Coordinated Control Strategy of Emulated Inertia and Damping for Grid-Forming Energy Storage Considering Capacity Characteristics

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Abstract. The grid-forming control method of the emulated synchronous generator can enhance the response capability of the electricity frequency and enhance the anti-interference capability of the new energy system. But the system frequency regulation ignores the fact that the active power of multiple energy storage is not proportional allocation, which can decrease the stability of the system. To solve this problem, a grid-forming control method of emulated rotational inertia and damping characteristics for multiple energy storage considering capacity characteristics is proposed. First, the control construction of the grid-forming inverter is presented, and the mathematical model of the grid-forming control of the emulated synchronous generator is established. Secondly, the frequency change and frequency deviation are introduced into the grid-forming control, and the grid-forming control method of emulated inertia and damping coefficient is designed. Each energy storage obtains the emulated rotational inertia and damping value through the real-time state of charge, which adjusts the frequency response of the power grid and active power of the distributed electricity storage system. And this method can realize proportional allocation according to the capacity of electricity storage system. Finally, the simulation analysis results of Matlab/Simulink simulation model is carried out to verify the effectiveness and feasibility of the proposed grid-forming control method.

Keywords: Grid-forming control; Distributed energy storage; Inertia; Damping; Coordinated control

1. Introduction
As a flexible and controllable regulating resource, electricity storage system would well enhance the output characteristics of renewable energy and enhance the new power system reliability, so it has an important role in type power system [1-3]. At the same time, distributed energy storage uses its characteristics of decentralized layout and flexible charging-discharging to solve the uncertainty of energy flow in weak grids, it improves the system reliability [4]. However, in recent years, the
cooperative control of multiple distributed energy storage and uneven load distribution is rarely considered in the new power system, which reduces the new power system reliability.

The increase in renewable energy sources poses challenges to the resiliency of the power grid. To enhance the new power system reliability, a droop control method is proposed by scholars, such as, the output characteristics of energy storage was better performance by the droop control. However, the droop control method has the characteristics of poor anti-load disturbance ability. When the control strategy is adopted, the response will be too violent, this will affect the power grid system stability. However, the poor ability of frequency can not mitigate the constant fluctuation in the supply and demand balance, which caused system oscillation and/or system stability by load variation [5-6]. There are many studies on the virtual synchronous control technology, which enables distributed electricity storage system have the external characteristics of grid-connected operation such as inertia, damping, and primary frequency control of synchronous generators (SG). In [7] shows current-controlled virtual synchronous generators that is seen to a current source. In [8-9], a current-controlled virtual synchronous generator (VSG) is proposed. In [10], a small-signal model of the current-controlled VSG is established, and the influence of parameters of current-controlled VSG on stability is studied. this paper shows that current-controlled virtual synchronous control would the responsibility to contribute to high-frequency or subsynchronous oscillation. To satisfy the demand of micro-grid on the seamless transfer of the virtual synchronous control between grid-tied and islanded operation modes, an advanced control strategy based on the phase-locked loop was proposed [11], it experimental results demonstrate that the presented control strategy can not only perform good dynamic response features on active and/or reactive tracking. However, when there is a large load disturbance in the power system, the frequency and power may fluctuate greatly.

At present, to enhance the dynamic response of frequency and power. There are many studies on the VSG based on adaptive parameter adjustment. In [12-13], the VSG based on adaptive adjusting is proposed, which effectively improved the frequency response characteristics. However, this control strategy is only applicable to the control of a single distributed energy source. In [14], enhanced adaptive control of virtual rotational inertia is studied. Meanwhile, the dynamic adjustment of virtual synchronous control active power and frequency is considered. However, the influence of damping is not considered in the paper, so that the active power of multi-micro sources is not proportional allocation, which will decrease the stability of the system.

Therefore, in this paper, a cooperative control strategy of emulated SG for the grid-forming energy storage considering capacity characteristics is proposed. Each energy storage obtains the emulated rotational inertia value and damping value through the real-time state of charge, which adjusts the frequency response of the new energy system and/or output active power of the electricity storage, and realizes proportional allocation according to the capacity of energy storage. Finally, the grid-forming control method is evaluated on Matlab/Simulink simulation in this paper.

This paper is organized as follows: the grid-forming control method of the emulated synchronous generator is presented in Section II. The coordinated control strategy of the grid-forming electricity storage is discussed in Section III. Parameter designs are proposed in Section IV. In Section V, the proposed cooperative control strategy is evaluated on Matlab/Simulink simulation. Section VI is the conclusions.

