A hybrid energy storage strategy based on multivariable fuzzy coordinated control of photovoltaic grid-connected power fluctuations

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Abstract
Aiming at the problem that the grid-connected power fluctuation of the photovoltaic power system affects the stability of grid operation, a multivariable fuzzy coordinated control strategy for photovoltaic grid-connected power fluctuation based on super-capacitor and battery is proposed. First, a multivariable fuzzy controller is established based on the grid-connected estimated fluctuation power of the photovoltaic power system and the current energy state of charge of super-capacitor and battery. The fuzzy relational matrix is used to introduce interaction effects of inputs into the fuzzy control, the fuzzy relation matrix is established by multiplying with weights, and the time constant of the low-pass filter is adjusted to coordinate the distribution of fluctuating power between different energy storage in real-time. Second, according to the SOC variation of HESS, a super-capacitor fuzzy controller and battery fuzzy controller are established to modify the charging and discharging instructions of battery and super-capacitor. The charging and discharging power of the energy storage are constraints to optimize the charging and discharging power of the energy storage, and the energy state of the HESS is updated in real-time. Finally, an overall example analysis of fuzzy coordinated control is performed to verify the effectiveness of the proposed control strategy.

1 | INTRODUCTION

In recent years, countries have rapidly developed clean renewable energy, and the proportion of installed capacity of photovoltaic (PV) power systems in the power system has been rising. Since the output power of the PV power system changes with the weather change, the grid connection of a large-scale PV power system will affect the stability and reliability of power grid operation [1–5]. The installation of the battery energy storage station (BESS) in the grid-connected PV power system to stabilize their output power fluctuations. To some extent, the PV energy can be converted into electricity grid distributed energy, and it will help reduce the impact of the PV power system on the grid [6, 7].

In order to reduce the amplitude fluctuation degree of the grid-connected power of the PV power system and achieve the expected suppressing effect of the energy storage system (ESS), it is necessary to establish a rational control strategy of ESS. At present, most grid-connected PV power systems use battery super-capacitor hybrid energy storage medium to meet energy storage needs [8–11]. In [12], power-control strategies of a grid-connected hybrid generation system with versatile power transfer was proposed, which improved the operational flexibility and power quality of the power grid flatten grid-connected power fluctuations. This paper presents a novel coordinated control strategy for use in a hybrid PV/BESS, and the fluctuated output of the PV farm is mitigated [13]. In [14], a unified control and power management scheme for hybrid microgrid based on PV-battery for grid-connected and islanded mode is proposed, which realizes the power balance between the hybrid microgrid system and the grid. Similarly, these papers have studied the HESS of grid-connected PV power systems to suppress grid-connected power fluctuation [15–17]. However, most literature seldom elaborates specific research on the power...
allocation of energy storage devices in HESS, which has an extremely important impact on the suppress power effect and working life of HESS.

Because fuzzy logic control is widely used in nonlinear systems, where parameter dynamic changes are difficult to predict and accurately modelled. HESS power distribution dynamically changes nonlinearly with photovoltaic output power and energy storage device’s state of charge (SOC), it is difficult to accurately describe the specific change process. In [18], a variable filter time constant two-stage low-pass filter (LPF) control strategy is designed, and the fuzzy control method for dynamic adjustment second-level filtering time constant, optimizing the allocation of power battery and super-capacitor. A neuro-fuzzy logic control strategy is proposed to distribute the power between dc power sources and stabilize the dc–link power [19]. In [20], an fuzzy logic control system for charging and discharging of the battery energy storage system is proposed in microgrid applications, which can maintain the energy balance between the storage and microgrid. Similarly, a control strategy of BESS based on fuzzy control theory is presented to alleviate the grid-connected fluctuating power of PV power plants [21]. In [22], a decentralized coordinated power control approach is proposed with considering the limits of maximum charging discharging power of ESS, combining dc bus voltage signal with fuzzy logic control to achieve power management for islanded dc microgrids. In [23], a fuzzy logic-based algorithm developed for battery storage power management (BSPM) and demand side power management (DSPM) is proposed, and the battery can suppress fluctuating power and save electricity costs under changing lighting. In [24], a fuzzy logic based controller is implemented for the boost converter connected at the fuel cell terminals, so that the fuel cell power output can be converted faster and more smoothly between different ratios of PV generation/load. A fuzzy logic control based power management strategy is presented in [25], with the purpose of reduce battery degradation to extend battery degradation significantly. In [26], a simple and low cost control strategy using PI controllers and fuzzy logic algorithm, which have a high speed in DC link voltage recovery, and extend the battery useful life. In [27], the fuzzy logic supervision and control strategy are capable of managing the power of an MVDC system, and the fuzzy logic supervisor can produce the demanded reference power of HESS to meet the load power requirement. Besides, in [28–30], the application of fuzzy logic control algorithm the optimal amount of charging discharging of the HESS based on the state of charge (SOC) constraints, and it proves that the fuzzy logic control algorithm is more suitable for the microgrid energy management system.

