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Target Power Determination for Real-time Stabilization of Grid-Connected Offshore Wind Power Fluctuation

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***Abstract*—This study mainly studies the calculation method of target power in the real-time stabilization strategy of power generation fluctuation of offshore wind farms so that the active power of wind power after stabilization meets the power fluctuation rate limit of two different time scales in the grid connection requirements. Among them, the wind power stabilization effect is mainly determined by the filter coefficient in the filter algorithm, and the time scale of wind power regulation is 1 second, which limits the play of the intelligent algorithm. This paper proposes a method to adaptively adjust the filter coefficient through updating the wind power generation fluctuation limit in a 1-minute time scale for different time scales. The proposed solution is evaluated through simulation experiments using MATLAB through a comparison with the low-pass filter algorithm. The performance results confirmed that the low-pass filter algorithm with adaptive adjustment of filter coefficient proposed in this work performs well in both the wind power stabilization effect and the reduction of energy storage consumption.**

Keywords-grid-connected operation; offshore wind farm; wind power stabilization; target power; power quality

I. INTRODUCTION

Offshore wind power booms around the world with the development of sustainable energy. The prediction of the International Renewable Energy Agency (IRENA) shows that offshore wind power is expected to maintain a high-speed development trend in the future, and the world's installed capacity of offshore wind power will reach 1000 GW in 2050. From the perspective of the world's offshore wind power construction and planning, the far-reaching sea areas with an offshore distance of more than 100 km and a water depth of more than 50 m have more abundant sea areas and wind energy resources. European offshore wind power technology powers represented by Germany and Britain have taken the lead in laying out far-reaching offshore wind power. Compared with the existing land-based wind farms, offshore wind farms are considered more complicated due to the difficulties of connection and transmission from the engineering perspective. The farther the offshore distance is, the higher the cost of the grid-connected transmission project, and different grid-connected transmission schemes will also affect the income of the project. To enhance the grid connection and transmission economically and efficiently has become one of the core challenges faced by offshore wind power construction.

At present, offshore wind turbines generally operate in the maximum wind energy capture mode, and the output power of wind power is mainly determined by the real-time wind speed. With the increase of wind power installed capacity and wind power penetration rate, the randomness, unpredictability and volatility of wind power itself will lead to the random fluctuation of wind power, which may have a great impact on the power quality (including voltage and frequency) and grid dispatching of the existing large power grid when it is connected to the grid (e.g., [1], [2]).

This study exploits the hybrid energy storage system consisting of battery-based storage and supercapacitors for the stabilization of fluctuated wind power generation. Due to the characteristics of the energy storage battery and the super-capacitor, the power fluctuations of wind power are coordinated and suppressed at two different time scales, i.e. 1-minute and 30-minute. The second problem is the charge and discharge control strategy of the hybrid energy storage system. Since the charge and discharge of the energy storage system itself have certain limitations, it may not be able to provide power according to the wind power stabilization requirements during operation. According to the state of the energy storage system itself, the charge and discharge process should be adjusted. At present, many people have studied it. In [3], the formulation of real-time control and management of the energy storage battery considered the state of charge of the energy storage battery. The output power of energy storage can be adjusted in a real-time fashion that meets the requirements. However, since the control strategy is based on wind power planned a few days ago, errors are easy occur in real-time control and affect the effect. The authors in [4] proposed a planning solution to identify the optimal capacity of the battery energy storage system (BESS) in the presence of offshore wind farms. In general, the operational objectives mainly include the battery cost and lifetime, availability of wind turbines (WTs), loss of load hour (LOLH), and expected energy not supplied (EENS) as well as the curtailment of wind energy. The work in [5] studied the real-time control strategy of the hybrid energy storage system, and the reduction of energy loss of the energy storage system is included in the optimization objective to extend the life of the energy storage battery. However, this method has only studied the internal working conditions of the hybrid energy storage system and has not combined it with the actual wind power stabilization application.