2. The grid-forming Control Method of the Emulated Synchronous Generator

2.1. Topology
The grid-forming control is to emulate the rocking equation that is originally from synchronous generators to the inverter control, which improves the frequency response and enhances the anti-disturbance capability. The control construction of grid-forming is shown in figure 1. L is filter inductor of inverter bridge. \( C_f \) is the filter capacitor of inverter bridge. \( I_{abc} \) is the current of inverter bridge. \( U_{abc} \) is the grid voltage. \( I_{abc} \) is the current of the main grid. \( P_c \) is the electricity storage output active power. \( Q_c \) is the electricity storage output reactive power.

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2.2. The Grid-forming Control

The grid-forming control of emulated synchronous generator given by

\[
\begin{align*}
\frac{d\phi}{dt} & = \psi - \psi_0 \\
K_j \frac{d\psi}{dt} & = P_m - P_e - K_p (\psi - \psi_d)
\end{align*}
\]

(1)

where, \(K_j\) is the rotational inertia value of the grid-forming control. \(P_m\) is the mechanical power of emulated synchronous generator. \(\psi_0\) is the rate angular velocity value; \(\psi\) is the real-time angular velocity value. \(\phi\) is the power-angle value. \(\psi_d\) is the virtual damping value.

To maximize the characteristics of the emulated rotational inertia control, the grid-forming control of electricity storage system is added to the prime mover model, the prime mover model is given by

\[
P_e = P_{ref} + K_v (\psi_0 - \psi)
\]

(2)

where, \(P_{ref}\) is the rate power. \(K_v\) is the adjustment value of frequency.

Equations (1) and (2), the expression would be given by:

\[
\frac{\psi_0 - \psi}{P_{ref} - P} = \frac{1}{K_j s + K_D \psi_0 + K_p}
\]

(3)

where, \(P\) is the real-time output power.

Meanwhile, in a power system containing two distributed electricity storage system, the following relationship can be obtained from equation (3)

\[
\frac{K_{11}}{K_{22}} = \frac{K_{11}}{K_{22}} = \frac{P_1}{P_2}
\]

(4)

Similarly, in a system with multiple distributed energy storage, we can obtain the proportional relationship of \(K_j, K_D, P\). Therefore, If the parameters \(K_j, K_D\) and \(P\) of distributed energy storage meet formula (4), the output power of distributed electricity storage system would be proportional allocation.

3. Coordinated Control Strategy of the Grid-forming Energy Storage

In a system with multiple distributed electricity storage system it is required to continuously adjust the rotational inertia value and damping value of the grid-forming to attenuate the oscillation amplitude during switching the distributed generation or the load disturbance, and it is also required to better obtain the dynamic response of the frequency. The emulate inertia of grid-forming control is determined by the electricity instantaneous angular velocity value change and instantaneous angular velocity derivative value. if electricity angular velocity change and electricity angular velocity deviation have the same sign, the emulate rotational inertia increases; if electricity angular velocity
change and electricity angular velocity deviation have the different signs, the emulate rotational inertia decreases. Therefore, considering the response characteristics of distributed energy storage, a dynamic adjustment technique of the rotational inertia and damping according to the electricity frequency change and electricity frequency deviation is designed. The working mode is as follows.

Operating mode 1: When the grid frequency is smaller than the set value of the system, the distributed energy storage obtains the initial inertia and initial damping according to the rated capacity. The distributed electricity storage system participates in electricity frequency adjustment of the grid if the state of charge is greater than 0.2; the distributed energy storage does not participate in electricity frequency adjustment of the grid if the state of charge is less than 0.2. The initial inertia and initial damping are given by

\[
\Delta K_{J,0i} = \frac{S_{r,i}}{S_{r,1} + S_{r,2} + \cdots + S_{r,n}} \cdot K^*_J
\]

\[
\Delta K_{D,0i} = \frac{S_{r,i}}{S_{r,1} + S_{r,2} + \cdots + S_{r,n}} \cdot K^*_D
\]

where, \(S_{r,i}(i \in 1 \cdots n)\) is the rated capacity of energy storage; \(K^*_J\) is the total initial inertia; \(\Delta K_{J,0i}\) is the initial rotational inertia of electricity storage unit; \(K^*_D\) is the total initial damping; \(\Delta K_{D,0i}\) is the initial damping of electricity storage unit.

