Research on Multi-mode Operation Control Strategy of Wind-power System with Wind Farm Benefits

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Abstract. With the increasing of wind power integration capacity, the characteristics of wind-power-specific volatility and anti-tune peaks bring new challenge to the system's stabilization fluctuation and peak-shaving plan. Aimed at the anti-tune peak and fluctuation of wind power, this paper uses the hybrid energy storage system of pumped storage and storage battery to develop a new operation control strategy of the hybrid energy storage system, so as to make the combined efficiency of the wind-storage system the highest. Considering the uncertainty of wind power, the restriction of pumped storage and storage battery, the new operation strategy can not only use the shifting mode of pumped storage, but also can use battery to stabilize the wind wave mode. Through the example analysis, it is proved that the control strategy of the hybrid system can smooth the fluctuation of wind power output and shifting.

1. Introduction
With the increasing of new energy permeability, more challenges are brought to the safe and reliable operation of power grid. The large-scale wind power grid-connected will have great influence on the system's peak modulation, safety and stability, power quality, etc. Compared with conventional power supply, wind energy is a kind of typical stochastic, intermittent power due to the influence of weather, and there are still some problems about the accuracy of wind power output prediction in real life, these characteristics lead to high volatility of the output power of wind farms, which cannot provide the continuous stable controllable power, so the dispatch of wind power is poor. Therefore, it is more and more important to improve the power quality of wind farm and improve the stability of output power of wind farm.

The energy storage system can absorb and release the power quickly, when the load energy demand is insufficient, the energy is released and stored and the output power of wind power can be smoothed effectively. The purpose of the combined operation of wind storage is to reduce the randomness, volatility and anti-tune peak characteristics of wind power fluctuations. For this feature, storage energy can be used to stabilize fluctuation, peak cut and standby supply modes. The stabilization of wind power fluctuation mode can reduce the standby demand provided by the system for wind power fluctuation, and avoid the unit output being in the very regulation operation state; The peak cut mode can reduce the peak and valley difference of wind power output, weaken the anti-tune peak characteristic of wind power, and avoid generating unit frequent start and stop due to the anti-tune peak characteristic of wind power; The standby supply mode can quickly respond to power change, thus slowing the pressure of AGC unit and reducing the capacity demand of AGC unit.
At present, the use of energy storage system and wind farm operation has become one of the important ways of smoothing the output power fluctuation of wind farm. The paper [1] contrasts the economic benefits and the amount of wind energy of the system in different modes, and analyzes the influence of the time-sharing power price and energy storage cost parameters on the results; The paper [2] takes the maximization of the profit of the wind reservoir as the goal, sets up the application scenario of the complex peak cut and plan tracking, and analyzes the influence of peak and valley electricity price and forecasting error on peak capacity coefficient and wind storage scheduling strategy; The paper [3] establishes a multi-mode application coordination scheme for complex peak cut and three times FM; The paper [4] establishes a multi-mode application scheme for energy storage with compound peak cut and compensation prediction error, the design of peak cut model is carried out, then the prediction error of energy storage compensation can be calculated by simulating the scene reduction technique. By comparing the economic benefits of storage energy used in multimodal and single mode, it is proved that the coordinated operation of many modes can improve the running state of the system. However, all the above literature use single energy storage equipment, the random fluctuation of the output power of wind farm is distributed in the time scale from millisecond to hour, and the single energy storage technology is very difficult to stabilize the demand of multi time scale power of wind power generation. This paper puts forward the way of Hybrid Energy Storage System (HESS), combines the characteristics of different types of energy storage system, using complementarity to achieve better output controllable performance.

In this paper, the hybrid energy storage system of pumped storage and battery is used, considering the uncertainties of wind power, pumped storage and storage battery, which can not only use the peak cut mode of pumped storage, but also use the battery to stabilize the fluctuation mode of wind power. At the same time, the operation control strategy of a new type of pumped storage-storage battery hybrid energy storage system is developed, which makes the combined efficiency of the wind storage system highest.

