and randomness of the output of photovoltaic power generation system, so that the output power of photovoltaic DC microgrid system tends to be stable, and the impact on the power grid is reduced. Hybrid energy storage can also coordinate and schedule the power grid and optimize the operation of the system. According to the characteristics of energy storage, batteries with low power density and long response time are used as energy-based energy storage modules, and supercapacitors with high power density and short response time are used as power-based energy storage modules. Storage batteries are suitable for suppressing low-frequency power fluctuations of high energy, while ultracapacitors are suitable for suppressing high-frequency fluctuations of low energy.

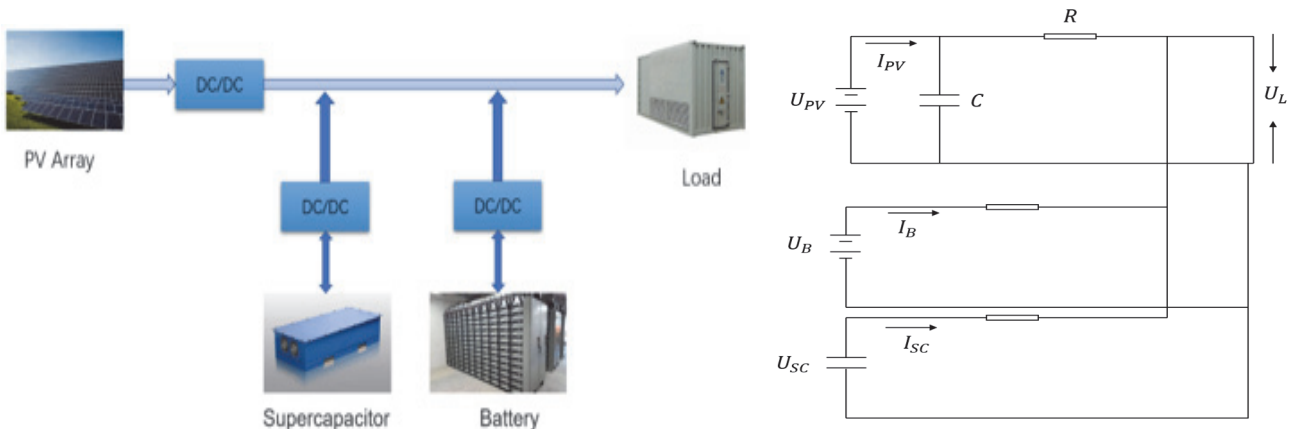


Figure 2 PV DC microgrid structure diagram and Equivalent circuit diagram

3 SYSTEM EEMD TRANSFORM AND POWER DISTRIBUTION

3.1 EEMD Decomposition Fundamentals

The energy storage device in the DC microgrid is a hybrid energy storage device, which makes use of the complementary charge-discharge characteristics of energy-type batteries and power-type supercapacitors to suppress the impact on the DC bus caused by load mutation and maintain voltage stability. The instantaneous power extraction of unbalanced signals in microgrid is the premise to ensure the rational distribution of complex energy storage in the system. In this paper, the method of EEMD decomposition is used to extract the instantaneous unbalanced power for optimization and coordinated control.

In order to solve the problems of modal aliasing in EMD algorithm, white noise with uniform distribution of frequency and amplitude is added to the signal for auxiliary signal processing. When decomposing signals on consists throughout the time-frequency spatial distribution of white noise background, the distribution of different time scale of signal automatically to the appropriate reference dimensions above, and after many times the average noise cancels each other out, the final integration average results can be as the final result. This method is the set Empirical Mode Decomposition (EEMD) algorithm, and the basic process is as follows.

(1) Add the white noise signal $w(t)$ to the original signal $X(t)$ to get the signal $\bar{X}(t)$.

$$\bar{X}(t) = X(t) + w(t) \tag{1}$$

(2) The signal $\bar{X}(t)$ was decomposed by EMD to obtain various IMF components, among which $R_i(t)$ is the remaining component after decomposition.

$$\bar{X}(t) = \sum_{i=1}^n c_i(t) + R_i(t) \tag{2}$$

(3) If $i < j$, repeat steps (1) and (2) to add white noise with the same intensity and unequal sequence each time.