To this end, this work exploits the calculation method of target power in the real-time fluctuation stabilization strategy of wind power generation, so that the active power of wind power after stabilization meets the power fluctuation rate limit of two different time scales in the grid connection requirements.

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The rest of the work is organized as follows: Section II firstly overviews the system architecture and formulates the problem; Section III presents the proposed solution of calculation method of target power in the real-time stabilization strategy of wind power fluctuation. Section IV carries out the simulation experiments and presents the numerical results. Finally, the work is concluded in Section V.

II. SYSTEM ARCHITECTURE AND MODELS

In this work, a low-pass filter algorithm with adaptive adjustment of the filter coefficient is proposed to determine the target power of the wind generation that meets the constraints of power generation functions at two different time scales. The structure of the wind farm system connected with the power grid is illustrated in Figure 1, consisting of an offshore wind farm and a hybrid energy storage system with a battery and supercapacitor.

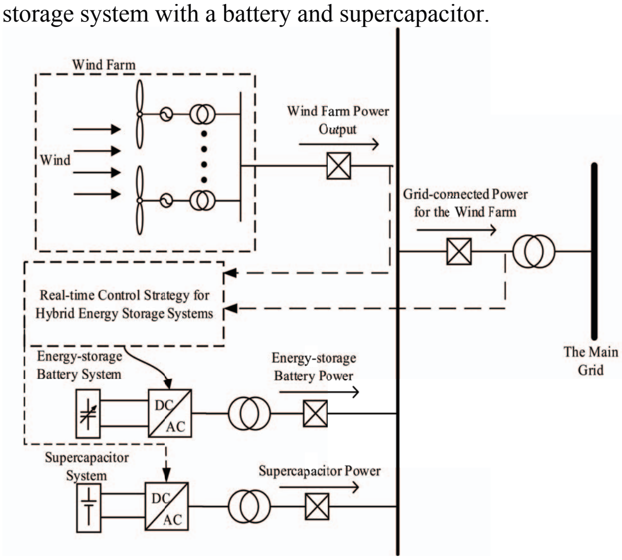

Figure 1. The offshore wind farm with a hybrid energy storage system

In practice, the wind farm is generally connected by several wind turbines according to a certain topological structure. The output power of all wind turbines is the real-time output power of the wind farm, denoted as P_W^t, wherein the real-time output power of the wind turbine P_w can be generated by the real-time wind speed, as given in (1).

$$P_w = \begin{cases} 0, & v < v_{ci}, v > v_{co} \\ \dfrac{v^3}{{v_N}^3 - {v_{ci}}^3} * P_N - \dfrac{{v_{ci}}^3}{{v_N}^3 - {v_{ci}}^3} * P_N, & v_{ci} \le v \le v_N \\ P_N, & v_{ci} \le v \le v_N \end{cases} \quad (1)$$

Where, P_N is the rated power of a wind turbine, v is the real-time wind speed, v_{ci} is the cut-in wind speed of the wind turbine, v_{co} is the cut-out wind speed of the wind turbine, and v_N is the rated wind speed of the wind turbine.

The hybrid energy storage system in the wind farm is composed of an energy storage battery and supercapacitor. As an energy buffer device, it can reduce the fluctuation of the output active power of the wind farm and make the real-time grid-connected active power of the wind farm P_O^t meet the grid-connected index. The real-time power of the energy storage battery P_B^t and the real-time power of the supercapacitor P_{SC}^t is determined by the real-time control strategy of the hybrid energy storage system and are obtained by controlling the charging and discharging of the energy storage battery and the supercapacitor through the DC/AC power converter. The real-time output power of the hybrid energy storage system is combined with the initial output power of the wind farm to obtain the grid-connected power of the wind farm, which is connected to the large power grid.

The real-time control solution based on the hybrid energy storage system is studied to determine the real-time target power of wind power that meets the active power requirements of wind power grid connection, to determine the real-time power that the hybrid energy storage system needs to provide.

