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Hybrid Energy Storage Power Allocation Strategy for Stabilizing Wind Power Fluctuations

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Abstract: In order to solve the problem of energy shortage, renewable energy such as wind power has developed rapidly worldwide. However, due to its time-varying and uncertain nature, wind power is prone to local fluctuations and operational safety hazards when connected to the power grid. In response to the stable grid connection problem of wind power generation, a hybrid energy storage system is proposed A method was proposed to achieve smooth power fluctuations in wind power generation using a model, and a charging and discharging control and allocation method for energy storage was proposed. Firstly, the preliminary power of hybrid energy storage was obtained using the model predictive control method, Then, an adaptive variational mode decomposition method was used to achieve energy distribution between batteries and supercapacitors. Finally, the measured data of a 100MW wind power plant in Xinjiang was analyzed as an example. The proposed method has been validated to not only achieve reasonable power allocation between hybrid energy storage systems, but also effectively reduce the impact of wind power generation on the power grid, achieving long-term safe operation of hybrid energy storage systems.

Keywords: Mixed Energy Storage; Model Predictive Control; Variational Mode Decomposition; Wind Power Stabilized; Wind Power Consumption.

1. Introduction

The development and utilization of renewable energy from wind energy and solar energy is an effective way to solve the energy problem. However, due to the influence of weather, climate and terrain, wind energy has strong time variability and does not have damping characteristics [1-2]. With the continuous growth of the grid connected capacity of wind power and the continuous growth of the grid connected capacity of wind power, it is easy to cause adverse effects such as local fluctuations and operation safety hazards when connecting to the grid [3]. The real-time charging and discharging characteristics of energy storage are used to solve the fluctuation of wind power and reduce the impact of grid voltage and frequency changes caused by wind power integration [4]. Using energy storage to enhance the stability of wind power output is of great significance for the stable grid connection of wind power [5].

At present, there has been a lot of discussion and research on the suppression of wind power generation both domestically and internationally. In terms of energy storage, the most commonly used method is to combine power-based energy storage with energy-based energy storage, using power-based energy storage to suppress high-frequency and low amplitude fluctuations with low energy and rapid changes, and utilizing energy-based energy storage. It is achieved by suppressing low-frequency and high-amplitude fluctuations with high energy and slow changes, fully compensating for the shortcomings of a single type of energy storage, and achieving better smooth performance of wind power generation [6-8]. There are various wind suppression power control algorithms and strategies for energy storage. Zhang Qing [9] and others used the sliding average filtering method to obtain the initial power of energy storage, and then decomposed the frequency division points of composite energy storage through empirical mode decomposition, aiming to achieve the highest net efficiency and achieve wind power suppression fluctuations. However, there is a phenomenon of pattern mixing in the empirical mode decomposition method, which often requires secondary allocation of power. Zhang Baoming [10] and Zhang Peng [11] used an allocation method based on wavelet packet decomposition to suppress the frequency division of wind power generation power, and combined with fuzzy control methods to develop charging and discharging strategies for energy storage systems. Jiang Xiuming [12] uses a first-order low-pass filtering method to suppress wind power fluctuations, and designs a cloud model controller to adjust the filtering time constant T0 in real-time to control the output power of the energy storage system. Chi Yongxin[13] uses an average sliding filtering method to smooth the wind power curve, After filtering the interference power, the frequency division power is determined through empirical mode decomposition method, and the high and low frequency power is respectively allocated to flywheel energy storage and lithium battery energy storage. The above filtering methods are relatively common and easy to implement. Not sensitive to fluctuations in wind power generation, and real-time control of wind power generation has certain limitations

In view of the above problems, the author proposes a wind power fluctuation stabilization strategy based on hybrid energy storage. Firstly, the model predictive control algorithm is used as the stabilizing control method, and the energy storage output and charge discharge balance are taken as the objectives. Under the condition of meeting the fluctuation rate of wind power grid connection, the state of charge and charge discharge power of energy storage are considered to realize the real-time optimization of wind power fluctuation stabilization and reduce the impact of grid connected power. Secondly, in the internal energy management and power allocation of the hybrid energy storage system, the frequency division of the initial power of the hybrid energy storage system is realized by the adaptive reconstruction of the components through the variational mode decomposition. Finally, the feasibility and effectiveness of the proposed method are verified by analyzing the measured data of a

100MW wind farm.