$$\bar{X}(t) = \sum_{i=1}^n c_{ij}(t) + w_j(t) \tag{3}$$

(4) Taking advantage of the zero mean value of the white noise spectrum, calculate the mean value of the above IMF to obtain the final IMF component $C_n(t)$.

$$C_n(t) = \frac{1}{n} \sum_{j=1}^m C_{jn}(t) \tag{4}$$

3.2 EEMD Transform and Power Distribution of Hybrid Energy Storage System

Fig. 3 shows the power distribution diagram of the PHOTOVOLTAIC DC microgrid system. The parameters in Fig. 2 are characterized as follows: C (F) is the equivalent capacitance of the DC bus. Assume that P_u is equivalent capacitor stored power of DC bus; P_{PV} (W) is photovoltaic output power; P_L is the required power of the load; P_B (W) and P_{SC} (W) are the charging and discharging powers of batteries and supercapacitors respectively. U_{DC} (V) is DC bus voltage; I_{PV} (A) is photovoltaic output current; I_B (A) is the charging and discharging current of the battery. I_{SC} (A) is the charging and discharging current of the supercapacitor. I_L (A) is the input current at load.

The power relationship in the system can be expressed as

$$P_U = P_{PV} + P_B + P_{SC} - P_L \tag{5}$$

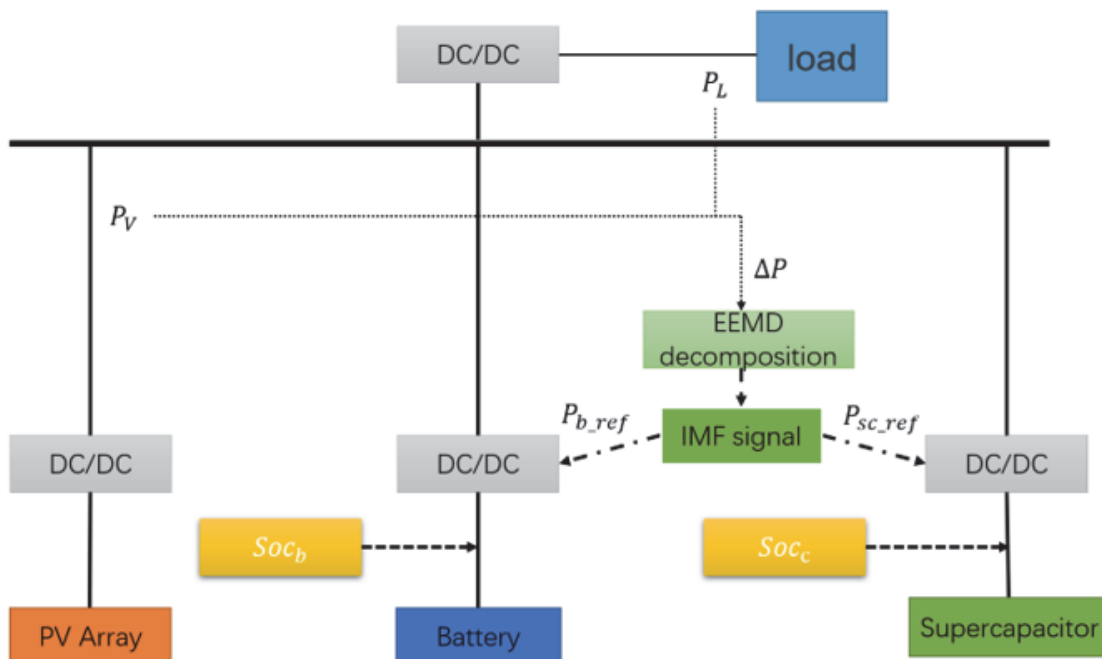


Figure 3 Power distribution diagram

The dynamic equation of DC bus voltage is obtained as follow

$$U_{DC} \frac{dU_{DC}}{dt} = \frac{1}{C} (P_{PV} + P_B + P_{SC} - P_L) \quad (6)$$

DC bus voltage is a reflection of the power balance in the system, the generation of unbalanced power affects the fluctuation of DC bus voltage.

$$C \frac{dU_{DC}}{dt} = I_{PV} + I_B + I_{SC} - I_L \quad (7)$$

If the output power of the hybrid energy storage system is PHESS, then

$$P_{HESS} = \Delta P_{SC} + \Delta P_B = U_{DC} I_{SC} + U_{DC} I_B \quad (8)$$

According to Eq. (7) and Eq. (8), adjust the charging and discharging currents of the supercapacitor and battery to change the output power.