2. Wind-Storage Combined System
Wind power is a kind of special energy. It has strong randomness, volatility, anti-tune and unpredictable. In view of the output characteristics of wind power, the energy storage system is set on the side of wind turbine, and the output of wind farm is centrally controlled and adjusted so that the total power of the wind-storage combined system is controlled into a curve that satisfies the fluctuation of the network power, and the simplified system schematic diagram shown in Figure 1.

![Figure 1. Simplified schematic diagram of combined air-storage System.](image)

A hybrid energy storage unit can be visualized as a generating set with positive and negative output value, and the output power of the wind storage combined system can be expressed as:
\[ P_z = P_w + P_h \]  

(1)

In the formula, represents the total output power of the wind-storage combined system; represents the output of a wind farm; represents the output power of a hybrid energy storage system, in which the energy storage system is a positive value when it is stored, conversely, the negative value when releasing energy. By making the operation strategy of Hess and controlling its cooperation with wind farm, control the fluctuation of the wind-storage combined output power of the access system within a certain range to meet the system's FM requirements or reduce the impact on the power grid frequency stability.

3. Multi-mode Operation Strategy of Wind-storage Combined System

In this paper, a novel hybrid energy storage operation control strategy is presented to peak cut and stabilizes the short time fluctuation of wind power two-stage layered rolling control strategy.

The two-stage layered rolling control strategy is based on the characteristics of pumped storage, battery charge and discharge and its capacity. This control strategy can read the value of t-period and t+1-period of wind power when analyzing the working state of the energy storage system. This will not only be able to schedule the current period of storage charge and discharge, but also consider the wind fluctuations in the latter part of the period to provide storage capacity for the latter segment. Because of the large capacity of pumped storage and the longer charge and discharge, so pumped storage in the outer layer to complete the peak cut mode; with the characteristics of small capacity and rapid charge and discharge time, so use the battery to stabilize the short time wind wave mode and to replenish pumped storage. The explanation is as follows:

First stage (outer layer): considering various constraints of pumped storage and using pumping energy to fill the valley; using pumped storage to release power shaving during a period of less wind power output. The method of determining the time period of large wind power output can be analyzed according to the historical data of wind power output, and the typical daily output curve of each quarter is set up according to the year, in order to find the time period which meets the requirement in the curve.

Second stage (inner layer): Under the precondition of satisfying its own constraint condition, the output of the battery can not only to ensure the current moment of fluctuation is not limited, but also finish detection of battery charge and discharge capability. Of course, the battery must satisfy its own constraint conditions and its charge and discharge status as follows:

References are cited in the text just by square brackets [1]. Two or more references at a time may be put in one set of brackets [3, 4]. The references are to be numbered in the order in which they are cited in the text and are to be listed at the end of the contribution under heading references, see our example below.

1) Status unchanged:

\[ \Delta P_w(t) \leq THD \text{ and } \Delta P_w(t+1) \leq THD \]  

(2)

\( \Delta P_w(t) \) means forecast fluctuation numerical value of wind power in t-period, and \( \Delta P_w(t+1) \) means the value in t+1-period. THD means volatility threshold, which can be adjusted according to the requirements of specific systems.

2) Charging status:

Situation①

\[ \Delta P_w(t) > THD \]  

(3)

Situation②
SOC (State-of-Charge) means charge state of battery, which is the ratio of battery surplus to battery capacity. $SOC_{\min}$ means low-limit of SOC status for battery t-period.

3) Discharge status

Situation①

$$\Delta P_w(t) < -THD$$

Situation②

$$\begin{align*}
\Delta P_w(t) & \geq -THD \\
\Delta P_w(t + 1) & < -THD \\
SOC(t) & \geq SOC_{\max}
\end{align*}$$

$SOC_{\max}$ means high-limit of SOC status for battery t-period.

4. Wind Storage Combined System Model

In order to comprehensively consider the economy and technical feasibility of HESS its cost and effect on the wind power fluctuation. This paper presents the income function model of wind-storage combined system with penalty cost of wind power fluctuation limit. The goal of the model is to maximize the revenue of the combined system of wind storage in the optimization period.