2. Construction of a Model for Suppressing Fluctuations in Wind Storage Systems

A wind power hybrid energy storage and generation system is composed of two parts: a wind power generation system consisting of a doubly fed wind turbine and its converter, and a hybrid energy storage system consisting of supercapacitors, batteries, and control systems. The grid connection structure diagram is shown in Figure 1, It can be seen that the wind power ultimately integrated into the power grid is determined by the power output of the wind power generation system and the output of energy storage that is integrated into the AC bus. In the selection of hybrid energy storage systems, both lead-acid batteries and supercapacitors are connected in parallel to the DC/DC converter and connected to the DC bus, improving the reliability of the system.

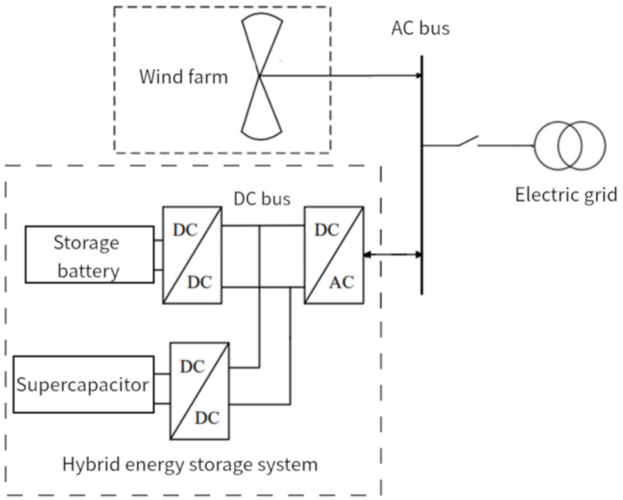


Fig 1. Grid connection structure diagram of wind storage hybrid system

After adding energy storage to the wind farm, when the actual wind power of the wind power system is surplus, the energy storage system can absorb power and store it in the energy storage system to reduce wind power. When the wind power is insufficient, the energy storage system can release power to increase wind power, reducing the fluctuation rate of wind power before and after grid connection, making wind power more stable and integrated into the grid, avoiding local fluctuations in the system.

The storage capacity of batteries is high and the cost is low, but the response speed of batteries is slow and not suitable for fast charging and discharging and frequent state transitions, making them more suitable for bearing low-frequency power fluctuations in energy storage systems. And supercapacitors have fast response speed and their service life is not affected by frequent charging and discharging. However, their low storage capacity and high cost make them more suitable for bearing low-frequency power fluctuations in energy storage systems. The hybrid energy storage system combines the respective advantages of batteries and supercapacitors, and achieves internal energy distribution through converter control to jointly complete the task of suppressing fluctuations, which can improve the system's economy and enhance the response effect of suppression.

3. Optimal Control of Energy Storage to Suppress Fluctuations

Consider the prediction error of wind power before conducting energy storage to suppress fluctuations. After compensating for the wind power, perform flattening processing to obtain the relationship between the wind power before flattening and the state of charge of energy storage.

$$\frac{|P_w(k)-P_y(k)|}{P_w(k)}<\varepsilon \tag{1}$$

$$SOC_1(k)=SOC(k-1)+\frac{T\times P_1(k)}{E} \tag{2}$$

where, $P_w(k)$ represents the predicted power of the wind farm at that time; $P_y(k)$ represents the actual power of the wind farm at that time; ε is the allowable prediction error for wind farms; $SOC_1(k)$ is the state of charge when compensating for prediction errors in energy storage at time k; $SOC(k)$ represents the state of charge during the joint optimization of energy storage at time k; T represents the control period of energy storage; $P_1(t)$ is the power of energy storage compensation prediction error; E is the rated capacity of energy storage.

The relationship between the grid connected power of wind power and the power before wind farm suppression, energy storage power, and state of charge is as follows:

$$P(k+1)=P_{wy}(k)-P_2(k) \tag{3}$$

$$SOC(k)=SOC_1(k) \tag{4}$$

$$SOC(k+1)=SOC(k)+\frac{T\times P_2(k)}{E} \tag{5}$$

where, $P(k+1)$ is the grid connected power at time k+1; $P_{wy}(k)$ is the wind power after the wind farm compensates for the prediction error at time k; $P_2(k)$ is the charging and discharging power for energy storage to suppress fluctuations; $SOC(k+1)$ is the state of charge at time k+1.