$P_{PV}(t)$ is the actual output power of photovoltaic power station; $P_L(t)$ is the load power in the system.

Unbalanced power in DC microgrid composed of photovoltaic and hybrid energy storage can be expressed as Eq. (9)

$$\Delta P(t) = P_{PV}(t) - P_L(t) \quad (9)$$

The unbalanced power in the microgrid will cause the fluctuation of dc bus voltage. In order to maintain the safe operation of the microgrid, the hybrid energy storage system needs to release or absorb power to compensate, s described as Eq. (10) below.

$$\Delta P(t) = P_B(t) + P_{SC}(t) \quad (10)$$

Unbalanced power in microgrid system is nonlinear, which can be adaptively decomposed into time scale data series with different characteristics by EEMD method, and then m IMF power components can be obtained. The specific design process is as follows:

Suppose: $P_i(t)$ is the unbalanced power signal after adding white noise for the i time in Eq. (11); $W_i(t)$ is the independent white noise; m is the number of EMD decomposition; The original unbalanced power signal to be decomposed is $\Delta P(t)$, and $X(t)$ is obtained by adding white noise $W(t)$

$$P_i(t) = \Delta P(t) + W_i(t), i = 1, 2, 3, \dots, m \quad (11)$$

$P_i(t)$ signal is decomposed into IMFs power signals by EMD:

$e_1(t) + e_2(t) + \dots + e_n(t)$ and a residual component $R_n(t)$, which is

$$P_i(t) = e_{1i}(t) + e_{2i}(t) + \dots + e_{ni}(t) + R_i(t)$$

$$\text{That is } P_i(t) = \sum_{i=1}^n e_i(t) + R_i(t)$$

Therefore, the unbalanced power obtained after EEMD decomposition can be expressed as Eq. (12):

$$P(t) = \sum_{i=1}^n e_i(t) + R_i(t) \quad (12)$$

Since the Hilbert transform does not change the power spectral density or the autocorrelation function, the EEMD method can be used to design the Hilbert filter, and the process is as follows:

(1) The Hilbert transform of IMF signal can be obtained:

$$E_i(t) = h(t) * e_i(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{e_i(\tau)}{t - \tau} d\tau, \text{ where } h(t) = \frac{1}{\pi t}$$

(2) The unbalanced power in microgrid can be decomposed into instantaneous power by Hilbert filter $\Delta P_h(t)$ and $\Delta P_l(t)$

Set the Hilbert resolution signal as: $Z_i(t) = e_i(t) + jE_i(t)$. The instantaneous frequency is obtained from the analytic signal $f_i(t)$. As the number of decomposition increases, the frequency $f_i(t)$ corresponding to $e_i(t)$ decreases. Set a frequency $f_c(t)$ between the decomposed frequencies. Suppose that three adjacent IMF power signals at a Δt time are: $e_{i-1}(t)$, $e_i(t)$, $e_{i+1}(t)$, then the absolute value of energy near Δt time is Q

$$Q = \sum_{i=1}^m |e_{i-1}(t)| \Delta t + \sum_{i=1}^m |e_i(t)| \Delta t + \sum_{i=1}^m |e_{i+1}(t)| \Delta t \quad (13)$$

Let Δt be 0.00001 Hz, design and calculate the minimum value of Q , the IMF power component is closest to the stable power at this time, and the frequency at this time is the fractional frequency $f_c(t)$

$$\Delta P_h(t) = p_1(t) + p_2(t) + \dots + p_{c-1}(t) + p_c(t)$$

$$\Delta P_l(t) = p_{c+1}(t) + p_{c+2}(t) + \dots + p_{i-1}(t) + p_i(t)$$

where, $\Delta P_h(t)$ is the high frequency component which can be absorbed by supercapacitor, and $\Delta P_l(t)$ is the low frequency component which can be absorbed by battery.

By using EEMD to design filters, the automatic distribution of signals in appropriate time scales is realized, which effectively solves the decomposition problem of high frequency power and low frequency power in the power fluctuation of the hybrid energy storage system, and improves the response capability of batteries and supercapacitors.