4.1. Objective Function

With the best interests of the wind-fed combined system as the goal:

$$\max p = \max \left( C_s - C_{pen} \right)$$

In the formula, $p$ means the overall interest of the wind-fed integrated system; $C_s$ means power sales revenue of wind-storage combined system during optimization period; $C_{pen}$ means penalty cost of wind fluctuation exceeding allowable fluctuation range during optimization period.

① Revenue from sales of electricity $C_s$:

$$C_s = \int_0^T P_z(t) \cdot B(t) dt$$

In the formula, $P_z(t)$ means network power of wind-storage combined system in t-period; $B(t)$ means t-period wind power price; T means number of tuning periods.

② Penalty cost $C_{pen}$:

$$C_{pen} = C(t) \int_0^T \left( \| \Delta P_z(t) - THD \| \times B(t) \times \beta \right) dt$$
In the formula, $C(t)$ means the duration of the penalty fluctuation in t-period is 1, whereas $0$; $B(t)$ means t-period wind power price; $\beta$ means penalty factor, and the penalty coefficient for this article is set to 10. $\Delta P_z$ means Power fluctuation rate.

4.2. Constraint Conditions
Constraint conditions include power balance constraints of wind farms, pumped storage constraints and storage battery constraints.

4.2.1. Power balance constraint of wind farm. Considering the smooth operation of wind farm, the power balance constraint of wind farm can be expressed as:

$$P_w = P_z - P_h$$

In the formula, $P_w$ means the output of wind farm; $P_z$ means total output power of wind storage combined system; $P_h$ means output power of hybrid energy storage system, in which the energy storage system is a positive value when it is stored, conversely, the negative value when releasing energy.

4.2.2. Pumped storage constraints.

$$P_{\min} \leq P_{c,t} \leq P_{\max}$$

$$T_{c,t} \geq 1h$$

$$S_{c,t,\min} \leq S_{c,t(t)} \leq S_{c,t,\max}$$

(12) means output restraint of pumped storage; (13) means time constraint of continuous power generation by pumped storage; (14) means capacity constraints of pumped storage. $P_{\min}$ and $P_{\max}$ are the minimum and maximum power generation of pumped storage power station units, $S_{c,t,\min}$ and $S_{c,t,\max}$ are maximum and minimum capacity of pumped storage.

4.2.3. Battery restraints. The restriction of the battery is mainly embodied in SOC (State-of-Charge) of the battery, which means the ratio of residual battery power to battery capacity should meet the upper and lower bound values.

$$SOC_{\min} \leq SOC_T \leq SOC_{\max}$$

$$E_{\min} \leq E_t \leq E_{\max}$$

$$E_T = E_0$$
\[ U_{ch,t} + U_{dis,t} = 1 \] (18)

(15) means SOC constraint of battery; (16) means capacity constraint of storage battery; (17) means constraints on the whole cycle of battery; (18) means constraints of battery’s charge and discharge state.

In the formula, \( SOC_t, \ SOC_{\max}, \ SOC_{\min} \) mean the SOC, the upper and lower limits of the battery in t-period respectively. When the SOC reaches the maximum value of the battery (\( SOC_{\max} = 0.9 \)), the battery stop charging; When the SOC reaches the minimum value of the battery (\( SOC_{\max} = 0.2 \)), the battery stop discharging. \( E_t \) is the battery T-period power, \( E_{\max} \) is the maximum battery power, \( E_{\min} \) is the minimum charge for the battery. \( E_T \) is the capacity of battery at the end of a cycle, \( E_0 \) is the capacity of battery at the beginning of a cycle. \( U_{ch,t} \) is the battery charge state in T-period, \( U_{dis,t} \) is the discharge state of battery in t-period.

5. Example Analysis

This paper takes a wind-reservoir combined system as an example with operation control strategy based on this paper, analysis on the effect of HESS to stabilize wind power fluctuation and peak cut and the economic benefit of wind-storage combined system.