However, the control method proposed in the above literature is based on two-dimensional fuzzy control, which hardly involves the interaction between PV power fluctuations and SOC of energy storage. Besides, and does not correct the stabilized power of hybrid energy storage devices, which is deficient in the accuracy and coordination of control power distribution. Moreover, the suppressing power of the energy storage is not corrected, which is lacking the accuracy and coordination of control power distribution.

In a grid-connected PV power system, not only HESS should reasonably allocate fluctuating power in energy storage, but coordinate control of the HESS scheduling scheme. Therefore, this paper proposes a hybrid energy storage strategy multi-variable fuzzy coordinated control strategy based on super-capacitor and battery, which comprehensively considers the power fluctuation of the PV power system and the SOC of energy storage. And a multivariable fuzzy controller is designed to adaptions the time constant of the low-pass filter, smoothing the low-frequency power from the battery; suppressing the high-frequency power from the super-capacitor battery, and accurately distribute the power of the battery and the super-capacitor. Besides, according to the residual capacity and SOC change of the energy storage at the time, the super-capacitor fuzzy controller and battery fuzzy controller are designed to modify energy storage fluctuating power, and the charge and discharge power of the energy storage were optimized. The control strategy proposed can not only accurately and effectively distribute the suppress fluctuating power of the battery and super-capacitor, but also optimize the charge and discharge commands of the energy storage, avoid the out-of-limit phenomenon of energy storage mediums, and extend the battery life and improve the overall working efficiency.

The rest of the paper is organized as follows. The structure of the grid-connected PV system with HESS is described and establishes the mathematical model of the HESS in Section 2. In Section 3, the HESS energy coordination scheduling scheme is introduced in detail, the HESS fuzzy coordination power allocation is optimized, and the multi-fuzzy coordination control program is analysed. Section 4 is the emphases of the paper. First, design and verify the accuracy of the multivariable fuzzy controller. Second, design and optimize the fuzzy controller of the energy storage device. Section 5 is the verification of the HESS fuzzy coordinated control algorithm. Finally, the conclusion of this paper is drawn in Section 6.

2  |  PV SYSTEM NETWORK STRUCTURE WITH HESS

2.1  |  Network structure

This paper studies the grid-connected PV power system with HESS shown in Figure 1. The system consists of the PV array, the two-stage inverter, the HESS, and the load. The front stage of the two-stage inverter is a Boost converter, which can realize the function of boosting, stabilizing, and controlling the PV power system to be in the maximum power point tracking (MPPT). And the latter stage is an LCL type inverter, which inverts the DC side power parameter to the AC quantity that meets the grid requirements. The two-stage inverter and HESS are connected to the DC bus. HESS undertakes the task of power compensation and maintaining the stability of the DC bus voltage. Through reasonable control of HESS, the coordinated and balanced control of power between the generation side, consumer side, and grid can be realized.
2.2 Establish of HESS power distribution mathematical model