4 FUZZY OPTIMIZATION COORDINATED CONTROL OF EEMD HYBRID ENERGY STORAGE SYSTEM

4.1 Hybrid Energy Storage Control for DC Microgrid Based on EEMD

According to the contents of the previous sections, in order to verify the performance of EEMD decomposition method in photovoltaic energy storage system, an example simulation analysis was carried out in Matlab/Simulink environment. The parameters of each part of the simulation model are as Tab. 1.

Table 1 Main parameters of the system

The module		Parameters and value
Photovoltaic system		Reference light intensity: 1000 W/s ² Reference temperature: T = 20 °C Maximum output power: 900 W
Hybrid energy storage system	Super capacitor	The rated voltage: 32 V The maximum capacity: 29 F
	battery	The rated voltage: 24 V
DC Bus IGBT		Internal resistance: 0.01 Ω Resistance: 10 ⁵ Ω capacitance: ∞

IMFs was obtained by EEMD, and the corresponding high-frequency and low-frequency fluctuation components of power respectively controlled the supercapacitor module and energy storage battery module of mixed energy storage.

Working condition 1: Assume that the illumination of the energy storage system decreases significantly from 1000 W²/m² to 600 W²/m² at 4.45 seconds. As shown in Fig. 4, the bus voltage *V_o* decreases due to the sudden decrease of photovoltaic power generation. To keep *V_o* stable, the battery provides the low frequency component of the required EEMD instantaneously and then goes to zero, while the ultracapacitor provides the high frequency component of the excess required EEMD to keep the bus voltage stable.

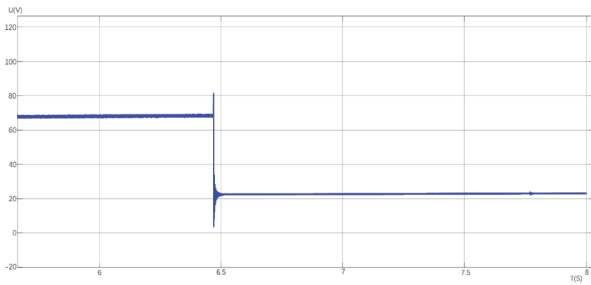


Figure 4 Working condition I

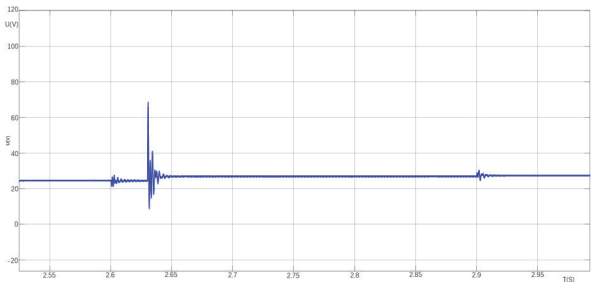


Figure 5 Working condition II

Working condition 2: Line load was removed at 2.6 seconds, as shown in Fig. 5. Because the photovoltaic power is unchanged, the bus load decreases and the voltage

V_o increases. Through EEMD frequency division control, the battery absorbs low frequency components and EEMD plays an obvious role in the system. The fluctuation time of bus voltage is shortened by about 0.02 s, due to the high power density of the supercapacitor, the supercapacitor SOC will exceed the limit with the result that the bus voltage fluctuation in the microgrid system cannot be stabilized by the hybrid energy storage system. So, there is still the problem of large fluctuation voltage to be solved.

4.2 Fuzzy Control Strategy for EEMD Optimization

In order to solve the defect of big fluctuation, fuzzy algorithm is used to improve and optimize the control strategy based on traditional EEMD algorithm. According to the charge and discharge conditions of the system, the power storage element *SOC_{sc}(t)* is used to constrain the system.

The constraint conditions are $SOC_{min}(t) \leq SOC_{sc}(t) \leq SOC_{max}(t)$, then the output of the fuzzy controller is described as Eq. (14).

$$\Delta P_{sc}(t) = \left(SOC_{sc}(t) + \frac{P_{scref}(t)\Delta t}{E} \right) \tag{14}$$

where, $\Delta P_{sc}(t)$ is the change of supercapacitor power at t, *SOC_{sc}(t)* is the state of supercapacitor charged, and E is the capacity of the supercapacitor.