The basic configuration of the hybrid storage energy in this paper is as follows: The installed capacity of the wind field is \( 150MW \), the maximum capacity of pumped storage power is \( 60MW \), the capacity of pumped storage power station is \( 300MW \cdot h \), the minimum volume is \( 30MW \cdot h \), and its comprehensive efficiency is 75%; The capacity of the battery to run with the wind farm is \( 2MW / 10MW \cdot h \), Lower limit of storage charge is \( 2MW \cdot h \), and its charge and discharge efficiency of 90%.

According to the actual situation in our country, set the wind power price as shown in table 1.

**Table 1.** The price of online wind power.

| Load Trough period | Time     | Price (yuan/KWh) |
|--------------------|----------|------------------|
| Low                | [0,7]∪[23,24] | 0.45             |
| Middle             | [11,17]∪[21,23] | 0.65             |
| Peak               | [7,11]∪[17,21] | 1.00             |

Here are two kinds of running schemes for the example. Scheme 1: The hybrid energy storage system composed of pumped storage and battery is not combined with wind farm according to the operation strategy proposed in this paper; Scheme 2: The hybrid energy storage system composed of pumped storage and battery is combined with wind farm according to the operation strategy proposed in this paper, and in consideration of the constraint conditions of energy storage system, a particle swarm optimization algorithm is used to simulate.

5.1. Energy Storage State Analysis

The Hess outputs of scheme 1 and scheme 2 are shown in Figure 2 and Figure 3.
Figure 2. The curve of Hess output of scheme 1.

It can be seen from the diagram that pumped storage can effectively improve the anti-tune peak characteristics of wind power. In the night of 0:00-7:00, the wind power forecast is larger and the price of electricity is lower, so the pumped storage energy; during the day when the electricity prices are higher and the wind power forecasts are smaller, pumped storage releases energy. Although the battery in the time period of wind power fluctuation is also actively charge and discharge, the number of charge and discharge reached 40 times. While the battery charge and discharge times more frequent, in the long run will shorten the service life of the battery.

Figure 3. The curve of Hess output of scheme 2.

As can be seen from the diagram, the output of pumped storage is roughly in line with the scheme one, charging during a period of low electricity price, discharging at higher electricity prices. But the battery charge and discharge state changes greatly, first, the battery charge and discharge times are 16 times, and decreased by 60%. In the period of frequent wind fluctuation, taking into account the
battery charge and discharge status and battery capacity in the next period of time, on this basis, to slow down the charge and discharge depth, which is conducive to the cost of storage battery and the growth of service life.

5.2. Analysis of benefit and stabilizing effect
Simulation results show that the output power of the two schemes is shown in the following figure. Figure 4 shows the output power of the wind-storage combined system based on the simulation of the scheme 1; Figure 5 shows the output power of the wind-storage combined system based on the simulation of the scheme 2.

![Figure 4](image1)
**Figure 4.** The curve of wind-storage combined system output power of scheme 1.

![Figure 5](image2)
**Figure 5.** The curve of wind-storage combined system output power of scheme 2.

As can be seen from the above diagram, compared with the scheme 1, the overall fluctuation trend of the scheme 2 is smoother and the anti-tune peak characteristics is much slower. The specific values are shown in table 2:
Table 2. The fluctuation of the wind-reservoir joint system.

| Scheme | The sum of the amplitude limit of fluctuation $\Delta P_r$ | Volatility limit probability $P_{out}$ |
|--------|----------------------------------------------------------|---------------------------------------|
| 1      | 0.69                                                     | 3.47                                  |
| 2      | 0.17                                                     | 1.69                                  |

According to the simulation results of the wind storage combined system, its revenue is as shown in table 3.

Table 3. The income of the wind-reservoir joint system.

| Scheme | Income/yuan |
|--------|-------------|
| 1      | 16713.307   |
| 2      | 18306.747   |

As can be seen from table 2 and table 3, compared with the scheme 1 in the fluctuation of wind power, the probability of fluctuation of scheme 2 is reduced by 52% and the sum of the amplitude limit of fluctuation is 75.4%; In the revenue of the combined system, the revenue of the combined system increased by 1593.44 yuan due to the decrease of the battery charge and discharge times. Compared with the scheme 1, the two-layer rolling advance control strategy in this paper can be used to restrain wind power fluctuation and peak cut on the basis of considering the charging and discharging times of the storage battery.