In the process of suppressing the grid-connected power fluctuation of the PV power system, it is necessary to know the maximum allowable charge-discharge power of battery and super-capacitor in the HESS at a certain time. In order to the purpose of formulating the total output power of the HESS, and to distribute power between the battery and super-capacitor. In this paper, the mathematical model of a HESS is established to record the remaining capacity in the process of charge-discharge, and calculate the maximum allowable charge-discharge power of battery and super-capacitor in the HESS at a certain time. In order to take advantage of the complementary character of power and energy in HESS, and to distribute power between the battery and super-capacitor. In this paper, the mathematical model of a HESS is sufficient. The suppress target power $P_{ref}(t)$ of HESS at time $t$ and the suppress target of outside power $ΔP(t)$ at this moment is expressed as follows:

$$P_{ref}(t) = (1 - λ(t)) P_{total}(t - 1) + λ(t) P_{PV}(t)$$  \tag{4}$$

$$ΔP(t) = (1 - λ(t))(P_{A,C}(t) - P_{total}(t - 1))$$  \tag{5}$$

$$λ(t) = \frac{Δt}{T(t) + Δt}$$  \tag{6}$$

The relationship between the filter coefficient $λ(t)$ and the residual capacity of the HESS is:

$$λ(t) = \begin{cases} k_1 \left(1 - \frac{E_{B_{max}} - E_{B}(t - 1) - E_{SC_{min}} - E_{SC}(t - 1)}{E_{B_{max}} - E_{B_{min}}}\right), & ΔP(t) ≥ 0 \\ k_2 \left(1 - \frac{E_{B_{max}} - E_{B}(t - 1) - E_{SC_{min}} - E_{SC}(t - 1)}{E_{B_{max}} - E_{B_{min}}}\right), & ΔP(t) < 0 \end{cases}$$  \tag{7}$$

In Equation (7), the paper compromises $k_1 = k_2 = 0.5$.

3 HESS POWER DISTRIBUTION CONTROL STRATEGY

Figure 2 shows the HESS power flow control scheme. Due to the complementary character of power and energy in HESS, grid-connected PV power fluctuations are broader in time and power scales, reducing system costs, and improving overall performance. The randomness and intermittent of the PV power system may cause the instability of the HESS charge and discharge working state, causing the SOC of the energy storage approximates the extreme value after the current charge and discharge, affecting the charge and discharge state at the next moment, and eventually leads to the grid-connected power effect becomes worse. Therefore, this paper proposes a HESS fuzzy control power allocation control strategy, which can adjust the charge and discharge power of the energy storage.

3.1 Fuzzy coordinated control of HESS power distribution

To improve the suppression effect of HESS, it is necessary to optimize the distribution of $ΔP_{HESS}(t)$ between different energy storage. Due to the closely connected between HESS control objects and the need to track the SOC of each energy storage in real-time during power distribution, HESS accurate charge and discharge power dynamic control fluctuation power show nonlinearity and time variability. In this paper, fuzzy control
FIGURE 2 The Control scheme of HESS power flow

is used to optimize the power distribution of the HESS, and the charge and discharge instructions of the energy storage are dynamic regulation according to the SOC of the battery and super-capacitor and the PV output power variable $\Delta P_{\text{PV}}$. The optimization objectives of HESS fuzzy control power distribution are as follows:

1. After the suppression, the fluctuation power outside the target is minimized:
   \[
   \Delta P(t) = \min \left| \Delta P_{\text{PV}}(t) - P_{\text{HESS}}(t) \right|
   \]  
   (8)

2. Super-capacitor maximizes conserving energy to suppress out power fluctuations at the next sampling moment:
   \[
   \Delta \text{SOC}_{\text{SC}} = \min \left| \text{SOC}_{\text{SC}}(t) - \text{SOC}_{\text{SC}}(0) \right|
   \]  
   (9)

3. Battery maximizes conserving energy to suppress out power fluctuations at the next sampling moment:
   \[
   \Delta \text{SOC}_{\text{Bat}} = \min \left| \text{SOC}_{\text{Bat}}(t) - \text{SOC}_{\text{Bat}}(0) \right|
   \]  
   (10)

3.2 Coordinated scheduling scheme of energy storage devices

According to Figure 1, the dynamic power balance condition of the PV power system with HESS is as follows:

\[
P_{\text{Load}}(t) = P_{\text{PV}}(t) - P_{\text{Bat}}(t) - P_{\text{SC}}(t)
\]  
(11)

According to Equation (11), when the load is constant, the charge and discharge power of the energy storage is related to $P_{\text{PV}}(t)$. HESS needs to suppress the grid-connected PV fluctuation power, which is the change in the output power of the PV power system. That is, $P_{\text{Bat}}(t)$ and $P_{\text{SC}}(t)$ are related to the change amount of the PV power system $P_{\text{PV}}(t)$. When $\Delta P_{\text{PV}}(t) < 0$, HESS needs to discharge to maintain the system power balance. At this time, it is necessary to control the discharge power of the energy storage devices according to the optimization goals of Equations (9) and (10). Similarly, when $\Delta P_{\text{PV}}(t) < 0$, the charging power of the energy storage devices needs to be controlled.