3.1. Suppression based on Model Predictive Control

The model predictive control algorithm predicts the future state in advance based on the current state and input of the energy storage system during each optimization cycle, and the rolling optimization of future energy storage generates power to achieve real-time control of wind power.

3.1.1. State Space

Objective function:

The objective function is to optimize the energy storage output and charge discharge balance in the future time domain. The expression of the objective function is as follows.

$$J=\min\sum_{i=0}^{M-1}P_2^2(k+i)+\sum_{i=1}^{M}SOC_2^2(k+i) \tag{6}$$

where, the two terms in the equation are the sum of squares of the energy storage output and the offset of the energy storage state of charge, M is the predicted time length.

Constraints:

After establishing the objective function, it is necessary to consider the charging and discharging capacity of energy storage, set charging and discharging power constraints, consider preventing the charging and discharging of energy

storage from exceeding its actual capacity, set capacity constraints for energy storage, and consider grid connection requirements to set fluctuation rate constraints. Finally, the solution is combined with constraint conditions.

$$-P_{\max} \le P_2(k+i) \le P_{\max} \tag{7}$$

$$SOC_{\min} \le SOC_2(t) \le SOC_{\max} \tag{8}$$

$$\frac{|P(k+i+1)\text{-}P(k+i)|}{P_{\text{rate}}} \le \delta \tag{9}$$

where, $P_{\max}$ is the maximum allowable charging and discharging power of the energy storage system; P_{rate} is the rated capacity of wind power; δ is the limit value for the fluctuation rate of wind power grid connection.

Set state variables $x_1(k)$ as grid connected power $P(k)$, $x_2(k)$ as energy storage to suppress state of charge $SOC_2(k)$, control quantity $u(k)$ is the energy storage charging and discharging power $P_2(k)$, wind farm actual power $P_y(k)$ as disturbance $r(k)$.The state space equation of the wind power system containing energy storage is:

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} -1 \\ \frac{T}{E} \end{bmatrix} u(k) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} r(k) \tag{10}$$

Be written as: $A = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$、$B = \begin{bmatrix} -1 \\ \frac{T}{E} \end{bmatrix}$、$C = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

3.1.2. MPC based Control Process

According to the state space model in 2.1.1, model predictive control is applied to the wind storage joint system. The rolling optimization process is shown in Figure 2, with the following steps:

Step 1: Initialize the parameters and verify that the length of the selected optimization interval is 5.

Step 2: Based on the objective function (6) and constraint conditions (7), (8), and (9), iteratively optimize the hybrid energy storage control instructions within the future optimization time interval, and solve for the corresponding optimal energy storage control sequence.

Step 3: Apply the first value of the optimal energy storage sequence to the hybrid energy storage system.

Step 4: Scroll to the next moment, update the system status, including SOC state variable values and grid connected power values, and then repeat the above steps.

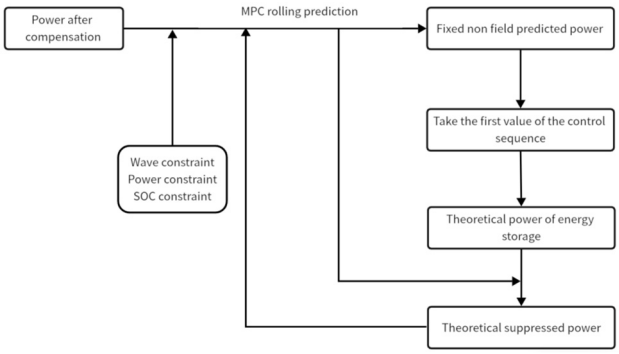


Fig 2. MPC Rolling Optimization Diagram

4. Energy Management of Energy Storage Systems

Variational modulus decomposition is a signal decomposition and estimation method [14]. By iteratively searching for the optimal solution of the variational model, the frequency center and bandwidth of each component can be determined during the process of obtaining decomposed components, thereby achieving adaptive frequency domain division of the signal and effective separation of each component [15].

$$U(t) = P_1(t) + P_2(t) \tag{11}$$

$$\begin{cases} \max \limits_{\{u_k\},\{\omega_k\}} \left\{ \sum \limits_{k=1}^{N} \| \partial \left[\left(\delta(t) + \frac{j}{\pi t} \right) u_k(t) \right] e^{-j\omega_k t} \|_2^2 \right\} \\ \text{s.t.} \ \sum \limits_{k=1}^{N} u_k(t) = U(t) \end{cases} \tag{12}$$

where, $U(t)$ represents the total charging and discharging power of the original energy storage to be decomposed, $\{u_k\} = \{u_1, u_2, ..., u_k\}$, $\{\omega_k\} = \{\omega_1, \omega_2, ..., \omega_k\}$, The superscripts and subscripts in $\| \|_2^2$ represent the square and L2 norm, respectively.