6. Conclusion
In order to improve the operating economy of wind power system reduce the adverse effect of wind power access on power system, this paper presents a coordinated optimal operation control strategy for hybrid energy storage of pumped storage-storage battery, the main conclusions are as follows:

1) According to the characteristics of hybrid energy storage system, a two-stage layered rolling operation strategy is proposed. The influence of current capacity and future power fluctuation of accumulator on current charging and discharging behavior of energy storage device is considered, which is a forward-looking control method.

2) The result of the example verifies the validity of the running strategy, the anti-tune peak characteristics of wind power can be solved well on a long time scale, and the peak mode of wind-storage combined system is provided. In the short time scale, the wind power fluctuations have a good smooth effect.

References
[1] SANG Bingyu, WANG Deshun, YANG Bo, YE Jilei, TAO Yibin. Optimal Allocation of Energy Storage System for Smoothing the Output Fluctuations of New Energy [J]. Proceedings of the CSEE, 2014, 34(22):3700-3706.
[2] DING Ming, WU Jianfeng, ZHU Chengzhi, ZHAO Bo, CHEN Zinian, LUO Yaqiao. A Real-time Smoothing Control Strategy With SOC Adjustment Function of Storage Systems [J]. Proceedings of the CSEE, 2013, 33(01):22-29.
[3] ZHANG Ye, GUO Li, JIA Hongjie, LI Zhanying, ZHANG Zhigang. An Energy Storage Control Method Based on State of Charge and Variable Filter Time Constant [J]. Automation of Electric Power System, 2012, 36(06):34-38+62.
[4] XIAO Jun, ZHANG Zequn, ZHANG Pan, LIANG Haishen, WANG Chengshan. A Capacity Optimization Method of Hybrid Energy Storage System for Optimizing Tie-line Power in Microgrids [J]. Automation of Electric Power System, 2014, 38(12):19-26.
[5] Cai Guowei, Kong Lingguo, Pan Chao, Yang Deyou, Sun Zhenglong. System Modeling of Wind-PV-ES Hybrid Power System and Its Control Strategy for Grid-Connected [J]. Proceedings of the CSEE, 2013, 28(09):196-204.
[6] JIANG Runzhou, QIU Xiaoyan, CHEN Guangtang. Optimal Configuration Method of Hybrid Energy Storage System for Wind Farm [J]. Proceedings of the CSU-EPSA, 2015, 27(01):37-42+48.

[7] WANG Zhenhao, LIU Jinlong, LI Guoqing, XIN Yechun, YANG Lin, YU Qiao. Power and voltage regulation of wind farm based on EDLC energy storage [J]. Electric Power Automation Equipment, 2011, 31(03):113-116.

[8] LI Guo-jie, TANG Zhi-wei, NIE Hong-zhan, TAN Jing. Modelling and controlling of vanadium redox flow battery to smooth wind power fluctuations [J]. Power System Protection and Control, 2010, 38(22):115-119+125.

[9] GUO Xue-ying, ZHENG Jian-yong, MEI Jun, XU You. Power conditioning and control system for grid connected wind farm based on super-capacitor energy storage [J]. Renewable Energy Resources, 2011, 29(02):28-32.

[10] Sercan T, Mesut E B, Bhattacharya S, et al. Optimal control of battery energy storage for wind farm dispatching [J].IEEE Trans on energy conversion, 2010, 25(3):787-794.

[11] YAN Gangui, LIU Jia, CUI Yang, MU Gang, LI Junhui, GE Weichun, GE Yanfeng. Economic Evaluation of Improving the Wind Power Scheduling Scale by Energy Storage System [J]. Proceedings of the CSEE, 2013, 33(22):45-52+9.

[12] YANG Yulong, LI Junhui, ZHU Xingxu. Economic assessment on the use of energy storage to improve clustered wind generation transmission [J]. Energy Storage Science and Technology, 2014, 3(01):47-52.