Research on Coordinated Control Strategy of Energy Storage Participating in Primary Frequency Regulation Considering Frequency Deviation Change Rate

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Abstract. In order to further improve the performance of primary frequency modulation (PFM) by battery energy storage, a new control strategy is proposed. By analysing the characteristics of virtual inertia response and virtual droop control, the artificial dead zone of energy storage participating in frequency modulation is set based on virtual inertial control to make it respond quickly and improve the characteristics of energy storage to suppress frequency deviation change rate; In this paper, the remaining energy and load disturbance of the energy storage battery are taken as the double inputs, and the fuzzy control strategy is used to derive the function relationship between the virtual droop coefficient and the two inputs to ensure that the charging and discharging power of the energy storage battery is suitable for the actual needs. The load change rate is used to predict the load change at the next moment. Based on this, the coefficients of virtual inertia control and virtual droop control are determined, and the output coefficients of both are optimized to achieve the optimal frequency regulation effect. Three evaluation indexes are proposed to evaluate the control strategy in this paper. Finally, the simulation model is established in MATLAB/ Simulink and the case study is carried out in a regional power grid. The proposed strategy can effectively improve the primary frequency regulation of power grid and has positive significance for maintaining energy storage battery.

1. Introduction

In recent years, with the depletion of fossil and other non-renewable energy, wind power has developed rapidly. The total installed capacity of wind power in China has reached 210 million KW, which ranks first in the world, accounting for 10% of the total installed capacity of power generation [1-2]. However, the large-scale integration of wind power leads to the increase of frequency fluctuation and the decrease of anti-interference ability. Under such dual pressure, new means are urgently needed to assist the power grid to participate in frequency regulation to make up for the power fluctuation caused by wind power integration. The frequency regulation of energy storage auxiliary power grid has been studied abroad for a long time, and more and more attention has been paid to the establishment of energy storage power station in China [3-4].

At present, the research on energy storage battery participating in primary frequency regulation of power grid mainly focuses on coordinated control strategy, especially the charge and discharge of energy storage battery, including the related battery types, battery capacity configuration, etc. In Ref [5], the physical functions of inertia support power and primary frequency regulation performance in power...
system are introduced and analysed in principle by using formula derivation, and the difference and location of frequency deviation change rate and frequency deviation are explained. In Ref [6], it is proposed that the use of virtual synchronous generator to increase the inertia support of power system can improve the anti-interference ability of power system. Ref [7] proposes that virtual inertia control and virtual droop control can be used in power system, and their feasibility and effectiveness are evaluated. Ref [8] proposes that energy storage can simulate the inertia response of synchronous generator and participate in grid frequency regulation, which can effectively improve the jitter degree of frequency deviation curve. In Ref [9], the model of energy storage participating in primary frequency regulation is established, and an adaptive control strategy considering energy storage is proposed. The traditional energy storage frequency modulation only considers the relationship between energy storage and energy storage to determine the output, but seldom considers the influence of frequency deviation deterioration on the output coefficient [10-12].

According to the above analysis, this paper separates the energy storage frequency modulation dead zone from the grid frequency modulation dead zone, sets the energy storage frequency modulation dead zone as a certain value, and uses the fast response speed of energy storage frequency modulation to predict the load disturbance. The strategy of virtual inertia control and virtual droop control is adopted to improve the change rate of frequency deviation and restrain the frequency deviation from falling out of the dead zone of grid frequency modulation. At the same time, according to the frequency deviation, the output combination of virtual inertia control and virtual droop control is further determined, and their configuration coefficients are optimized to make the frequency deviation value reach a new steady state. Finally, taking a regional power grid as an example, the effectiveness of the proposed control strategy is verified by simulation under the condition of step disturbance.

2. Analysis of frequency modulation characteristics of regional power grid with energy storage

Virtual inertia control and virtual droop control are two classical control methods for battery energy storage to participate in primary frequency regulation of power grid, which are widely used. According to the actual situation of power grid frequency regulation specification and frequency regulation dead zone, the coordinated application of the two methods can better optimize the power grid frequency regulation performance. Virtual inertial control can fully simulate the inertia response of synchronous generator, improve the system inertia time constant, and restrain the deterioration of frequency deviation change rate.

Fig. 1 shows the three major parts in the process of power system frequency regulation.

The virtual inertial control of battery energy storage is mainly used to suppress the rate of frequency deviation change in time, which hinders the further deterioration of disturbance. The virtual droop control plays an important role in the process of recovering the frequency deviation to the new steady state. The virtual droop control can compensate the power shortage, compensate the frequency deviation, and make it return to a fixed value with deviation from the rated value.

According to the above analysis, the dynamic model diagram of energy storage participating in primary frequency regulation as shown in Fig. 2 is established [13].
In the figure, $M$ is the equivalent inertia of the power grid, $D$ is the damping coefficient of the grid, $\Delta f$ is the frequency deviation of the grid, $\Delta P_L$ is the load disturbance of the grid, $K_{g1}$ is the unit regulated power of the traditional generating units in the grid, and $K_{g2}$ is the droop coefficient of energy storage participating in primary frequency regulation.