In this paper, coordinated scheduling of the HESS using PV power changes $\Delta P_{\text{PV}}$, $\text{SOC}_{\text{Bat}}$ and $\text{SOC}_{\text{SC}}$. The energy storage system can be divided into three states: charging, discharging, and standby according to the energy reserve of the device. To reduce the number of charge and discharge of the battery and extend its work life, according to the energy storage quick response characteristics of the super-capacitor and the high number of charge and discharge cycles, the super-capacitor is priority stabilized when the output power of the PV power system changes and the battery determines its operation mode according to $\Delta P_{\text{PV}}$ and the SOC of the super-capacitor. Besides, for the problem of permanent damage to the plates caused by excessive charging and discharging of the battery, buffer operating conditions are set. In this paper, the capacity of the PV power system needs to be connected to the distribution grid with a grid voltage of 380 V, therefore, the allowable range of grid-connected power fluctuations is taken as $[-10^{-3}P_{\text{PV}}, 10^{-3}P_{\text{PV}}]$.

4 HESS POWER DISTRIBUTION CONTROL STRATEGY

4.1 Multivariable fuzzy control design

The two-dimensional fuzzy controller only considers the input error and error rate of change related to the control object, but it doesn’t consider the influence of other related state parameters, and usually only controls a certain variable in the system. In this paper, because the HESS power optimal allocation proposed needs to detect the three state parameters $\text{SOC}_{\text{SC}}(t)$, $\text{SOC}_{\text{Bat}}(t)$ and $\Delta P_{\text{PV}}(t)$, and the relationship among them is closely related. For example, the amplitude change of $\Delta P_{\text{PV}}(t)$ will affect the capacity of $\text{SOC}_{\text{SC}}(t)$ and $\text{SOC}_{\text{Bat}}(t)$, and the SOC control of the energy storage needs to consider the change of $\Delta P_{\text{PV}}(t)$. Because the 2D fuzzy controller is limited by input and output, it cannot meet the multi-objective coordination requirements. Besides, it doesn’t consider the interaction between input variables, resulting in incomplete fuzzy control rules and low
control accuracy. In this paper, the two-dimensional fuzzy controller cannot achieve the multi-objective coordinated control scheme of HESS. So, a multi-variable fuzzy controller needs to be designed to coordinate control of multiple objectives.

There is no complete theory for the design of multivariable fuzzy controllers. The following figure shows the multivariable fuzzy controller designed according to the actual situation of this paper. Fuzzing is carried out with the inputs of \( \Delta P_{PV} \), \( SOC_{Bat} \) and \( SOC_{SC} \) as inputs, and the interaction effect between the inputs is introduced into the fuzzy control by using the fuzzy relation matrix, and the energy storage capacity of \( SOC_{Bat} \) and \( SOC_{SC} \) is measured by matrix operations to establish the fuzzy rule base. The fuzzy output result is obtained after the fuzzy rule, and the time constant \( T(t) \) of the low-pass filter is finally obtained after the fuzzy solution.