III. PROPOSED SOLUTION

A. Generation fluctuation rate

Here, the wind farm is considered to be connected to the bulk power grid. Thus, the active power generation fluctuation is the main concern that needs to be addressed. The following describes the definition of active power fluctuation in different time scales of wind power. In this paper, the sampling time is 1s, and it is defined that the fluctuation rate of wind power active power in 1 minute in the *t-th* second is the ratio of the difference between the maximum power and the minimum power and the rated power of the wind farm in the one minute time window ending at the time of T-second, as given in (2):

$$\Delta P_{o,1\min}\%(t) = (\max(P_o^s) - \min(P_o^s)) / P_r, s \in \{t, t-1, ..., t-59\} \quad (2)$$

Wherein, P_o^s represents the wind power sampling value within the one-minute time window and P_r is the rated wind farm power generation. The fluctuation rate of wind power active power in 30 minutes of the *t-th* second is defined as the ratio of the difference between the maximum and minimum average power per minute and the wind farm rated power in the 30-minute window ending at this second, as shown in (3):

$$\begin{cases} \Delta P_{o,30\min}\%(t) = (\max(P_{o,1\min}^s) - \min(P_{o,1\min}^s)) / P_r, s \in \{1, 2, .., 30\} \\ P_{o,1\min}^s = \dfrac{\sum_{j=t-60*s+1}^{t-60*(s-1)} P_o^j}{60} \end{cases} \quad (3)$$

Where $P_{o,1\min}^s$ is the average power at the s minute within the 30-minute time window. From the definition of 30-minute wind power fluctuation, 30-minute power fluctuation is accumulated by 1-minute power fluctuation. Therefore, when determining the target power of wind power stabilization, the constraint of 1-minute wind power fluctuation in grid-connection requirements needs to be first met before the consideration of the 30-minute wind power fluctuation.

However, the target power is constrained by the wind power fluctuation of 1 minute and 30 minutes at the same time. Once the constraint of 1-minute fluctuation is well met, the power fluctuation of 30 minutes may not be satisfied in reality. When adjusting the filter coefficient, if the 1-minute wind power limit can be reset through the previously existing data to obtain a reference that can make the 30-minute wind power fluctuation in this second meet the limit, the problem of determining the filter coefficient can be solved.

B. *Multi-timescale power fluctuation characteristics*

When the filter algorithm is applied to wind power stabilization, it is mainly to determine the target power of wind power stabilization by changing the filter coefficient, so that the wind power fluctuation after the stabilization meets the constraints of 1 minute and 30 minutes. It can be seen that the fluctuation of wind power output power in 1 minute and 30 minutes is related to each other and affects each other. Since the 1-minute and 30-minute time windows are moving, to meet the fluctuation limit, it can be found that the 30-minute power fluctuation rate $\Delta P_{o,30\min}\%(t)$ after wind power filtering in this second has a great influence on the one-minute wind power fluctuation rate in the next second $\Delta P_{o,1\min}\%(t+1)$. The relationship between them is illustrated in Fig. 2.

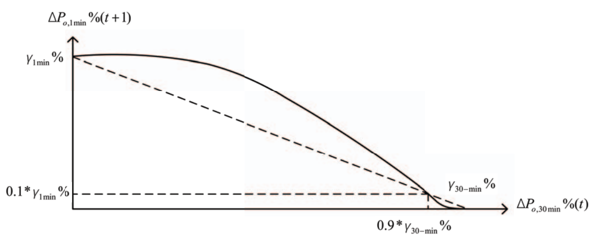

Figure 2. Fluctuation relationship of wind power at two different time scales at adjacent times

The 30-minute power determined according to the target power after the wind power is stabilized in this second can determine the 1-minute fluctuation reference value of the wind power target power in the next second, thereby determining the reference value of the low-pass filter coefficient. Where, $\gamma_{1\min}\%$ and $\gamma_{30\min}\%$ are the maximum values of wind power fluctuation rate in 1 minute and 30 minutes respectively specified in the wind power grid connection standard, then the wind power stabilization target power must meet the fluctuation limits in 1 minute and 30 minutes. Therefore, it is improved as described by the solid line in Figure 3, and gentle treatment is carried out near the limit value. This wind power fluctuation relation curve links the fluctuation at the adjacent time when the generation is stabilized that can be used as a reference for the implementation of the real-time adjustment of the filter coefficient.