Operating mode 2: When the grid frequency is bigger than the set value, the rotational inertia and damping were got by the frequency change rate and frequency deviation. The distributed electricity storage system participates in electricity frequency adjustment of the grid if the state of charge is greater than 0.2; the distributed energy storage does not participate in electricity frequency adjustment of the new energy system if the state of charge is less than 0.2. The inertia and damping are given by

\[
K_{J,i} = \Delta K_{J,0i} + K_f \cdot (f - 50) \cdot \frac{df}{dt} \quad \left| \frac{df}{dt} \right| > \Phi
\]

\[
K_{D,i} = \Delta K_{D,0i} + \lambda_i \cdot (f - 50) \cdot \frac{df}{dt} \quad \left| \frac{df}{dt} \right| > \Phi
\]

\[
K_f = \frac{SOC_i(t) \cdot K_f}{SOC_i(t) + SOC_{i+1}(t) + \cdots + SOC_n(t)}
\]

\[
\lambda_i = \frac{S_{r,i}}{S_{r,1}} \cdot K^*_J
\]

where, \(K_{J,i}\) is the rotational inertia of electricity storage unit; \(K_f\) is the distribution coefficient of each energy storage rotational inertia; \(f\) is the electricity frequency of the grid; \(\Phi\) is the threshold value of the grid frequency deviation; \(K_{D,i}\) is the damping of electricity storage unit; \(\lambda_i\) is the damping coefficient of each distributed electricity storage system; \(SOC_i(t)(i \in 1 \cdots n)\) is the state of charge at time \(t\); \(K_f\) is the unit electricity frequency tracking value of the electricity storage. The capability of the electricity frequency adjustment error-feedback is got by the \(K_f\), i.e., this refers to the capability of rotational inertia to follow the system electricity frequency. The unit electricity frequency tracking coefficient \(K_f\) is given by

\[
K_f = \frac{2\pi \cdot \Delta f \cdot (K_D \cdot \psi_0 + K_v)}{(K_J - K_f)}
\]
Therefore, in the multiple distributed electricity storage system, each unit adopts the emulate rotational inertia value and damping coefficient to adjust the dynamic output characteristics for the grid. This control strategy would enhance the dynamic output characteristics of the grid electricity frequency and restrain the power of the distributed electricity storage system. The distributed energy storage active power can be proportional allocation, thereby improving the stability of the system.

4. Parameter Design
The virtual rotational inertia of the proposed grid-forming control given by the University of Leuven, virtual rotational inertia of the grid-forming control is given by [15]:

\[
K_j \leq \frac{P_{\text{max}}}{\psi_0 \cdot \max(\psi \cdot \frac{d\psi}{dt})}
\]

where, \( P_{\text{max}} \) is the maximum output power. The maximum equation would be got by adopting equation (11) and (12):

\[
K_j = \frac{2\pi \cdot \Delta f \cdot (K_p \cdot \psi_0 + K_\psi)}{\psi_0 \cdot \max(\psi \cdot \frac{d\psi}{dt})} - K_j^*
\]

We can be seen from (13) where it is bound up with the electricity energy increment \( \Delta P \) for the new energy system, the maximum power \( P_{\text{max}} \) of distributed energy storage, the virtual damping \( K_p \) and the frequency change value \( K_\psi \). In practice projects, \( K_j \) would be involved and equilibrium the restraining of the direct-current source and/or the power system operating performance.

5. Simulation Analysis
To discuss the performances of the grid-forming control method, the new energy system included three distributed electricity storage units are established in simulation software. The given active power of the three electricity storage system are 15 kW, 25 kW, and 35 kW respectively. The simulation key parameter are given in table 1. The simulation is carried out through two case study of the decreased distributed electricity storage and the increased load.

| Table 1. The simulation parameters of the grid-forming control. |
|---------------|-----------|---------------|-----------|
| Main circuit parameter | Value | Controller parameter | Value |
| \( L / \text{mH} \) | 2 | \( K_j^*/(\text{kg} \cdot \text{m}^2) \) | 0.15 |
| \( C_j / \mu\text{F} \) | 40 | \( K_p \) | 15 |
| \( U_m / \text{V} \) | 700 | \( K_\psi \) | 100 |
| \( U_s / \text{V} \) | 311 | |

5.1. Increased the Load
When the system increases the load, the results of the new energy system frequency and the output power that were obtained by using the proposed coordinated control strategy and the traditional adaptive control strategy are given by figure 2 and figure 3, respectively. At start time, the total power is \( R_1=15 \text{ kW} \). At 2s, the new energy system increased a load \( R_2=15\text{kW} \).