### 4.2 Input variable fuzzification

To increase the control accuracy, this paper quantifies based on dividing the \( \Delta P_{PV} \) interval in Table 1. Taking the domain of \( \Delta P_{PV} \) as \([-0.05 P_{PV}, 0.05 P_{PV}]\), the sampled values are quantized into 5 levels \{NB (Negative Big), NS (Negative Small), ZO (Zero), PS (Positive Small), PB (Positive Big)\}, and the Gauss distribution fuzzy relationship \( \Delta f_{\Delta P_{PV}} \) of \( \Delta P_{PV} \) is as follows Equations (12), the median of the Gauss membership function for each level are \{0.35, 0.5, 0.65\}, the corresponding function widths are \{0.4, 0.5, 0.4\}, and the membership degree is \( c \). Among them, the introduction of membership \( a, b, c \) aims to improve the flexibility of the membership function of fuzzy input variables, and its values \( x_i(i = 1, 2, 3, 4, 5) \). \( x_j(j = 1, 2, 3) \) and \( z_k(k = 1, 2, 3) \) are all \((0,1)\). For example, when \( \Delta f_{\Delta P_{PV}} = NS \), the output power variable \( \Delta P_{PV} \) of the PV power system is large, and the output power \( P_{PV} \) of the PV power system is low, and there is a power shortage. When \( \Delta f_{\Delta P_{PV}} = PB \), the output power variable \( \Delta P_{PV} \) of the PV power system is larger, the output power \( P_{PV} \) of the PV power system is higher, and there is excess power. At this time, the value of \( a \) is small, which is \( x_3 \).

\[
\begin{align*}
\Delta f_{\Delta P_{PV}} &= ZOa = x_3 & (12) \\
\Delta f_{SOC_{SC}} &= \begin{cases} 
  Lb = y_1 \\
  Mb = y_2 \\
  Hb = y_3
\end{cases} & (13) \\
\Delta f_{SOC_{Bat}} &= \begin{cases} 
  Lc = z_1 \\
  Mc = z_2 \\
  Hc = z_3
\end{cases} & (14)
\end{align*}
\]

### 4.3 Fuzzy rules and deblurring

The membership relationship of the above fuzzy input is represented by a matrix, and the interpolation is used to fill in 0 as a
fuzzy matrix with the same dimension.

\[
\begin{align*}
A &= [x_1, x_2, x_3, x_4, x_5] \\
B &= [y_1, y_2, y_3, y_4, y_5] \\
C &= [z_1, z_2, z_3, z_4, z_5]
\end{align*}
\]  

(15)

The weight coefficient is used to characterize the fuzzy relationship between the input from the higher level and the lower level, multiply \( A \) by the weight \( \gamma \) and dot-multiply the \( B \) matrix, and remove the "0" element to get the new fuzzy matrix \( \bar{B} \). Similarly, the fuzzy matrix \( C \) is added with the influence of \( \alpha \) and \( \beta \) to obtain the \( \bar{C} \) matrix. Therefore, the new input matrix considering the fuzzy relationship is as shown in Equation (16).

\[
\begin{align*}
\bar{A} &= [x_1, x_2, x_3, x_4, x_5] \\
\bar{B} &= [\gamma x_1 y_1, \gamma x_3 y_3, \gamma x_5 y_5] \\
\bar{C} &= [\alpha x_1 z_1 + \beta y_1 z_1, \alpha x_3 z_3 + \beta y_3 z_3, \alpha x_5 z_5 + \beta y_5 z_5]
\end{align*}
\]

(16)

In Equation (16): \( \gamma \), \( \alpha \) and \( \beta \) are weight coefficients, and their value range is \([0, 1]\). It can be seen that the above elements \( \bar{A} \), \( \bar{B} \) and \( \bar{C} \) have a value range of \((0, 1)\). Because the three variables have different magnitude classificatory, the new fuzzy input matrix doesn’t contain \( x_2 \) and \( x_4 \) terms. If \( \Delta P_{PV} \), \( SOC_{SC} \) and \( SOC_{Bat} \) are all quantized into 5 levels, adding too many fuzzy rules leads to complicated control. Therefore, the extreme values around \( x_1 \) and \( x_3 \) are taken to reflect the relationship between the superior and the subordinate, and the influence of missing items is ignored. Directly product the new fuzzy relation matrix \( \bar{A} \), \( \bar{B} \) to obtain the fuzzy rule matrix \( R_{AB} = \bar{A}\bar{B} \), the elements in \( \bar{A} \) and \( \bar{B} \) are shorthand as \( \bar{x} \) and \( \bar{y} \) to obtain Equation (17). From Equation (17), there are 15 fuzzy rules when only \( \Delta P_{PV} \) and \( SOC_{SC} \) or \( SOC_{Bat} \) are considered in the system. Rewrite the fuzzy matrix \( R_{AB} \) into a vector form \( \bar{R}_{AB} \) as in Equation (18):

