Active Power Sharing Method of Battery Energy Storage Systems for Frequency Control of Commercial Park Power Grids

Yue Li¹, Xiang-jun Li¹,*, Zi-cheng MAO¹, Shang-xing WANG¹, Xue-cui JIA¹, Yue-zhong TANG², Chen FANG², Hao-jing WANG² and Yu ZHANG²

¹State Key Laboratory of Control and Operation of Renewable Energy and Storage Systems, Energy Storage and Electrical Engineering Department, China Electric Power Research Institute, Beijing, 100192, China
²State Grid Shanghai Municipal Electric Power Company, Shanghai 200122, China
*Corresponding author

Keywords: Battery energy storage system, Virtual synchronous machine, Frequency regulation, Multi-machine parallel connection.

Abstract. In this paper, a frequency control method for off-grid operation of energy storage systems has been proposed with virtual synchronous control. Firstly, the single-machine mathematical model of the power converter system (PCS) controlled by the virtual synchronous machine is established. Secondly, energy storage systems based on virtual synchronous control have been analyzed. Finally, two battery energy storage systems (BESS) were built on the SIMULINK simulation platform to realize island operation of the energy storage system, which verified the effectiveness of the proposed control strategy.

Introduction

The traditional energy sources of the current power system are all integrated into the grid with synchronous generators, and the research on the power system is based on the synchronous generator. When disturbance occurs, the synchronous generator can exchange power with the grid through the energy stored in the rotor, which helps the stability of the grid. Distributed power sources are mostly incorporated into grids with power electronic grid-connected converters. Compared with synchronous generators, grid-connected converters have flexible control and rapid response[1-2]. However, because the inverter response speed is too fast and it is a stationary equipment, it cannot provide enough inertia and damping support for the grid. In order to solve the above-mentioned problems, some research results have been published.

Dinh Hoa Nguyen et al [3] proposes a novel distributed control method for frequency and voltage of distributed battery energy storage systems (BESSs) taking in account communication delays and the droop frequency/voltage control. Mehmood K K et al [4] proposes the optimal location and size of BESS to regulate voltage in a distribution system for battery lifespan. This paper proposes a frequency control method with virtual synchronous machine theory for storage-load system that can be operated on or off the power grid. This method could improve the current frequency control and active power sharing accuracy without additional hardware devices to be added into the initial loop.

This paper presents the frequency control strategy based on the isolated island operation of business park power grids. The commercial park is composed of photovoltaic, wind power, energy storage, load, etc. When the commercial park is off-grid due to distribution power grid failure and the PV power generation becomes zero in the night, it is difficult to maintain the stability of commercial park power grids. Therefore, in such case, it is necessary to have a voltage source based on virtual synchronous machine control for PCS to maintain the frequency stability of the power grids.
The Basic Principle of Virtual Synchronous Machine

This section first analyzes the control model of the virtual synchronous machine (VSM)\(^{[5-6]}\). Assuming that the number of pole pairs is 1, that is, establishing a mathematical model with a classical second-order model, the stator equation is as shown in Eq.(1)

\[
u_{abc} = e_{abc} - Ri_{abc} - L \frac{di_{abc}}{dt}
\]

(1)

\(u_{abc}\) represents the terminal voltage; \(i_{abc}\) represents the current of the VSM; \(e_{abc}\) represents the internal potential of the VSM, \(e_{abc} = E[\sin(\varphi), \sin(\varphi - 2\pi/3), \sin(\varphi + 2\pi/3)]\), where \(E\) is the electromotive force and \(L\) is the inductance. \(R\) is the resistance of the virtual synchronous machine, and the virtual inductance is conducive to power decoupling.

The rotor equation rotor is shown in Eq.(2):

\[
J \frac{d\omega}{dt} = T_m - T_e - T_d
\]

(2)

In equation (2), \(J\) is the rotational inertia of the synchronous machine; \(\omega\) is the mechanical angular velocity; \(T_m\) and \(T_e\) are the mechanical and electromagnetic torque; \(D_p\) represents the damping coefficient; \(\omega_n\) is the rated angular velocity; \(P_m\) is the mechanical power of the virtual synchronous machine; \(P_e\) is the energy storage change Electromagnetic power output from a virtual synchronous generator.

Virtual Synchronizer Control Algorithm

Frequency Droop Control

In order to more accurately simulate the characteristics of the synchronous machine, the adjustment equation of the prime mover is added to the virtual synchronous machine control, as shown in Figure 1.

The prime mover adjustment equation in Figure 1 is shown in Eq. (3):

\[
P_m = P_{set} + k_f (\omega_{ref} - \omega)
\]

(3)

By controlling the virtual mechanical power \(P_m\), the adjustment of the grid frequency is achieved. That is, the mechanical power command \(P_m\) is composed of two parts, the power set value \(P_{set}\) and the power deviation feedback command \(k_f (\omega_{ref} - \omega)\).