In figure 2, at start time, the output power of DES1, DES2, and DES3 smoothly increase from 0kW to 3kW, 5kW, and 7kW, and the frequency is 50Hz. At 2s, the load R2 is put into the system, the output power of DES1, DES2, and DES3 increase smoothly from 3kW, 5kW, and 7kW to 6kW, 10kW, and 14kW, respectively. And the system frequency drops smoothly to 49.75Hz. Before and after the
load increase, the three energy storage system can all allocate active power according to their capacity when the grid-forming control method is used. The active power increase of the electricity storage and/or the frequency decrease of the new energy system are relatively smooth.

In figure 3, at the initial moment, the output power of DES1, DES2, and DES3 increase from 0kW to 1kW, 5kW, and 9kW respectively, the output power had large fluctuations. And the power grid frequency is 50Hz. At 2s, the load R2 is put into the system, the output power of DES1, DES2, and DES3 increased from 1kW 5kW and 9kW increase to 5.5kW, 10kW, 14.5kW, respectively. The system frequency is reduced to 49.75Hz, it is smaller than the system frequency of the proposed coordinated control strategy. The system frequency changes have certain fluctuations. Before and after the load increases, the distributed electricity storage system fails to allocate the active power according to its capacity when the traditional adaptive control strategy is used, and there is a certain fluctuation when the active power increases and the frequency decreases. Meanwhile, the system frequency is greatly reduced.

Therefore, when the system increased load, the grid-forming control method would enhance the dynamic response of frequency better than the traditional adaptive control method. and the proposed grid-forming control method can effectively reduce the power oscillation and/or enhance the reliability and stability of the new energy system.

5.2. Decreased Distributed Energy Storage
When the power grid reduces distributed electricity storage, the results of the frequency and output power that were obtained by using the proposed grid-forming control strategy and the traditional adaptive control strategy are shown in figure 4 and figure 5, respectively. At the start time, the active power of the load is R1=15 kW. At 2s, the power grid removes the DES2.

In figure 4, at the start time, the output power of DES1, DES2, DES3 smoothly increases from 0kW to 3kW, 5kW, and 7kW, and the frequency is 50Hz. At 2s, the load R2 is put into the system, the output power of DES1, DES2, and DES3 increase smoothly from 3kW, 5kW, 7kW to 4.5kW, 0kW, 10.5kW, respectively. And the system frequency drops smoothly to 49.8Hz. Before and after distributed energy storage decrease, the three energy storage can all allocate active power according to
their capacity when the proposed coordinated control strategy is used. The active power increase of the electricity storage and/or the electricity frequency decrease of the new energy system are relatively smooth.

In figure 5, at the initial moment, the output power of DES1, DES2, and DES3 increase from 0kW to 1kW, 5kW, 9kW, respectively; the output power had large fluctuations. And the system frequency is 50Hz. At 2s, the system removes the DES2. the output power of DES1, DES2, and DES3 increased from 1kW 5kW and 9kW increase to 3.5kW, 0kW, 11.5kW, respectively. The system frequency is reduced to 49.78Hz, it is smaller than the system electricity frequency of the proposed coordinated control strategy. The system frequency changes have certain fluctuations. Before and after the distributed energy storage reduction, the distributed electricity storage fails to allocate the active power according to its capacity when the traditional adaptive control strategy is used, and there is a certain fluctuation when the active power increases and the frequency decreases. Meanwhile, the system frequency is greatly reduced.

Therefore, when the system decreases distributed energy storage, the grid-forming control strategy would enhance the dynamic response of the power grid better than the traditional adaptive control strategy. and the grid-forming control strategy would effectively reduce the output power oscillation and strength the reliability and stability of the new energy system.

6. Conclusion
The distributed energy storage of the power grid often use the grid-forming control method of emulated synchronous generator, which improves the frequency response and enhances the anti-disturbance capability. However, the influence of the damping coefficient is often ignored in adaptive control, which leads to the poor dynamic characteristics of the power grid frequency and active power of distributed energy storage. We proposed a the grid-forming control strategy of characteristic value for emulated for energy storage considering capacity characteristics. Each distributed energy storage obtains the emulated inertia and damping coefficient through the real-time state of charge, which adjusts the frequency characteristics of the power grid and output power of the energy storage. Finally,
to carried out to verify the performances of the grid-forming control strategy, the increased load power and the decreased distributed energy storage unit have been discussed on the model. The result demonstrates that the grid-forming control method improves the dynamic response of the system better than the traditional adaptive control strategy. And the grid-forming control strategy can effectively cut down the power oscillation and improve the reliability and stability of the new energy system.

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