C. *Wind power real-time stabilization strategy*

In the real-time stabilization of wind power active power, the main methods are the average value method, the average moving method including the simple average moving method and exponential average moving method, the low-pass filtering algorithm, etc. Among these methods, a low-pass filter is the most widely used control algorithm at present. It has the greatest flexibility and can adjust the filter coefficient in real-time according to the required smoothing effect.

The time scale of active power fluctuation limit of wind power studied in this paper is 1 minute and 30 minutes. Due to the randomness of wind power output power, to effectively limit the fluctuation of wind power within one minute, the sampling period of wind power is selected as 1s. At the same time, because the current short-term prediction error of wind power can not meet the requirements of real-time regulation, it is still relatively small in the application. The sampling period of 1s also limits the application of intelligent algorithms. Therefore, when determining the wind power stabilization target, this paper does not involve the short-term prediction of wind power, only uses the real-time power of wind power to adjust the filter coefficient, and aims to reduce the energy storage consumption.

Based on the analysis, the low-pass filter algorithm is adopted in this work. The filter coefficient is adaptively adjusted according to the relationship model of wind power fluctuation in two different time scales at the adjacent time to determine the target output power of the wind power grid connection that meets the fluctuation limit of two different time scales. The algorithm flow is shown in Figure 3:

The filter coefficient $a_1(t)$ is first determined by the 1-minute wind power fluctuation limit determined by the wind power fluctuation relationship of the two different time scales as a reference, and is calculated as follows:

$$\begin{cases} a_1(t) = \dfrac{\Delta P^t_{O,1-\min}\%*P_r + \min\_1(t-1) - P_O(t-1)}{P_W(t) - P_O(t-1)}, P_W(t) > P_O(t-1) \\ a_1(t) = \dfrac{\max\_1(t-1) - P_O(t-1) - \Delta P^t_{O,1-\min}\%*P_r}{P_W(t) - P_O(t-1)}, P_W(t) < P_O(t-1) \\ a_1(t) = 1 \qquad , P_W(t) = P_O(t-1) \end{cases} \tag{4}$$

Based on the filtering principle, the filter coefficient constraint can be obtained and $P_O(t)$ between $P_O(t-1)$ and $P_W(t)$ is guaranteed.

$$0 \le a_1(t) \le 1 \tag{5}$$

IV. Simulations and Result Analysis

In the case study, the rated output power of the wind farm is 6MW and the fluctuation index of the grid-connected active power is specified as follows: the power fluctuation in 1 minute does not exceed 2% of the rated power, and the power fluctuation in 30 minutes does not exceed 10% of the rated power, that is: $\gamma_{1\min}\% = 2\%, \gamma_{30\min}\% = 10\%$. The simulation experiments are carried out using MATLAB.

The simulation performance results of the proposed stabilization solution and the power utilization of battery-based storage and supercapacitor are shown in Fig.4-Fig. 6. It can be seen that the target power of wind power per second in 24 hours was obtained after the real-time stabilization of the output power of the wind farm according to the wind power stabilization strategy in this study.