In order to stabilize the super capacitor with high frequency and low amplitude fluctuation and the battery with low frequency and high amplitude fluctuation, an adaptive reconstruction method of VMD component is proposed. That is, during VMD component reconstruction, different reconstruction ranges are selected for each component at each time. Where k represents the number of components required to reconstruct low-frequency components. In the reconstruction process, if the amplitude of the high-frequency component is greater than that of the low-frequency component, the K value is increased. The formula of high and low frequency reconstruction is:

$$u_L(t) = \sum_{k=1}^{K} u_k(t) \tag{13}$$

$$u_H(t) = \sum_{k=K+1}^{N} u_k(t) \tag{14}$$

where, $u_k(t)$ is the k-th component of the compensation power decomposed by VMD at time t, $u_H(t)$、$u_L(t)$ are the high and low frequency components of the compensation power for initial reconstruction at the time.

However, the above VMD component reconstruction method is not accurate because the inaccurate selection of VMD decomposition quantity N can lead to excessive decomposition of the original signal, and the sum of the high and low frequency components reconstructed by VMD components is smaller than the amplitude of the original signal. However, these reconstructed high and low frequency components are multiples of the mixed energy storage capacity. As a basis for the value, if the decomposition is not accurate and the energy storage capacity configuration is not accurate, it cannot effectively suppress wind power fluctuations. Therefore, the reconstruction process is adjusted to: If excessive decomposition occurs, adjust the high-frequency component value to the same value as the original signal width, and reconstruct the VMD component by subtracting the adjusted low-frequency component of the adjusted high-frequency component from the original signal to solve the problem of different widths from the original signal.

$$P_L(t) = \sum_{k=1}^{K} u_k(t) + (P(t) - \sum_{k=1}^{K} u_k(t) - \sum_{k=K+1}^{N} u_k(t)) = U(t) - u_{H1}(t) \tag{15}$$

$$P_H(t) = u_{H1}(t) \tag{16}$$

where, $u_{H1}(t)$ is the adjusted high-frequency component; $P_L(t)$ is the low-frequency component of the compensated power at time t; $P_H(t)$ is the high-frequency component of the compensated power at time t.

5. Example Analysis

Select the measured wind power data of a 100MW wind power plant in Xinjiang in 2019, and select the day with the highest standard deviation of volatility for sampling. The sampling period is 15 minutes. Figure 3 shows the actual power of the wind power plant in one day and the power predicted through neural networks.

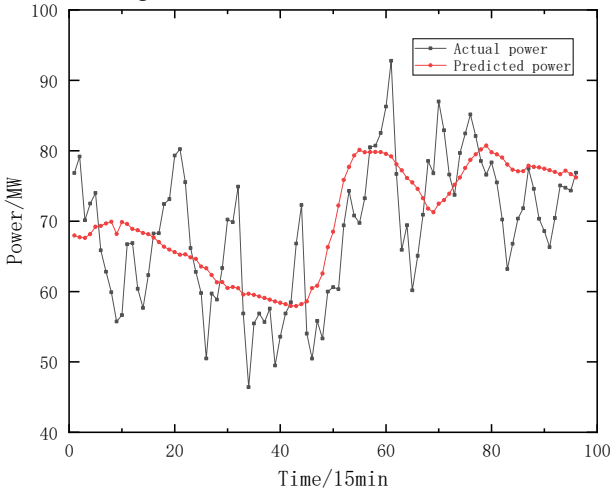


Fig 3. One day power curve of wind farm

According to the constraints of equations (1) and (9), set the target prediction error to be less than 10% and the target volatility to be less than 3%. The theoretical rated capacity of energy storage is 48MW · h, with an upper limit of 0.9 and a lower limit of 0.1 for the SOC state of energy storage. Based on the above model parameter settings, the quadratic programming method of MATLAB is used to optimize the MPC objective function and constraint function determined by equations (6) - (10) within each control cycle. Through this optimization process, the effect of hybrid energy storage on compensating error scope, suppressing fluctuation scope, and the total scope of the combination of the two is obtained.