\[
\begin{align*}
R_{AB} &= \begin{bmatrix}
(\bar{x}_1, \bar{y}_1) & (\bar{x}_2, \bar{y}_2) & (\bar{x}_3, \bar{y}_3) & (\bar{x}_4, \bar{y}_4) & (\bar{x}_5, \bar{y}_5)
\end{bmatrix} \\
\bar{R}_{AB} &= \begin{bmatrix}
(\bar{x}_1, \bar{y}_1) & (\bar{x}_2, \bar{y}_2) & (\bar{x}_3, \bar{y}_3) & (\bar{x}_4, \bar{y}_4) & (\bar{x}_5, \bar{y}_5)
\end{bmatrix} \\
\end{align*}
\]

(17)

\[
\bar{R}_{AB} = \begin{bmatrix}
(\bar{x}_1, \bar{y}_1) & (\bar{x}_2, \bar{y}_2) & (\bar{x}_3, \bar{y}_3)
\end{bmatrix}
\]

(18)

The elements in \( C \) are replaced with “\( z' \)”. According to the direct product operation, the fuzzy rule matrix \( \bar{R}_{ABC} = \bar{R}_{AB}\bar{C} \) is considered when the system considers the influence of the battery energy storage state. At this time, there are 45 fuzzy rules, combining the output relationship of the fuzzy controller, a control rule table such as Equation (19) can be generated.

\[
\begin{align*}
\bar{R}_{ABC} &= \begin{bmatrix}
(\bar{x}_1, \bar{y}_1) & (\bar{x}_2, \bar{y}_2) & (\bar{x}_3, \bar{y}_3)
\end{bmatrix} \times \begin{bmatrix}
\bar{z}_1 \\
\bar{z}_2 \\
\bar{z}_3
\end{bmatrix}
\end{align*}
\]

(19)

4.4 Accuracy verification of multivariable fuzzy controller

To verify the influence of the correlation between input quantities on the accuracy of fuzzy control, when setting \( SOC_{SC} = 0.5 \) or \( SOC_{Bat} = 0.5 \), the fuzzy controller only considers the influence of \( SOC_{Bat} \), only considers \( SOC_{SC} \) influence and \( SOC_{Bat} \) and \( SOC_{SC} \) simultaneously consider the three situations to conduct a comparative analysis, establish \( \Delta P_{PV} \), \( SOC_{SC} \) and \( SOC_{Bat} \) as X-axis or Y-axis, and de-fuzzy the result \( T(t) \) is the Z-axis of a 3D diagram. At this time, suppose the PV is 20 kW.

For example, when \( \Delta P_{PV} = 300 \) and \( SOC_{SC} = 0.5 \), the over-voltage, and the HESS need to store electrical energy. At times, the super-capacitor should be given priority to store energy, and the battery is in standby. Figure 4(a) shows the influence of \( SOC_{Bat} \) is not considered, the \( SOC_{SC} = 0.5 \) is maintained at about 0.5. Because of the rapidity of the super-capacitor charging instruction, it shows that the scheduling scheme is to charge the super-capacitor and the battery at the same time. Figure 4(b) considers the influence of \( SOC_{Bat} \), \( SOC_{SC} \) rises rapidly on the surface of \( \Delta P_{PV} = 300 \), and \( SOC_{Bat} \) remains unchanged, indicating that the scheduling scheme charges the super-capacitor while the battery is on standby. Therefore, after considering the influence of \( SOC_{Bat} \), the control result is consistent with the energy storage scheduling scheme, and the comparison of simulation results shows that considering the interaction
energy to provide certain buffer time for the battery when the power fluctuates. Therefore, the constraints of super-capacitors are as follows:

$$\begin{align*}
0.1 \leq SOC_{SC}(t) \leq 0.9 \\
|P_{SC, ch}(t)| \leq P_{SC}(t) \leq |P_{SC, dh}(t)|
\end{align*}$$  \hspace{1cm} (22)

In the above equation, $P_{bat, ch}(t)$ and $P_{bat, dh}(t)$ are the maximum charging power and discharge power of the battery under ignoring the self-discharge of the energy storage at time $t$. $P_{SC, ch}(t)$ and $P_{SC, dh}(t)$ are the maximum charging power and discharge power of the super-capacitor.

