Optimization Strategy for Hybrid Energy Storage Power Distribution Based on Fuzzy Control

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Abstract. In order to solve the problem of intermittence and fluctuation of output power of photovoltaic (PV) power generation system, a fuzzy control based optimization method for power distribution of hybrid energy storage system is proposed. Compared with the traditional hybrid energy storage system (HESS) control method, this method can use the ensemble empirical mode decomposition (EEMD) and fuzzy control algorithm to realize the reasonable distribution of charge and discharge power of hybrid energy storage system. EEMD technology is used to decompose the unbalanced power signal in the system, and realize the power distribution of super capacitor and battery according to the characteristics of energy storage system. The fuzzy controller is used to optimize the distribution power of the hybrid energy storage system, to control the charge and discharge of the energy storage device reasonably. Under the action of the fuzzy controller, the hybrid energy storage system can choose the appropriate operation mode to maintain the stability of DC bus voltage according to the energy storage state of charge (SOC) and power fluctuation. Finally, the simulation example verifies the rationality and superiority of the proposed method.

1. Introduction

Compared with AC microgrid, DC microgrid's outstanding advantages are no frequency fluctuation, no power angle change, no eddy current and reactive power loss. Therefore, DC bus voltage fluctuation is a measure of system power balance and reliable operation of microgrid Important technical indicators [1, 2]. The DC bus voltage fluctuations will inevitably affect the normal operation of the load, and even cause protection malfunction or equipment damage. Aiming at the characteristics of intermittent and fluctuating output power of distributed power sources, not only need to consider increasing hybrid energy storage to increase system inertia, but also need to propose a reasonable power distribution control strategy to improve the overall voltage stabilization capability of the system [3, 4, 5].

In order to realize the stability of DC microgrid bus voltage, experts at home and abroad have carried out relevant research work from different levels. In reference [6], in order to suppress wind power fluctuations and make power meet grid-connected standards, a hybrid energy storage system control strategy based on wavelet analysis was proposed to dynamically change power distribution. However, before the wavelet signal is decomposed, a suitable wavelet basis function needs to be constructed, so this method is not universally applicable. Reference [7] uses a power feedforward compensation method, using the power disturbance component of the bus voltage as a disturbance signal, and suppressing the...
bus voltage fluctuation through feedforward control, but it needs to add additional voltage and current sensors, which is not conducive to plug and play of the microgrid DG. Reference [8] uses a first-order low-pass filtering method to smooth the wind power output. Although the power smoothing control performance of the traditional first-order filter method is improved, the selection of the filtering time constant is strict, otherwise it will affect the smoothing effect.

This paper proposes a power distribution optimization control strategy for hybrid energy storage systems based on fuzzy control. First, the unbalanced power generated at the DC bus is decomposed by EEMD to generate a series of intrinsic mode function components (IMF). The high-frequency component and low-frequency component are taken as the reference values of supercapacitor and battery output power respectively to complete the initial distribution of unbalanced power. Secondly, in view of the advantages of the power-type energy storage element in the charge and discharge response speed and the number of uses, the charging state of the super capacitor and the unbalanced power generated by the system are used as the input signals of the fuzzy controller to output the corresponding adjustment coefficients, To achieve secondary optimization of hybrid energy storage power allocation.

2. DC microgrid system structure and stability analysis
The structure of the DC microgrid system is shown in Figure 1. The photovoltaic array, super capacitor, battery and AC / DC load are connected to the DC bus through their respective conversion circuits.

Ignoring the converter and line losses, the power balance in the system is

\[ P_a = P_{pv} + P_b + P_{sc} - P_L \]  

(1)

Where \( P_a \) is the storage capacity of the DC bus equivalent capacitor, \( P_{pv} \) is the photovoltaic output power, \( P_L \) is the demand power of the load, \( P_b \) and \( P_{sc} \) are the charge and discharge power of the battery and super capacitor (negative sign indicates charging, positive sign indicates discharging).
From formula (1.1), the dynamic equation of DC bus voltage can be obtained as

\[ U_{dc} \frac{dU_{dc}}{dt} = \frac{1}{C} (P_{pv} + P_b + P_{sc} + P_L) \]  
(2)

Where \( U_{dc} \) is the DC bus voltage, \( C \) is the equivalent capacitance of the DC bus.

