Research on energy storage participating in frequency modulation based on fuzzy partition coordinated control

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Abstract. Energy storage has the advantages of fast response and accurate power tracking when participates in frequency modulation. By dividing the Area Control Error (ACE) and battery’s State of Charge (SOC) into different regions, combining them with four different emergency frequency modulation states, this paper proposes a partition coordinated control strategy for energy storage to participate in frequency modulation. According to the regional interconnected system, the model of energy storage participating in power grid frequency modulation is built in MATLAB/Simulink. Based on the conventional control and the partition coordinated control, the frequency waveform analyzed. The results show that the energy storage participating in frequency modulation can effectively shorten the regulation time and reduce the frequency fluctuation. The fuzzy control used to optimize the partition coordinated control strategy to make the whole link have better frequency modulation ability.

1. Introduction
Aiming at the problem of energy storage participating in the operation of power grid frequency modulation, this paper proposes a partition coordinated control strategy combining energy storage SOC and power grid ACE. According to the frequency modulation status of ACE in four different emergency states, the areas suitable for SOC charging and discharging divided to extend the cycle life of energy storage. Fuzzy control used to optimize the above control strategy, and the generated fuzzy controller added to the regional power grid frequency modulation model with energy storage. Simulation modeling in MATLAB/Simulink shows that energy storage is helpful to reduce the FM deviation and shorten the FM time. Compared with the traditional model, the frequency modulation effect of the fuzzy partition coordinated control model is better.

2. Frequency modulation model of regional power grid with energy storage
The process of energy storage participating in power grid frequency modulation is as follows:
In the above frequency regulation process, there are two kinds of frequency variables: Interregional frequency deviation and tie line frequency deviation [1-2]. In this paper, the model used to simulate the large system with small fluctuations. The control mode between the two regions is TBC ~ TBC, and the tie line control mode is also TBC.

2.1. Frequency modulation model of regional power grid

The regional power grid frequency modulation model with energy storage is as follows:

Among them, the transfer function module used to simulate the output power of conventional units. The transfer functions with \( T_g \), \( T_t \), \( K_r \) and \( \tau \) as coefficients correspond to the governor, turbine and re-heater respectively, and correspond to the conventional unit as a whole. \( D \), \( M \) is the transfer function of the coefficient corresponding to the rotor and inertia load module.

2.2. Energy storage model

At present, flywheel energy storage, battery energy storage and super capacitor energy storage commonly used to assist regional power grid frequency modulation. According to the comparison of technical parameters of different types of energy storage in reference [3], it concluded that battery energy storage and flywheel energy storage are better in technology and economy. This paper adopts battery energy storage. The chemical reaction inside the energy storage battery is not considered, but the battery capacity, SOC and charge-discharge rate are considered. The energy storage battery model shall include the following modules [4]:

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**Fig. 1** Flow chart of energy storage participating in power grid frequency modulation

**Fig 2** Two area interconnection model

**Fig 3** Model of energy storage link
3. Coordinated control strategy of power grid frequency modulation with energy storage

3.1. Partition coordinated control strategy

In the frequency modulation model of regional power grid with energy storage, the equation of active power between energy storage and conventional units is as follows:

$$|P_{ACE}| = |P_{ess}| + |P_{gen}|$$  \((1)\)

Among them, \(|P_{ACE}|\) is the active power of ACE required by the power grid, \(|P_{ess}|\) is the real-time adjustment power of energy storage, and \(|P_{gen}|\) is the active power of conventional units.

Considering the SOC limitation and ACE control index of power grid, this paper proposes a partition control method combining SOC and ACE. It can avoid the SOC beyond its own constraints to adjust the ACE area that is in consistent with its adjustment direction, in order to avoid excessive charge and discharge of energy storage, and extend the life of battery. At present, the emergency degree of AGC FM mainly divided into: 1) No FM area; 2) Normal FM area; 3) Sub emergency FM area; 4) Emergency FM area [5]. As follows:

- **No FM area**: At this moment, the conventional unit cannot operate, and the energy storage should adjust the power used for SOC recovery adaptively. When recovering SOC, ACE must not enlarge and SOC should be located in shallow charge and shallow discharge area as far as possible [13].