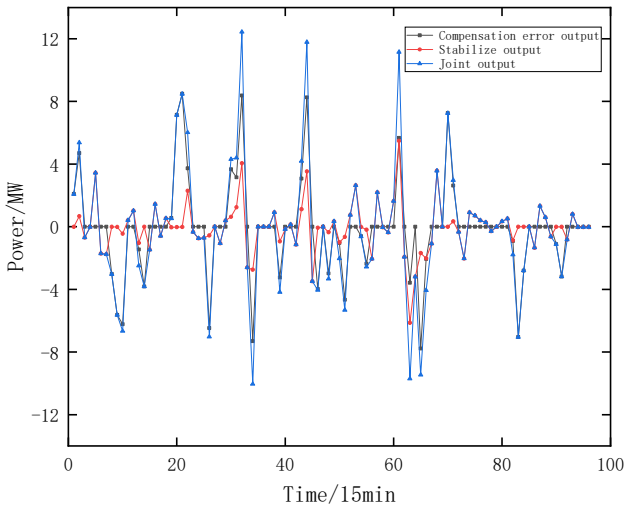


Fig 4. Energy storage scope

From Figure 4, it can be seen that the output power curve of the hybrid energy storage system frequently fluctuates around 0. If a single lead-acid battery is used for energy storage, frequent charging and discharging may shorten the battery's service life. Adding supercapacitors to the hybrid energy storage system can assist in absorbing high-frequency fluctuations in wind power.

The initial scope of energy storage obtained is allocated to the battery and supercapacitor through adaptive variational mode decomposition. Figure 5 shows the IMF obtained through VMD decomposition, and Figure 6 shows the final frequency division result adjusted by adaptive variational mode decomposition.

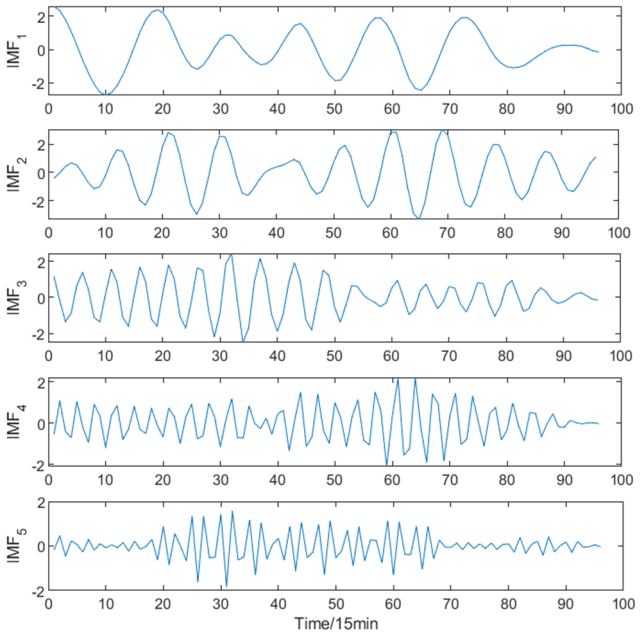


Fig 5. IMF obtained from VMD decomposition

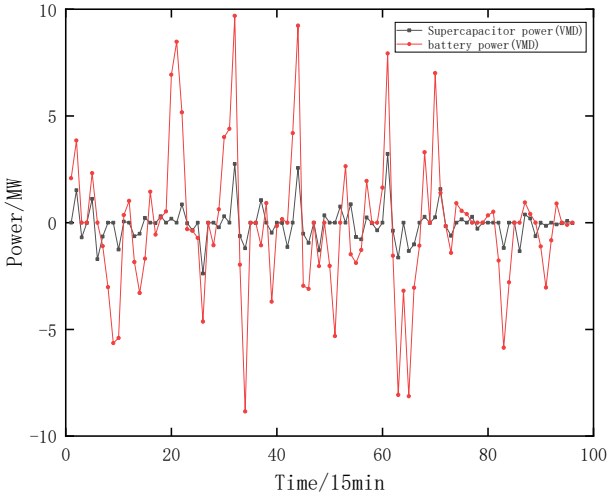


Fig 6. Frequency division power obtained by VMD

In order to verify the superiority of VMD algorithm, it was compared with traditional low-pass filtering algorithm in energy allocation of hybrid energy. Comparing the power allocation results in Figure 6 and Figure 7, the low-pass filtered power instructions in Figure 6 indicate that the battery is basically in a stationary state. The initial power command value of the supercapacitor far exceeds the power command value decomposed by VMD in Figure 7, which means that the output command of the supercapacitor exists throughout the entire frequency band. If the cut-off frequency of the low-pass

filter is incorrectly selected, hysteresis phenomenon will occur, leading to long-term overcharging or discharging of the supercapacitor, greatly reducing its efficiency, because it cannot achieve good economic benefits.