It can be known from equation (1.2) that the DC bus voltage is an important indicator of power balance in the reaction system. The generation of unbalanced power will inevitably affect the fluctuation of the DC bus voltage.

Continued from the transformation of formula (1.2),

\[ C \frac{dU_{dc}}{dt} = I_{pv} + I_b + I_{sc} - I_L \]  
(3)

Where \( I_{pv} \) is the photovoltaic output current, \( I_b \) is the battery charging and discharging current, \( I_{sc} \) is the super capacitor charging and discharging current, \( I_L \) is the input current at the load.

If the power required by the hybrid energy storage system is \( P_{hess} \), then

\[ P_{hess} = \Delta P_{sc} + \Delta P_b \]
\[ = U_{dc} I_{sc} + U_{dc} I_b \]  
(4)

From formula (1.4), it can be known that by adjusting the size of the super capacitor and the battery charge and discharge current, the respective output power can be changed, and the power distribution can be completed on the basis of ensuring the stability of the DC bus voltage.

3. Characteristics and power distribution of hybrid energy storage systems

3.1. Energy storage characteristics

The energy storage system (ESS) can effectively reduce the randomness and intermittence of renewable energy generation, make its output smooth, and facilitate the rapid access of microgrid; on the other hand, it can realize the energy cross-time scheduling, participate in the optimal configuration of distribution network, and increase the inertia of microgrid system [9]. The battery has the significant advantage of high energy density, but the power density is small and the response is slow. Super capacitor has the characteristics of high power density and fast response, but its energy density is limited, which is suitable for suppressing high frequency power fluctuation [10-11]. The hybrid energy storage system is composed of battery and super capacitor in order to play a more effective role in stabilizing power fluctuation.

3.2. Stabilize power distribution of hybrid energy storage system

It can be seen from Figure 1 that the unbalanced power in the DC microgrid composed of photovoltaic and hybrid energy storage can be expressed as

\[ \Delta P(t) = P_{pv}(t) - P_L(t) \]  
(5)

Where \( P_{pv}(t) \) is the actual output power of photovoltaic power station, \( P_L(t) \) is the load power in the system.
The unbalanced power in microgrid will cause the fluctuation of DC bus voltage. In order to maintain the safe operation of microgrid, the hybrid energy storage system needs to release or absorb power to compensate

\[ \Delta P(t) = P_{\text{bat}}(t) + P_{\text{sc}}(t) \]  

(6)

According to the characteristics of energy storage, reasonable power distribution for batteries and super capacitors can not only quickly suppress power fluctuations, but also effectively reduce battery losses.

Because the stable unbalanced power of the interference system is nonlinear, EEMD is used to adaptively decompose it to obtain n IMF components, that is

\[ T_i(t) = e_1(t) + e_2(t) + \cdots + e_n(t) + R(t) \]

\[ = \sum_{i=1}^{n} e_i(t) + R(t) \]  

(7)

Where \( e_i(t) \) is the eigenmode function component, and \( R(t) \) is the residual term after multiple decompositions.

After transforming \( e_i(t) \) by Hilbert, get the transformation result \( E_i(t) \), that is

\[ E_i(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{e_i(t)}{t-\tau} d\tau \]

\[ = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{e_i(t-\tau)}{\tau} d\tau \]

\[ = \frac{e_i(t)}{\pi t} \]  

(8)

Define the analytic signal \( Z_i(t) = e_i(t) + jE_i(t) \), then

\[ z_i(t) = A_i(t)e^{j\theta_i(t)} \]  

(9)

among them

\[ A_i(t) = \sqrt{\int_{-\infty}^{+\infty} e_i^2(t) + E_i^2(t)} \]  

(10)

\[ \theta_i(t) = \arctan \frac{E_i(t)}{e_i(t)} \]  

(11)

Where \( A_i(t) \) is the instantaneous amplitude, \( \theta_i(t) \) is the instantaneous phase.