- **Normal FM area**:  
  \[ACE \in (-ACE_{min}, 0) \cap SOC \in (SOC_{mid}, 65\%)\]  
  \[ACE \in (0, ACE_{min}) \cap SOC \in (35\%, SOC_{mid})\]  \((3)\)

At this time, the active power of ACE balance required by the power grid is not very large, which can undertake by the primary frequency regulation of thermal power units. (The upper formula is case \(\Delta f < 0\), the lower formula is case \(\Delta f > 0\), the same below) The corresponding state of discharge and charge of energy storage battery is as follows:

$$\begin{align*}  P_d &= P(s) \quad P_c = P(s) \\  P_e &= P(s) \quad P_e = P(s) \end{align*}$$  \((4)\)

Fig 4 Partition control of ACE and SOC

The arrow represents the state of SOC and the trend of system frequency in the process of frequency modulation. It can see from the figure that the ACE regulation area is opposite to the SOC regulation area: When \(\Delta f < 0\), ACE is in the negative area, the system frequency drops, and the active power is deficient. The battery energy storage should be at a higher state of charge as far as possible, and the energy storage discharged \((P_{ess} > 0)\). When \(\Delta f > 0\), ACE is in positive area, the system frequency rises, and active power is redundant. The battery energy storage should be in a low state of charge as far as possible, energy storage charging \((P_{ess} < 0)\). Therefore, formula (1) further supplemented as follows:

$$-P_{ACE} = P_{ess} + P_{gen}$$  \((2)\)
3) Sub emergency FM area:
\[
ACE \in (ACE_{\text{min}}, -ACE_{\text{mid}}) \cap SOC \in (SO\text{C}_{\text{low}}, 35\%)
\]
At this time, the active power of ACE balance required by the power grid is slightly larger, which shared by thermal power units and energy storage. Due to the fast response speed of energy storage, the energy storage given priority to adjust. The corresponding state of discharge and charge of energy storage battery is as follows:
\[
\begin{align*}
P_d &= P(s) \quad P_c = \lambda_s P(s) \\
\lambda_s &= 1 - \frac{\text{SOC} - 50\%}{50\%}
\end{align*}
\]
(6)

4) Emergency FM area:
\[
ACE \in (ACE_{\text{min}}, -ACE_{\text{max}}) \cap SOC \in (SO\text{C}_{\text{high}}, SO\text{C}_{\text{min}})
\]
At this time, the active power of ACE balance required by the power grid is very large, and the energy storage will coordinate the thermal power unit to output as much as possible. The emergency should report in time, and emergency intervention should take when necessary. The corresponding state of discharge and charge of energy storage battery is as follows:
\[
\begin{align*}
P_d &= P(s) \quad P_c = 0 \\
\lambda_s &= 1 - \frac{50\% - \text{SOC}}{50\%}
\end{align*}
\]
(7)

The relationship between the discharge and charge power value of energy storage and SOC simulated by logistic regression function, and the expression is as follows:
\[
P(s) = \frac{KP_s e^{\frac{\text{SOC} - \text{SOC}_{\text{max}}}{\text{SOC}_{\text{max}} - \text{SOC}_{\text{min}}}}}{K + P_s e^{\frac{\text{SOC} - \text{SOC}_{\text{max}}}{\text{SOC}_{\text{max}} - \text{SOC}_{\text{min}}}}}
\]
(9)

Among them, when the SOC regulation state is discharge, \( \lambda_s = SO\text{C}_{\text{max}} - SO\text{C} \). When the SOC is in regulation state of charge, \( \lambda_s = SO\text{C} - SO\text{C}_{\text{min}} \).

To sum up, when the ACE adjustable FM areas given, to ensure that the energy storage output within the corresponding range can greatly extend the battery life and improve the energy storage adjustment ability.