The inputs of the battery fuzzy controller and a super-capacitor fuzzy controller are $SOC_{Bat} \cdot SOC_{SC}$ and the required changes $\Delta SOC_{Bat} \cdot \Delta SOC_{SC}$ the next time, which adjusts the charge and discharges the power of the energy storage medium. The SOC of the energy storage medium is maintained in a reasonable state to respond to the next charge and discharge.

The detailed control strategies of the energy storage medium are as follows:

1. If $SOC_{SC}$ is appropriate, the super-capacitor charges and discharges normally as instructed.
2. If $SOC_{SC}$ is small and super-capacitor ready to discharge or $SOC_{SC}$ is big and super-capacitor ready to charge, the super-capacitor fuzzy controller performs adaptive control on super-capacitor and outputs a correction factor $k_{SC}$. Next, calculate the super-capacitor correction power $\Delta P_{SC}$ according to Equation (23), and finally calculate the super-capacitor suppressing power $P_{SC2}$.

$$\Delta P_{SC} = (1 - k_{SC}) P_{SC1}$$  \hspace{1cm} (23)

3. $P_{bat1}$ is corrected again according to the instruction difference $\Delta P_{SC}$ of charge and discharge of the super-capacitor to obtain the battery suppression power $P_{bat2}$. Battery fuzzy controller performs adaptive control on $SOC_{Bat}$ based on the same strategy, and outputs a correction factor $k_{Bat}$. Next, calculate the battery correction power $\Delta P_{bat}$ according to Equation (24). Finally, calculate the battery suppressing power $P_{bat3}$.

$$\Delta P_{bat} = (1 - k_{Bat}) P_{bat2}$$  \hspace{1cm} (24)

5 | VERIFICATION OF HESS FUZZY COORDINATED CONTROL ALGORITHM

5.1 | HESS fuzzy coordinated control algorithm

Fuzzy control algorithms are established according to the control process and rules to achieve real-time control of grid-connected power fluctuations of photovoltaic power systems. The power allocation process of HESS fuzzy control is shown in Figure 5.
To verify the practicability and effectiveness of the HESS fuzzy coordinated control algorithm, the paper takes the sampling data of the PV demonstration project of a division in Xinjiang on May 02, 2019, and the sampling interval of each data is 15 min. The installed capacity of the sub-station of the photovoltaic power station is 12.5 MW, and the load is about 10% of the installed capacity of the sub-station of the photovoltaic power station, and the highest temperature of the day was 21°C and the lowest temperature was 11°C. It was cloudy with northwest wind class 2. HESS parameters are shown in Table 2.

The output power of the PV power system and the output power after HESS stabilization are shown in Figure 6. Considering the amplitude change of the output power fluctuation of the PV power system and the sensitivity and efficiency of verifying the ESM charge and discharge instructions, the parameters of the super-capacitor and battery during the period of 10:00–12:00 on that day are taken. To easily observe of ESL power fluctuations, the sampling interval is the 30 s/time; other sampling intervals are 1 min/time.

Figures 6 and 9 show that HESS effectively suppresses grid-connected power fluctuations of PV power systems. Figure 9 shows the power change amount in the adjacent sampling period of a certain period. Figure 7 shows the SOC of ESM within the same sampling time interval. The change of battery SOC is not as drastic as that of super-capacitor SOC, and there is no SOC over-limit situation in EMS, indicating that the fuzzy coordinated control strategy bound the SOC of the EMS and optimizes the charge and discharge instructions of the battery and super-capacitor, and reasonably allocates the smooth fluctuation power of the battery and super-capacitor. Figure 8 and Table 3 shows EMS power fluctuations. In Figure 8, the super-capacitor is charged and discharged 214 times and the battery is charged and discharged 147 times during the sampling period, indicating that the super-capacitor can be operated alone when its SOC is reasonable, and independently assume the suppression target. At this time, the power of the battery is buffered or standby, which effectively reduces the number of charge and discharge of the battery and extends the working life of the battery.
Table 3 is a comparison of the output power of the PV power system before and after stabilization. It can be obtained that HESS has a significant effect of stabilizing the output power of the PV power, which can effectively suppress the fluctuation of grid-connected power.