Super capacitor $\Delta P_{sc}(t)$ makes different adjustments according to different charging and discharging conditions. The specific power regulation strategy is described as follow:

1. When *SOC_{sc}(t)* is moderate, the battery and supercapacitor are controlled and adjusted by EEMD high-frequency signal, and the supercapacitor and battery are charged and discharged according to the primary distribution instructions.

2. When $\Delta P(t) < 0$ and *SOC_{sc}(t)* is small, or $\Delta P(t) > 0$ and *SOC_{sc}(t)* is relatively large, adjust *K_{sc}(t)* to decrease. By analyzing the low-frequency power of EEMD, the reference power of the ultracapacitor decreases, and the reduced difference power is borne by the battery.

3. When $\Delta P(t) < 0$ and *SOC_{sc}(t)* is large, or $\Delta P(t) > 0$ and *SOC_{sc}(t)* is relatively small, we do not need to adjust the reference power of the supercapacitor, and the supercapacitor works according to the initial reference power.

The supercapacitor power adjustment scheme instructions are described in Tab. 2. And the specific process is shown in Fig. 6.

Table 2 The supercapacitor power adjustment scheme instructions

State of <i>SOC_{sc}</i>	State of $\Delta P_{sc}(t)$	Action plan
Small <i>SOC_{sc}</i> values	$\Delta P_{sc}(t) > 0$	<i>K_{sc}(t)</i> increase
Small <i>SOC_{sc}</i> values	$\Delta P_{sc}(t) < 0$	<i>K_{sc}(t)</i> decrease
Big <i>SOC_{sc}</i> values	$\Delta P_{sc}(t) > 0$	<i>K_{sc}(t)</i> decrease
Big <i>SOC_{sc}</i> values	$\Delta P_{sc}(t) < 0$	<i>K_{sc}(t)</i> increase
<i>SOC_{sc}</i> value is moderate		No action

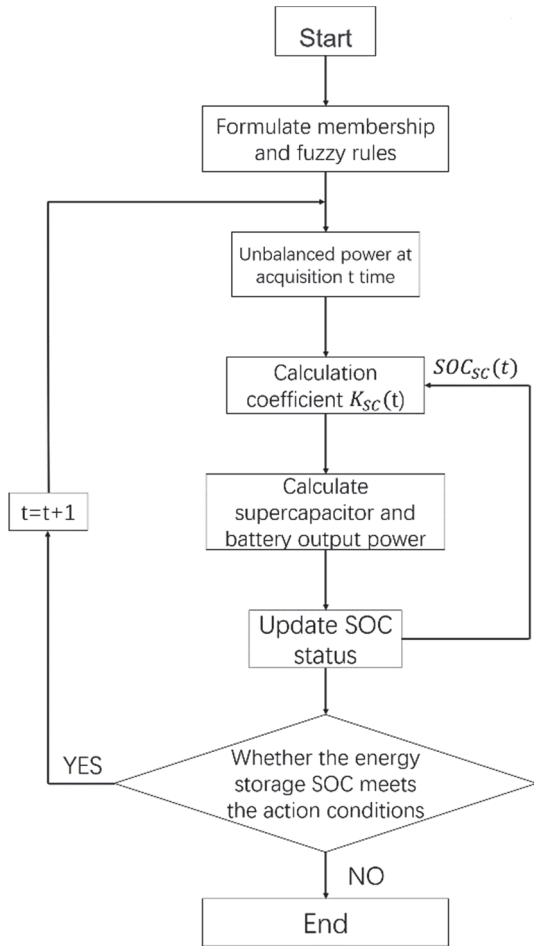


Figure 6 Fuzzy control flow chart

To ensure the safe and reliable operation of the supercapacitor, the capacity of the supercapacitor is required as Eq. (15):

$$E = \frac{[\max \sum_{i=0}^t \Delta P_h(t+i) - \min \sum_{i=0}^t \Delta P_h(t+i)] \Delta t}{SOC_{\max}(t) - SOC_{\min}(t)} \quad (15)$$

where, $\Delta P_h(t+i)$ is the power change of the supercapacitor at $t+i$; Δt is the corresponding time interval. Therefore, the input of the fuzzy controller has two parts: supercapacitor $SOC_{sc}(t)$ and $P_{sc_ref}(t)$ of power storage element after time t . And the output of fuzzy controller is power regulation coefficient $K_{sc}(t)$ of power storage element. In the hybrid energy storage system, the optimization idea of fuzzy controller is to reduce the use frequency of the energy storage element, namely the storage battery, so that it can be used for a long time. Inputs, output and membership function curves of fuzzy control are shown in Figs. 7, 8 and Fig. 9. Tab. 3 shows the table of fuzzy rules.