The instantaneous frequency \( f_i(t) \) is

\[ f_i(t) = \frac{d\theta_i(t)}{dt} \]  

(12)
The sum of IMF components can be obtained by rearranging them according to the instantaneous frequency

\[ \Delta P_i(t) = e_{f_1}(t) + e_{f_2}(t) + \cdots + e_{f_n}(t) \]  
(13)

Set the division frequency to \( f_k(t) \), and its corresponding IMF component is \( e_{f_k}(t) \).

\[ \Delta P_H(t) = e_{f_1}(t) + e_{f_2}(t) + \cdots + e_{f_k}(t) \]
\[ = \sum_{i=1}^{k} e_{f_i}(t) \]  
(14)

\[ \Delta P_L(t) = e_{f_{k+1}}(t) + e_{f_{k+2}}(t) + \cdots + e_{f_n}(t) \]
\[ = \sum_{i=k+1}^{n} e_{f_i}(t) \]  
(15)

The reference power of the super capacitor and the battery can be obtained respectively

\[ P_{sc,ref}(t) = \Delta P_H(t) \]  
(16)

\[ P_{b,ref}(t) = \Delta P_L(t) \]  
(17)

When performing power distribution, it is also necessary to consider the state of charge of supercapacitors and batteries to ensure that \( SOC_{sc} \) and \( SOC_b \) are within the allowable working range to avoid overcharging and overdischarging of energy storage equipment. The block diagram of the initial power distribution of hybrid energy storage is shown in Figure 2.

**Figure 2.** Primary power distribution block diagram of hybrid energy storage.
4. secondary optimization of hybrid energy storage power distribution based on fuzzy control

Super capacitor has the characteristics of fast response speed and long cycle life, while battery is limited by the number of charge and discharge, frequent use will reduce its life. Therefore, in the process of power distribution of hybrid energy storage system, it is necessary to coordinate the power-type storage and energy-type storage to adjust their reference power instructions, reduce the possibility of power storage reaching the upper and lower limits, so as to play the best performance of hybrid energy storage system. Therefore, in the design of the fuzzy controller, the charge state $SOC_{sc}(t)$ of the super capacitor and the unbalanced power $\Delta P(t)$ in the system are taken as its input signals, and the output signal is the charge discharge regulation coefficient $K_{sc}(t)$ of the super capacitor.

The fuzzy controller's power adjustment strategy for supercapacitors and batteries is: When the $SOC_{sc}(t)$ is moderate, the super capacitor and battery are charged and discharged according to the primary allocation instructions; when $\Delta P(t) < 0$ and $SOC_{sc}(t)$ is small, $\Delta P(t) > 0$ and $SOC_{sc}(t)$ is large, adjusting $K_{sc}(t)$ decreases, the reference power of the super capacitor decreases, and the difference is reduced Power borne by the battery; When $\Delta P(t) < 0$ and $SOC_{sc}(t)$ is larger, $\Delta P(t) > 0$ and $SOC_{sc}(t)$ is small, there is no need to adjust the reference power of the supercapacitor, and the supercapacitor works according to the initial reference power.

The adjusted reference power of the super capacitor and battery are

$$P_{sc,ref}(t+1) = K_{sc}(t)P_{sc,ref}(t)$$

$$P_{b,ref}(t+1) = \Delta P(t+1) - P_{sc,ref}(t+1)$$

The membership function of the input and output of the fuzzy controller is as follows:

1) The domain of charge state $SOC_{sc}(t)$ of the super capacitor is $[0,1]$, and the fuzzy set is \{ES, CS, S, M, B, CB, EB\}, which is defined as \{extremely small, comparatively small, small, moderate, big, comparatively big, extremely big\}. The membership function of $SOC_{sc}(t)$ is shown in Figure 3.