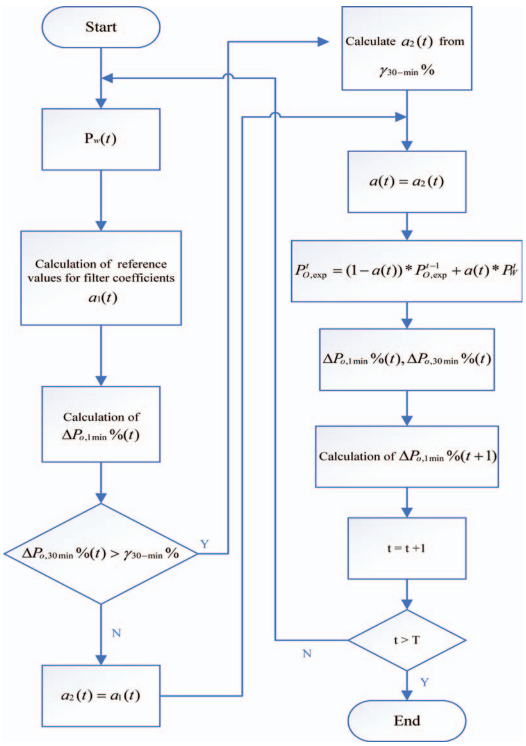

Figure 3. Flow chart of wind power stabilization algorithm

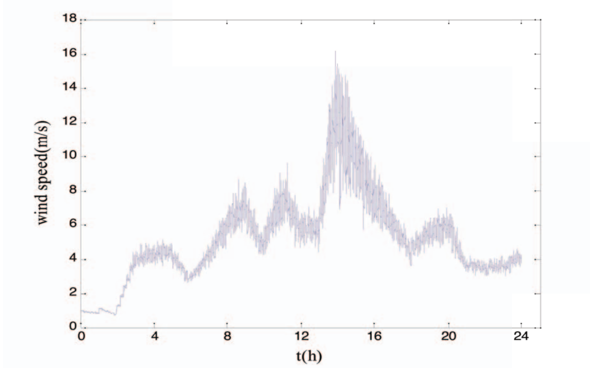

Figure 4. Original power generation of the wind farm over a day

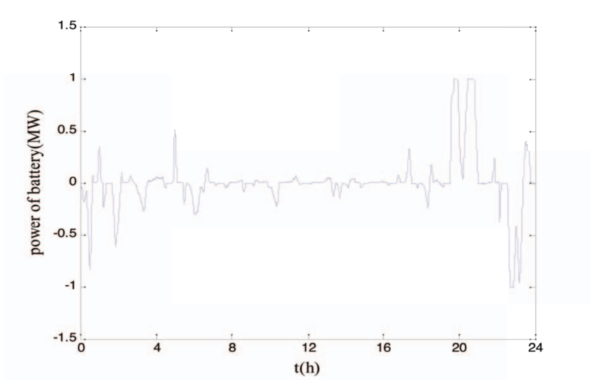

Figure 5. Charing and discharging behavior of the battery storage system

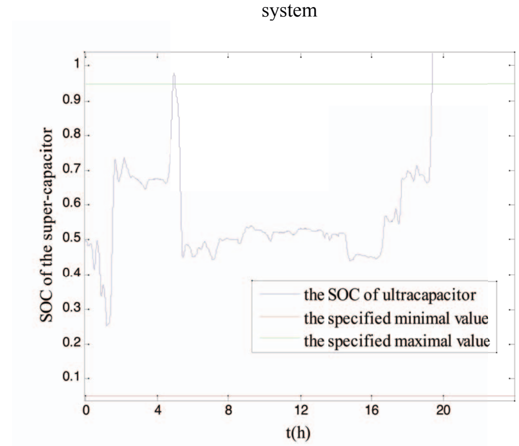

Figure 6. Charing and discharging behavior of the supercapacitor system

V. Conclusive Remarks

This paper mainly studies the calculation method of target power in the real-time generation stabilization management solution for offshore wind farms, so that the active power of wind power after stabilization meets the power fluctuation rate limit of two different time scales in the grid connection requirements. This paper proposes a method to adaptively adjust the filter coefficient by updating the fluctuation limit on a one-minute time scale in real-time. The numerical results obtained from simulation experiments through comparative study showed the effectiveness and superiority of the proposed control solution. Further study can be carried out to validate the solution in more operational scenarios of offshore wind farms.

Acknowledgments

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