Since the frequency dynamic characteristics of thermal power units are mainly affected by governor and steam turbine, the models of governor and steam turbine are mainly considered.

The transfer function of governor of thermal power unit is as follows:

$$G_g(s) = \frac{1}{1+sT_g}$$

(1)

The transfer function of steam turbine is as follows:

$$G_s(s) = \frac{1+F_R*s}{(1+sT_e)(1+sT_g)}$$

(2)

Where: $T_e$ is the time constant of governor, the time constant of main intake volume and gas chamber, $T_g$ is the time constant of re-heater, and $F_R$ is the gain of re-heater.

The model of energy storage battery participating in power grid frequency regulation can be equivalent to the first-order inertial link, and its transfer function is as follows:

$$G_E(s) = \frac{1}{1+sT_L}$$

(3)

3. Research on coordinated control strategy of primary frequency modulation with two energy storage

When the dead zone of energy storage frequency modulation is set as an appropriate value, the load disturbance is predicted by using the fast response characteristics of energy storage frequency modulation. The strategy of virtual inertia control as the main and virtual droop control as the auxiliary is adopted to improve the change rate of frequency deviation and restrain the frequency deviation from falling out of the dead zone.

3.1. Primary frequency control strategy of power system

3.1.1. Virtual inertial control

By simulating the inertia response characteristics of synchronous generator, the virtual inertial control can give appropriate virtual inertia coefficient to improve the dynamic stability of the system [14].
Where: $\Delta P_1$ is the virtual inertia control output, $M_1$ is its output coefficient, $T_J$ is the inertia time constant of synchronous generator, $\Delta \sigma(t)$ is the change rate of frequency deviation. Obviously, it can be concluded from the third formula above that when the virtual inertia force is constant, the greater the virtual inertia force is, the higher the tolerance of the system to the frequency deviation change rate.

### 3.1.2. Virtual droop control

Droop response is an automatic regulation characteristic of power grid frequency change caused by generator set inertia response, which is the primary frequency regulation characteristic of power grid. Its work output is as follows [15]:

$$
\Delta P_2 = \begin{cases} 
0 & |\Delta f| \leq f_d \\
-K_i \cdot \Delta f & |\Delta f| > f_d 
\end{cases}
$$

Where: $\Delta P_2$ is the virtual droop control output, $K_i$ is its output coefficient, $K_s$ is the output coefficient of energy storage battery participating in frequency modulation stage, $K_r$ is the output coefficient of energy storage battery recovery stage.

As shown in Figure 3, the fast response characteristics of energy storage battery are fully considered, and the value smoothing output is taken into account. The fuzzy controller with double input and clear single output is adopted, and the virtual droop coefficient is effectively set to make it consider the load disturbance and value to smooth the output.

![Normalized SOC of energy storage and universe of load disturbance](image)

When the energy storage battery is used as the input of the fuzzy controller, the range of 0.15-0.95 can be set as the normal value, and the abnormal operation state of the energy storage battery is lower than 0.15 or higher than 0.95. as shown in Tab.1.

| SOC   | NB | NS | ZO | PS | PB |
|-------|----|----|----|----|----|
| NB    | NB | NB | NS | ZO | ZO |
| NS    | NS | NS | ZO | PS | PS |
| ZO    | NS | NS | ZO | PS | PS |
| PS    | ZO | ZO | ZO | PS | PB |
| PB    | ZO | ZO | PS | PB | PB |

Fig. 4 is to clarify the fuzzy set of the output according to the area centre method, and Fig. 5 is the virtual droop coefficient considering the load disturbance and the smooth output of the battery itself participating in the primary frequency regulation.
3.2. SOC recovery control strategy
The recovery of energy storage battery can be divided into the following two conditions: normal recovery and abnormal recovery.

As shown in Fig. 6, the following functions can quantitatively describe the functional relationship between $\Delta f$, SOC self-recovery power of energy storage.

$$y = M \cdot \tan^{-1} x$$

As shown in Fig. 7, under abnormal operation conditions, i.e. frequency and extreme deterioration ($> 0, > 0.85; < 0, < 0.15$), the existing conditions should be fully utilized, and the actual disturbance demand should be met. A new round of suppression should be given to the power coefficient of energy storage self-recovery to prevent over discharge or overcharge [15].
Therefore, the formula of self-recovery power of energy storage under extreme conditions can be obtained as follows:

\[
\begin{align*}
P_{c1} &= \begin{cases} 
P_{\text{max}} & \text{SOC} \leq 0.15 \\
\frac{1}{2} \cdot P_{\text{max}} \cdot \left(2 - \frac{\text{SOC}}{2}\right) & 0.15 < \text{SOC} \leq 0.5 \\
\frac{1}{2} \cdot P_{\text{max}} \cdot (5 \cdot \text{SOC} - 3) & 0.5 < \text{SOC} \leq 0.85 \\
P_{\text{max}} & \text{SOC} > 0.85
\end{cases}
\end{align*}
\]  
(8)