### Table 3 Comparison of the output power of the PV power system before and after HESS stabilization

| Parameter type     | Max power change rate (MW/(1 min)) | Total power change rate (MW/(1 min)) |
|--------------------|------------------------------------|-------------------------------------|
| Suppress before    | 7.96                               | 39.91                               |
| Suppress after     | 6.67                               | 13.94                               |
| Drop percentage (%)| 16.21                              | 65.07                               |

1. Establish a fuzzy controller to modify and optimize the power distribution of a hybrid energy storage system, effectively improve the fluctuation of the grid-connected PV power system, the change rate of the maximum power change rate of the HESS to the PV grid-connected power system is 16.21%, and the power change rate is reduced to 65.07%, which effectively reduces the unbalanced power of supply and demand and makes the overall grid-connected power of the system smoother.

2. According to HESS’s current SOC and grid-connected power fluctuations of the PV power system, fuzzy control is used to optimize the power distribution of the HESS system. The multivariable fuzzy controller is established to adjust the time constant of the low-pass filter in real-time, accurately track the power change of the PV power system, and improve the power distribution efficiency among different energy storage.

3. The supercapacitor fuzzy controller battery and fuzzy controller are designed to control the charge and discharge power of the energy storage, and the corrected power after the distribution is calculated. The paper takes the minimization of the fluctuation power outside the target after the suppression and the maximization of the energy storage as the optimization goal to suppress the power fluctuation at the next working time. And the charging and discharging power of the energy storage is optimized under the constraint conditions of the instantaneous power balance and charge and discharge limitation of the energy storage. Reduce the charge and discharge times of battery and extend its service life.

4. In the future work, the HESS studied should consider the filter coefficient optimization problem of the first-order low-pass filter, to adapt to the more complex load changes affecting the stability of the grid-connected power of the system, and the experimental prototype of the HESS will be developed.

### NOMENCLATURE

- $P_{\text{ESS\_lim}}(t)$: The maximum allowable charge-discharge power of the energy storage medium at the time $t$.
- $P_{\text{Bat\_lim}}(t)$: The maximum charge-discharge power of the energy storage medium at the time $t$.
- $\sigma_{\text{sd}}$: The self-discharge rate of the energy storage medium.
- $\eta_{\text{C}}$: The charge efficiencies of the energy storage medium.
- $\eta_{\text{D}}$: The discharge efficiencies of the energy storage medium.
- $\Delta t$: The calculation time for each sample.
- $E_{\text{max}}$: The energy storage medium power constraints the upper limit.
- $P_{\text{HESS\_lim}}(t)$: The maximum charge-discharge power allowed by the HESS at time $t$.
- $P_{\text{SC\_lim}}(t)$: The maximum charge-discharge power of the super-capacitor at time $t$. 
\( P_{\text{Bat lim}}(t) \) The maximum charge-discharge power of the battery at time \( t \).

\( T(t) \) The LPF filter's time constant at time \( t \).

\( P_{\text{ref}}(t) \) The suppress target power of HESS at time \( t \).

\( \Delta P(t) \) Suppress the fluctuating power outside the target at time \( t \).

\( \lambda(t) \) The filter coefficient at time \( t \).

\( P_{\text{PV}}(t) \) The power of the PV system at time \( t \).

\( P_{\text{total}}(t - 1) \) The output power after suppress at time \( t - 1 \).

\( k_1 \) The proportional coefficient when \( \Delta P(t) \geq 0 \).

\( k_2 \) The are proportional coefficient when \( \Delta P(t) < 0 \).

\( U_{\text{PV}} \) The output voltage of the PV system [V].

\( I_{\text{PV}} \) The output current of the PV system [A].

\( P_{\text{PV}} \) The output power of the PV system [W].

\( P_{\text{Load}} \) The load power [W].

\( P_{\text{HESS}} \) The power assumed by HESS [W].

\( \text{SOC}_{\text{bat}}(t) \) The SOC of the battery at time \( t \).

\( \text{SOC}_{\text{SC}}(t) \) The SOC of the super-capacitor at time \( t \).

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