Voltage Droop Control

The expression of the VSM reactive voltage droop control is shown in Eq.(4).
In the formula, $E_0$ is the empty potential. $Q_{ref}$ is the reactive power setting; $Q_e$ is the reactive power output by the VSM, and $K_v$ is the reactive droop coefficient. Figure 2 shows the reactive power droop control block diagram.

![Diagram of reactive power droop control](image)

**Figure 2. Active frequency droop control.**

### Inertia Matching and Frequency Control of Parallel BESS

Droop control introduces Eqs (2) and (3) in the PCS, and the internal electromagnetic characteristics of the PCS simulate the synchronous machine, so that the PCS has the internal operating mechanism of the synchronous generator (synchronization mechanism) and external features\(^{[7-8]}\).

Eqs. (5) and (6) can be obtained according to Eqs (2) and (3).

\[
\frac{w_0 \omega - w}{P_{ref} - P} = -\frac{1}{Jw_0 \omega + Dw_0 + k_f} = -\frac{m_p}{\tau s + 1}
\]

\[
\begin{align*}
\tau &= \frac{Jw_0}{Dw_0 + k_f} \\
m_p &= \frac{1}{Dw_0 + k_f}
\end{align*}
\]

(5)

When the system is operating stably, each converter in the system must operate at the same frequency. Assuming that the active power is accurately distributed, and the proportional relationship between the power commands is set $P_{ref} = nP_{ref2}$.

\[
m_{p1}P_{ref1} = m_{p2}P_{ref2}
\]

(7)

When multiple PCSs are operated in parallel, each PCS should have the same time constant $\tau$ when the load disturbance frequency shifts.

\[
\tau_1 = \tau_2
\]

(8)

And on the premise of system stability, the output reactive power of each virtual synchronous machine does not affect their respective output active power. Therefore, the active power is distributed according to the proportion. In combination with Eqs. (7) and (8), the following inertia matching principle can be obtained.

\[
\begin{align*}
\frac{J_1}{J_2} &= \frac{D_1}{D_2} = \frac{K_{w1}}{K_{w2}} = \frac{m_{p1}}{m_{p2}} = \frac{P_{ref1}}{P_{ref2}}
\end{align*}
\]

(9)

For the PV-storage-load based commercial park power grids, to verify the frequency adjustment performance of the BESS based on virtual synchronous machine control, only short-term windless conditions are considered. Based on the Simulink simulation platform, BESS simulation model
based on the control of two 500kW virtual synchronous based PCS in parallel have been constructed, and it is assumed that the load suddenly increases at a certain moment.

The following describes the two parallel-connected models of energy storage batteries based on virtual synchronous machine control. The rated power of each energy storage is 500 kW and the total maximum load is 1000 kW. At the time of 3.5 seconds, the load suddenly changes 120kW. Because the discharge power of BESS is limited by its capacity, it is assumed that the remaining capacity of the second BESS is greater than that of the first one. Therefore, the power command for the first BESS is now set to 350 kW, the power command for the second BESS is set to 450 kW, and the damping coefficient, inertia coefficient, active droop coefficient of each PCS is based on Eq. (9).

The common bus frequency, current, voltage, and active power results obtained by simulation are shown as Figs. 3-6. The partial enlarged view of common bus current is shown in Figure 6. As can be seen from Figure 3, a virtual synchronous machine based on BESS control can effectively implement no-frequency control.

![Figure 3. Common node frequency.](image)

![Figure 4. Total active power of parallel BESS output.](image)

![Figure 5. Common bus voltage.](image)

![Figure 6. Partial enlarged view of common bus current.](image)

The output power of each parallel PCS is shown in Figure 7. Before the sudden load change at 3.5 seconds, each PCS operates stably at the respective set power. After 3.5 seconds, the load suddenly increases. Due to the virtual inertia, the output power of each PCS reaches a steady state power after a certain period of time. And it can be seen from Figure 7 that due to the adaptation of parameters such
as virtual inertia and damping, the ratio of the power increment of each power step of the PCS to the set value of the power command is equal. The ratio is 1.25 times.

![Figure 7. Active power of each parallel BESS output.](image)

**Summary**

When the load disturbance occurs, the dynamic characteristics of the commercial park power grid system are related to the damping and inertia. Therefore, in order to optimize the frequency of the BESS virtual synchronous machine, suitable damping and inertia should be selected. Based on the off-grid operation of commercial park power grid, this paper proposes the frequency control method to realize the dynamic droop characteristics and the maintenance of system voltage. The theoretical and experimental results show that the proposed control method is easy to implement the frequency control and can ensure the system voltage quality.

**Acknowledgment**

This work is supported by State Grid Science & Technology Program “Research and Demonstration of Key Technologies of 'Generation-Storage-Load' Coordinative Operation in Commercial Districts” (52094016000F).

**References**