Based on the above four working modes of the normal state and the power relation of the abnormal state energy storage self-recovery, combined with the SOC of the energy storage and the load disturbance changes in the two states, the self-recovery power of the energy storage is modified:

\[
P_e = \begin{cases} 
P_{\text{max}} & \text{SOC} \leq 0.15, \ \text{SOC} > 0.85 \\
M \arctan(\text{SOC}) & 0.15 < \text{SOC} \leq 0.85
\end{cases}
\]

(9)

4. Coordinated control strategy and evaluation index of battery energy storage participating in primary frequency regulation

Fig. 9 shows the coordinated control strategy of battery energy storage participating in primary frequency regulation of power grid. In this paper, a new artificial dead zone is set as the limit of power grid FM dead zone when energy storage is involved in frequency regulation.

\[
f_d = \frac{1}{5} \cdot f_e, \ f_e = 0.033 \text{Hz}
\]

(10)

As shown in Fig. 8, if the value of current load disturbance \((T > 0)\) and the magnitude and direction of its change rate \(\lambda\) are known (the calculation of \(\lambda\) is based on the change rate), then the load disturbance and change at the next moment can be predicted preliminarily in a short time (taking the relatively small value). The following formula can be obtained by iteration in turn.

\[
P_e(t + 1) = P_e(t) + \lambda(t) \cdot \Delta t
\]

(11)

Where is the load disturbance change rate at the moment, which is relatively small \(T\).
The output coefficients of virtual inertia control and virtual droop control are optimized as follows.

\[ P_L = a_1 M_1 \frac{d\Delta f}{dt} + a_2 K_i \Delta f \]  \hspace{1cm} (12)

\[ \begin{align*}
  a_1 &= e^{\alpha M_1} \\
  a_2 &= 1 - e^{\alpha M_1}
\end{align*} \]  \hspace{1cm} (13)

Where \( M_1 \) is the virtual inertia control output coefficient, \( a_1 \) is the virtual droop control output coefficient. It is the fitness factor of the allocation coefficient, which can be taken as 10 generally.

Formula (12) shows that when the total power of battery energy storage is constant, the optimal output combination can be achieved by optimizing the coefficients of the two control modes.

Fig. 9 shows the flow chart of coordinated control strategy for battery energy storage participating in primary frequency regulation of power grid.

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**Fig. 8 Load change trend diagram**

**Fig. 9 Control strategy flow chart**
5. Case study
In this paper, a regional power grid simulation model as shown in Figure 1 is built in Matlab/ Simulink. For example, the load disturbance increases and the frequency drops downward. The results as shown in the figure below can be obtained and analysed.

As shown in Fig.10 above, there is a significant gap compared with the proposed strategy. Under the coordinated control strategy, the maximum frequency deviation is smaller, the recovery time is shorter, the final steady-state deviation is smaller, and the frequency response curve is significantly improved.

As shown in Fig. 11, the maximum frequency deviation part of the frequency response curve is enlarged. Through local magnifying observation, the superiority of the coordinated control strategy used in this paper can be clearly judged, which is superior to the conventional adaptive control method without energy storage.

As shown in Fig.12, the change curve of the battery SOC shows the effectiveness of the coordinated control strategy. The strategy of this paper maintains a higher SOC compared to the conventional adaptive control method and the general variation K method.
As shown in Fig. 12, the coordinated control strategy, the discharge state of energy storage battery is better. Not only in the discharge of the other side can be more smooth output, discharge time is longer, after the adjustment will be left a certain amount, fully consider the recovery status of the energy storage battery, better protect the service life of the energy storage battery.

As shown in Fig. 13, It can be seen that the coordinated control strategy in this paper is smoother and more durable for the output of frequency modulation system, and has stronger ability of fast response. It can make quick instantaneous response to load disturbance and output with large power.

6. Conclusion
In this paper, a coordinated control strategy of energy storage considering frequency deviation change rate is proposed. Some conclusions can be derived by the model analysis and case study.

1) In this paper, the dead zone of energy storage frequency modulation is separated from the dead zone of power grid frequency regulation. When the dead zone of energy storage frequency modulation is set as a certain value, the unnecessary action times of conventional units can be effectively participated in frequency regulation by power grid.

2) The virtual droop coefficient of energy storage participating in frequency modulation is controlled by fuzzy control, so that the output can be smooth when adjusting.

3) The load disturbance and its change rate are used to predict the load change, and the combination of virtual inertia control and virtual droop control is judged. The actual situation of frequency deviation change rate and frequency deviation is comprehensively studied to achieve the optimal combined output.

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