After optimizing the fuzzy control $\Delta P_{sc}(t)$, the new power distribution instructions of the ultracapacitor and battery are obtained.

$$\begin{cases} \hat{P}_{sc_ref}(t+1) = K_{sc}(t) * \hat{P}_{sc_ref}(t) \\ \hat{P}_{b_ref}(t+1) = (1 - K_{sc}(t)) \hat{P}_{sc_ref}(t) + \hat{P}_{b_ref}(t) \end{cases}$$

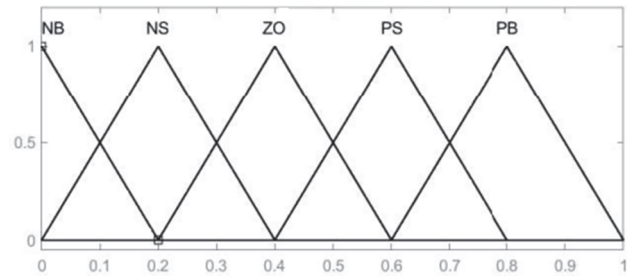


Figure 7 $SOC_{sc}(t)$ input membership degree diagram

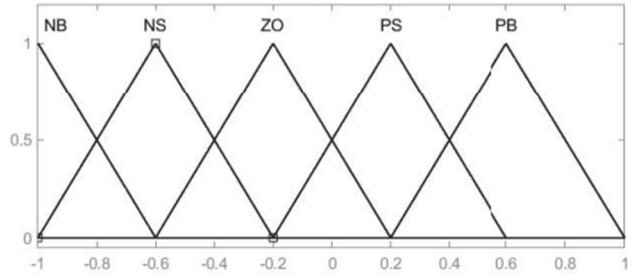


Figure 8 $\Delta P_{sc}(t)$ input membership degree diagram

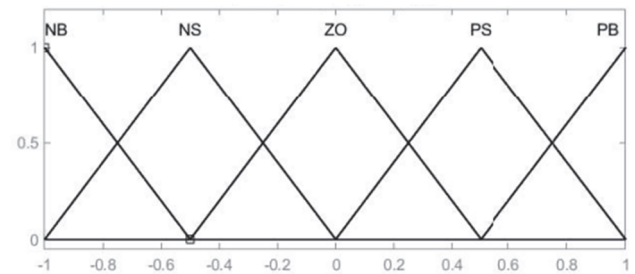


Figure 9 $K_{sc}(t)$ membership degree diagram

Table 3 Fuzzy rules table

		$SOC_{sc}(t)$				
		NB	NS	ZO	PS	PB
$\Delta P_{sc}(t)$	NB	NB	NB	NS	NS	NS
	NS	NB	NB	NS	NS	NS
	ZO	ZO	ZO	ZO	ZO	ZO
	PS	PB	PB	PS	PS	PS
	PB	PB	PB	PS	PS	PS

To sum up, the structural block diagram of EEMD optimized fuzzy control algorithm is shown in Fig. 10.

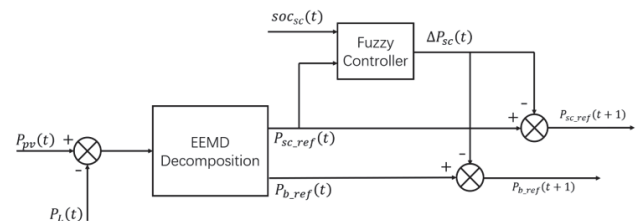


Figure 10 Fuzzy control algorithm for EEMD optimization

4.3 Fuzzy EEMD Optimization Analysis

Working condition 1: As shown in Fig. 11, the illumination intensity of the system decreases from $1000 \text{ W}^2/\text{m}^2$ to $600 \text{ W}^2/\text{m}^2$, and the bus voltage V_o decreases. To maintain V_o stability, the battery provides the low frequency component of the required EEMD for a fraction of a second, then zero, while the ultracapacitor provides the high frequency component of the excess required EEMD, after which the system output voltage stabilizes to 26 V.