2) The domain of unbalanced power $\Delta P(t)$ is $(-\infty, +\infty)$, and the fuzzy set is \{NB, NM, NS, ZERO, PS, PM, PB\}, which is defined as \{negative large, negative medium, negative small, zero, positive small, positive medium, positive large\}, the setting of zero can prevent the power electronic switch from repeatedly operating, and the energy storage equipment does not participate in the adjustment within the allowable power fluctuation range. The membership function of $\Delta P(t)$ is shown in Figure 4.
3) The domain of the adjustment coefficient $K_{sc}(t)$ is $[0,1]$, and the fuzzy set is \{ES, RS, S, M, B, RB, EB\}, which is defined as \{extremely small, comparatively small, small, moderate, big, comparatively big, extremely big\}. $K_{sc}(t)$ membership function is shown in Figure 5.

Figure 4. Membership function of $\Delta P(t)$.

Figure 5. Membership function of $K_{sc}(t)$.

The membership function of fuzzy controller is composed of trigonometric function and trapezoidal function. The area center of gravity method is selected when defuzzifying. The fuzzy controller rules are shown in Table 1.

Table 1. Fuzzy rules.

| $K_{sc}(t)$  | $SO_{sc}(t)$ | ES | CS | S | M | B | CB | EB |
|--------------|--------------|----|----|---|---|---|----|----|
| NB           | ES           | ES | CS | S | M | B | EB | EB |
| NM           | ES           | S  | M  | B | EB | EB | EB | EB |
| NS           | ES           | CS | B  | EB | EB | EB | EB | EB |
| PS           | EB           | EB | EB | EB | B  | CS | ES | ES |
| PM           | EB           | EB | EB | EB | B  | M  | S  | ES |
| PB           | EB           | CB | B  | M  | S  | CS | ES | ES |
5. Simulation analysis

In order to verify the rationality and effectiveness of the proposed optimal control method for hybrid energy storage power distribution, a simulation model is built according to the structure of Figure 1. The setting parameters are as follows: the rated frequency of the system is 50 Hz, the DC bus voltage is 800 V, the converter switching frequency is 15 kHz, and the maximum photovoltaic output power is 40 kW. The parameters configuration of the hybrid energy storage system is shown in Table 2.

The power supply and demand relationship in the DC microgrid is shown in Figure 6 (a). At the beginning, the photovoltaic output and load demand reached a balance between supply and demand, and the hybrid energy storage system does not work. At $t = 0.4$ s, the load demand of increases, photovoltaic output cannot be met, power difference $\Delta P < 0$, and the energy storage system starts to discharge. Due to the small power difference, the super capacitor works alone to reduce the number of battery discharges. At $t = 0.8$ s, the load demand continues to increase, photovoltaic output decreases, power difference increases, single energy storage is difficult to compensate, and supercapacitors and batteries discharge at the same time. Because the supercapacitor has sufficient power, the output power is greater during power distribution, and the discharge speed is faster. At $t = 1.2$ s, the photovoltaic output increases, but it still cannot meet the load demand. At this time, the supercapacitor has a lower state of charge and the output power decreases, then the output power of the battery increases. The changes in the output power of the supercapacitor and the battery are shown in Figure 6 (b).

![Power variation in DC microgrid](image_url)

(a) Power variation in DC microgrid

| Parameters                  | Super capacitor | Battery |
|----------------------------|-----------------|---------|
| Rated power/kW             | 20              | 15      |
| Maximum capacity/(W·h)     | 120             | 232     |
| Optimal operating range/%  | 15~85           | 20~80   |
| Initial state of charge/%  | 50              | 50      |
| Self-discharge rate/%      | 2               | 5       |
| Charge and discharge efficiency/% | 95         | 90      |