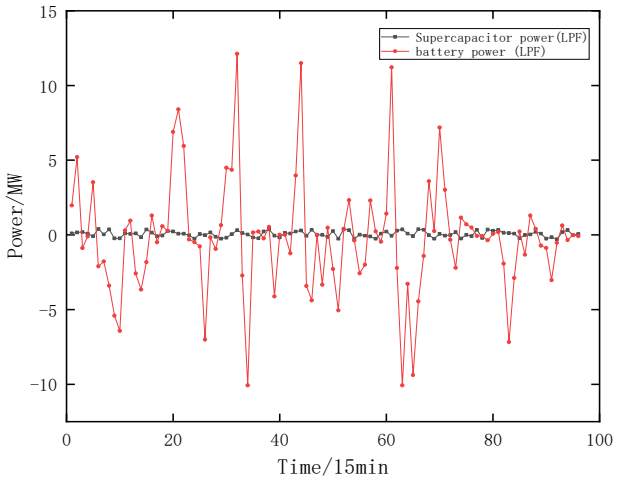


Fig 7. Frequency division power obtained by LPF

On the other hand, the energy storage power output decomposed by VMD in Figure 6 conforms to the performance characteristics of battery and super capacitor: battery energy storage is suitable for suppressing power with low frequency and high amplitude, and super capacitor is more suitable for withstanding power fluctuations with high frequency and low amplitude in the system.

By mixing the total charging and discharging power of energy storage, the wind power curve is flattened, and the flattened wind power effect is shown in Figure 8.

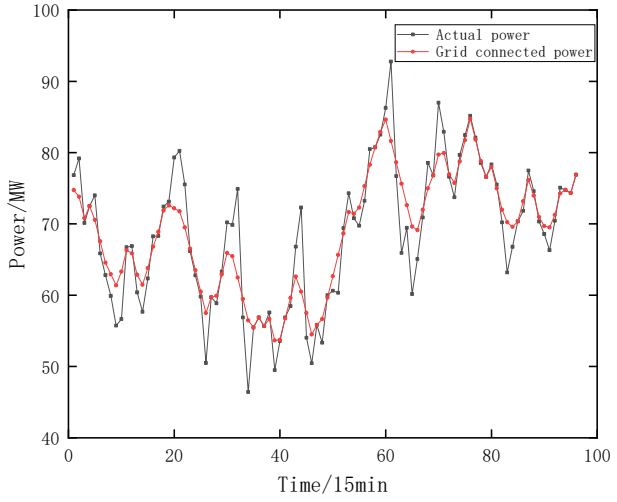


Fig 8. Actual wind power and grid connected power

From Figure 8, it can be seen that the maximum fluctuation rate of the flattened grid connected power curve is 3%. Compared with the fluctuation rate of the original wind power curve, the flattened grid connected fluctuation rate has decreased by 13%.

6. Conclusion

When wind energy is integrated into the power grid, its randomness and variability pose safety hazards to the stability and reliability of the grid operation. Energy storage systems can compensate for fluctuations and intermittency in renewable energy generation such as wind energy, in order to facilitate power adjustment and control, and reduce the impact on the power quality of the grid.

Taking a 100MW wind farm as an example, the initial scope of energy storage is determined by combining prediction error and fluctuation rate limitations. The energy storage power is decomposed into low-frequency and high-frequency parts through adaptive VMD algorithm to achieve reasonable allocation of battery and supercapacitor power. The energy storage control sequence command is obtained by combining the model predictive control algorithm to suppress wind power. The proposed control method has been validated through MATLAB simulation to reasonably allocate the power of hybrid energy storage, suppress the output power of wind farms, and reduce the impact of wind power on the power grid. Further research will be conducted on the capacity and power configuration of energy storage devices that meet economic operation indicators.

Acknowledgments

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