### 3.2. Fuzzy partition coordinated control strategy

A fuzzy partition control strategy combined with fuzzy control and partition coordinated control is proposed. In the previous chapter, SOC and ACE divided into seven areas. In the fuzzy control, input variables SOC and ACE also divided into seven fuzzy sets (NL, NM, NS, ZO, PS, PM, PL). The output variable Pess is divided into seven regions, the interval of the domain of the input and output variable are located in [0,1]. The membership functions of SOC using trapezoidal, the membership function of ACE and Pess using trapezoidal and triangular [6]. According to the active power of SOC and ACE partition coordinated control given in the previous chapter, the fuzzy control rules are as follows:

| Pess | SOC | NL | NM | NS | PS | PM | PL |
|------|-----|----|----|----|----|----|----|
| NL   | PS  | PM | PM | PM | PL | PL | PL |
| NM   | ZO  | PS | PM | PM | PM | PL | PL |
| YES  | ZO  | ZO | ZO | ZO | ZO | ZO | ZO |
| ZO   | ZO  | ZO | ZO | ZO | ZO | ZO | ZO |
| NS   | NL  | NM | NM | NM | NS | NS | ZO |
To sum up, this paper proposes a partition coordinated control strategy combining energy storage SOC and power grid ACE to coordinate energy storage output and prevent excessive charge and discharge, in order to extend battery life. Through the fuzzy control to optimize the above partition control strategy, a fuzzy partition control strategy obtained, which verified by simulation.

4. Simulation analysis
The installed capacity of conventional units is 100MW and the rated frequency is 50HZ. Take it as the benchmark for the system. Taking step signal as load disturbance, the simulation waveforms of four cases are as follows:

1) Conventional control: ① Frequency modulation waveform of conventional unit only. ② Frequency modulation waveform of conventional unit coordinated by battery energy storage.

2) Regional coordinated control: ① Frequency modulation waveform of battery energy storage coordination conventional unit based on partition coordinated control. ② Frequency modulation waveform diagram of battery energy storage coordination conventional unit based on fuzzy partition coordinated control.

| Control | Cases | FM deviation (HZ) | FM time (s) |
|---------|-------|-------------------|-------------|
|         |       | Area 1            | Area 2      | Area 1 | Area 2 |
| 1)      | ①     | 1.657–2.78        | 1.567–2.412 | 29.5   | 27.5   |
|         | ②     | 0.816–0.964       | 0.897–1.056 | 6.35   | 6.8    |
| 2)      | ①     | 0.95–1.05         | 0.904–1.105 | 15.4   | 17.5   |
|         | ②     | 0.827–0.975       | 0.897–1.1   | 12.8   | 13.6   |
It can be seen that for frequency modulation of only conventional units, the FM deviation is large, and the FM time is long. After the energy storage equipment participates in the frequency modulation, the FM deviation and the FM time have been greatly alleviated, which proves the technical superiority of energy storage participating in frequency modulation. When the module based on partition coordination control, compared with the conventional control, the FM deviation and FM time are slightly increased. This is because after considering the SOC and ACE area limited, the storage reduces the number of excessive charge and discharge. After adding the fuzzy controller, the FM deviation and FM time can be shorten, and they are close to the data with the conventional control. It proves that the model has optimized. It can see that the energy storage coordination unit frequency modulation based on fuzzy partition control can reduce the FM deviation and shorten the FM time, and avoid the excessive charge and discharge of the energy storage.

5. Conclusion
In this paper, a model of energy storage participating in frequency modulation established based on partition coordinated control strategy, and it optimized into fuzzy partition coordinated control by fuzzy control.

1) Energy storage participating in frequency modulation can effectively reduce frequency fluctuation, shorten frequency modulation time, FM ability of conventional unit improved.

2) A coordinated control strategy based on SOC and ACE proposed to restrict the output of energy storage in the process of frequency modulation. The strategy divides SOC and ACE into four FM states and seven areas.

3) Compared with the conventional control, the frequency modulation ability of the energy storage based on the partition coordinated control slightly reduced. The fuzzy control used to optimize the partition coordinated control strategy, and the fuzzy partition control method obtained. It proved that the energy storage system based on fuzzy partition control has better frequency modulation ability, which can use as a reference for formulating rules when energy storage participates in power grid frequency modulation in the future.

Acknowledgments
This work was financially supported by the Applied Research Project of Liaoning Province joint natural fund project of innovation ability promotion.

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