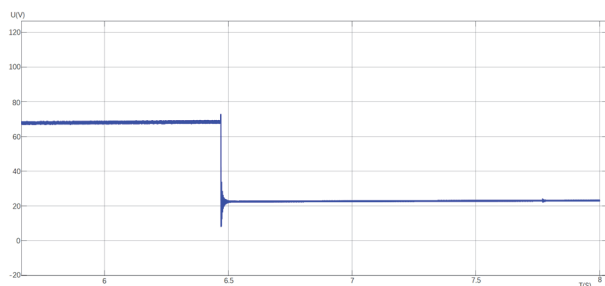


Figure 11 Working condition I Fuzzy optimization

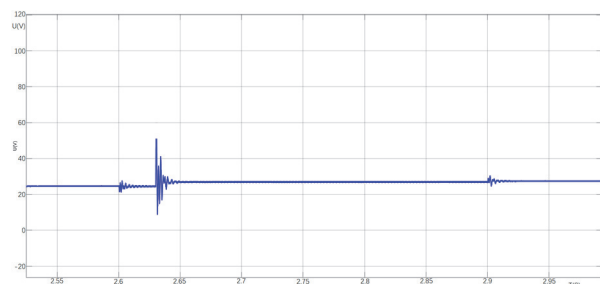


Figure 12 Working condition II Fuzzy optimization

Working condition 2: as shown in Fig. 12, the load is cut off at 2.6 seconds, the photovoltaic power remains unchanged, and the bus voltage V_0 decreases. In order to maintain the stability of V_0 and power, the battery absorbs the low frequency component of the required EEMD instantaneously and then becomes zero, while the ultracapacitor absorbs the high frequency component of the excess required EEMD, and then the system outputs a stable voltage of 26 V.

The simulation results show that after optimizing EEMD algorithm with fuzzy algorithm, the fluctuation of power and voltage of the system decreases obviously, which is about 13% of the bus voltage, and the overshoot decreases obviously. The fuzzy control algorithm has high optimization ability for EEMD decomposition algorithm, realizes the coordinated control of the whole photovoltaic microgrid hybrid energy storage system, and the stabilization effect is better than the traditional method.

5 CONCLUSIONS

Aiming at the strong random fluctuation of power in the DC microgrid photovoltaic hybrid energy storage system, an EEMD decomposition method for unstable power fluctuation signals is proposed in this paper. Using fuzzy algorithm to optimize EEMD power decomposition method, combined with the charge state of hybrid energy storage system, a microgrid fluctuation suppression strategy is proposed. The effectiveness and accuracy of the controller are verified by simulation experiments. The following findings are drawn from the analysis and design of fuzzy optimization EEMD strategy, as well as simulated analysis of several scenarios when there is light radiation reduction and load removal in a microgrid.

1. Using EEMD to design filters can realize automatic distribution of signals at appropriate time scales, effectively solve the decomposition problem of high frequency power and low frequency power at the power fluctuation of hybrid energy storage system, and improve the response ability of batteries and supercapacitors.

2. Based on the traditional EEMD algorithm, fuzzy algorithm is used to improve and optimize the control strategy. Compared with ordinary EEMD signal decomposition, the protection of battery and ultracapacitor and low fluctuation of voltage in the system are realized. The reduction of bus grid overshoot is about 13%. The proposed method has a good suppression ability for the large bus voltage and power fluctuation.

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Contact information:**Chunhui LIANG**

(Corresponding author)
School of Electrical and Information Engineering,
Changchun Institute of Technology,
Changchun 130022, China
National and Local Joint Engineering Research Center Of Intelligent Distribution,
Network Measurement and Control and Safe Operation Technology,
Changchun 130022, China
E-mail: liangchunhui001@163.com

Weihong REN

School of Electrical and Information Engineering,
Changchun Institute of Technology,
Changchun 130022, China
E-mail: qsjzhdhhj@163.com

Peng CHENG

School of Electrical and Information Engineering,
Changchun Institute of Technology,
Changchun 130022, China
E-mail: 1615979387@qq.com

Chao DING

School of Electrical and Information Engineering,
Changchun Institute of Technology,
Changchun 130022, China
E-mail: 419805010@qq.com