Table 2. Parameters configuration.
Figures 7(a)-7(c) respectively reflect the changes in DC bus voltage fluctuations, supercapacitor and Battery state of charge before and after the power distribution in a hybrid energy storage system. It can be seen from Figure 7(a) that DC bus voltage drop caused by power imbalance, and the voltage per unit value fluctuates $\Delta U > 0.05$. The hybrid energy storage system releases electric energy to participate in the adjustment. The power in the microgrid tends to balance, and DC bus voltage restored to rated value. the simulation results show that after adding the EMD and fuzzy controller, the hybrid energy storage system has a better effect when maintaining the DC bus voltage stability. It can be known from Figure 7(b) that as the SOC of the supercapacitor continues to decrease, to avoid overcharging and discharging the super capacitor, adjust $K_{sc}$ to reduce its output power, and maintaining the $SOC_{sc}$ at a reasonable level. After determining the output power of the supercapacitor, the battery uses its own high energy density to provide the remaining power compensation. The $SOC$ of battery changes are shown in Figure 7(c).
6. Conclusion
A hybrid energy storage scheduling scheme based on fuzzy control is proposed, which comprehensively considers photovoltaic output, load demand, and energy storage equipment status. The unbalanced power generated by the microgrid system is decomposed using EMD to achieve the initial distribution of hybrid energy storage output power, and designed a fuzzy controller with the SOC of supercapacitor and unbalanced power as input variables. The secondary optimization of the hybrid energy storage power distribution through the fuzzy controller makes full use of the advantages of the supercapacitor's fast response to ensure that it works within a reasonable interval, reduces the number of charge and discharge times of the battery, extends the service life of the battery and improves economic benefits; In addition, after adding EEMD and fuzzy control modules to the hybrid energy storage system, the DC bus voltage is more stable than under its conventional control, and the adjustment time is shorter, so that the super capacitor and battery can work more efficiently within a reasonable range of state of charge.

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References

[1] LIU Jian, WEI Haokun, ZHANG Zhihua, et al. Future architecture of power distribution network—— low-voltage direct current micro-grids based on energy storage[J]. Power System Protection and Control, 2018, 46(18): 11-16.

[2] LI Xialin, LI Zhiwang, GUO Li, et al. Flexible control and stability analysis of AC / DC microgrid cluster[J]. Proceedings of the CSEE, 2019, 39(20): 5948-5961+6175.

[3] ZHANG Jianglin, ZHUANG Huimin, LIU Junyong, et al. Two-stage coordinated voltage control scheme of active distribution network with voltage support of distributed energy storage system[J]. Electric Power Automation Equipment, 2019, 39(05): 15-21+29.

[4] LEE W C, YEE W W, RAJPRASAD K Rr, et al. An adaptive learning control strategy for standalone PV system with battery-supercapacitor hybrid energy storage system[J]. Journal of Power Sources, 2018, 394(1): 35-49.

[5] ZHU Xiaorong, CHEN Chaoqian, ZHANG Yumeng, et al. Comprehensive control strategy of grid-connected current and DC microgrid voltage under unbalanced grid voltage[J]. High Voltage Engineering, 2019, 45(08): 2562-2570.

[6] ZHU Yuwei, LYU Lin, LIU Youbo, et al. A hybrid energy storage smoothing control strategy based on dynamic wavelet transform[J]. Electric Power Construction, 2017, 38(09): 111-119.

[7] LYU Zhilin, TANG Wenqiang, ZENG Xianjin. Voltage stability control of isolated DC microgrid based on power feed forward[J]. Power Electronics, 2015, 49(08): 32-36.

[8] KAN Zhizhong, CHAI Xiuhui, JIN Benhao, et al. Wind power smoothing control based on battery and super capacitor hybrid energy storage system[J]. Journal of Yanshan University, 2018, 42(06): 501-509.

[9] WANG Shouxiang, WANG Kai, ZHAO Ge. Configuration and control of energy storage system for fluctuation mitigation in an active distribution network—A review[J]. Energy Storage Science and Technology, 2017, 6(06): 1188-1195.

[10] LI Jianlin, XIU Xiaoqing, LYU Xiangyu, et al. Review on Capacity Optimization Configuration and Life Cycle Economic Evaluation Method for Energy Storage System[J]. Journal of power supply, 2018, 16(04): 1-13.

[11] CHEN Kebin, QIU Xiaoyan, ZHAO Jinhua, et al. Sizing and Cost Analysis of Hybrid Energy Storage System for Compensating Wind Power Forecast Errors[J]. High Voltage Apparatus, 2018, 54(06): 189-196.