International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 941

THIRD-ORDER SYNCHRONOUS MACHINE MODEL BASED ACTIVE SUPPORT CONTROL OF BESS AND ITS CONTRIBUTION ANALYSIS FOR PRIMARY FREQUENCY RESPONSE

Yanfeng Ge[1], Tong Sun[2], Chuang Liu[2*], Chenqi Wang[3], Jinning Shan[3], Xin Wang[3]

1 State Grid Liaoning Province Electric Power Company Limited, Shenyang 110006, Liaoning Province, China;

2 School of Electrical Engineering, Northeast Electric Power University, Jilin 132012, Jilin Province, China;

3 Fuxin Power Supply Company, Liaoning Electric Power Company Limited, State Grid, Fuxin 123000, Liaoning Province, China

ABSTRACT

In this paper, an active support control strategy based on the third-order model of synchronous generator is proposed for battery energy storage system in renewable energy systems. The control strategy converts grid-connected inverters of energy storage system into synchronous voltage sources with excitation and speed control systems, which provides necessary inertia and damping characteristics for grid-connected renewable energy sources. The difference coefficient $\sigma_{battery}$% of the BESS is defined by the power-frequency proportional coefficient K_m and the damping coefficient D. By setting the difference coefficient $\sigma_{battery}$%, it is possible to control the frequency modulation depth of the BESS to participate in the primary frequency response of renewable power generation system. The output power for primary frequency response of the synchronous generator is reduced, and the steady frequency deviation of the system after primary frequency modulation can be reduced. Therefore, the frequency stability of the renewable energy systems for power generation are improved.

Keywords: BESS, active-supporting control, primary frequency response

NONMENCLATURE

Abbreviations

BESS	Battery energy storage system
SOC	State of charge
PV	Photovoltaic
SG	Synchronous generator
EMF	Electronic manufacturing facility
RoCoF	Rate of change of frequency

Symbols

H	Virtual inertia
D	Damping coefficient
P_m	Mechanical power
P_e	Electromagnetic power
δ	Power angle
ω	Angular frequency
ω_0	Rated angular frequency
T_{d0}'	Transient time constant
E_d'	Direct-axis transient EMF
E_q'	Quadrature-axis transient EMF
E_{dref}	Direct-axis EMF reference value
E_{qref}	Quadrature-axis EMF reference value
E_{qe}	No-load EMF
i_d	Direct-axis current
i_q	Quadrature-axis current
x_d	Direct-axis synchronous
x_d'	Direct-axis transient reactance
r	Virtual stator resistance
x	Virtual stator reactance
P_{bref}	Active power reference value of BESS
P_{b0}	Active power measurements of BESS
K_m	Power-frequency proportional coefficient
f_{meas}	Frequency measurements of BESS
f_{ref}	frequency reference value
U_{meas}	Voltage measurements of BESS
U_{ref}	Voltage reference value
x_{ad}	Direct-axis armature reaction reactance
r_f	Field of quotient resistance
K_f	Excitation proportion coefficient
u_f	Excitation voltage

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

$K_{battery}$	Unit power regulation of BESS
$\sigma_{battery}\%$	Difference coefficient of BESS
Δf	Steady-state frequency deviation
$\Delta P_{battery}$	Frequency modulation output of BESS
$\Delta P_{battery\text{-}max}$	Maximum frequency modulation output of BESS
$P_{battery\text{-}N}$	Rated active power of BESS
P_N	Active power reference value
f_N	Frequency reference value
$E_{battery}$	Rated capacity of BESS
$\eta_{battery}$	Ramp rate of BESS
K_G	Unit power regulation of SG
K_L	Unit power regulation of aggregate loud
λ	Contribution factor of BESS
K_{GN}	Total unit power regulation of SGs
$K_{batteryN}$	Total unit power regulation of BESS
$\sigma_{batteryM}\%$	Total difference coefficient of BESS

1. INTRODUCTION

Since renewable energy generation and its grid-connected inverter ports have almost no damping and inertia, the renewable energy generation system exhibits low inertia and weak damping characteristics [1]. Flexibility according to the absorbed power or output power of BESS, The battery energy storage power station can stabilize the unbalanced power in power system and improve the frequency stability support capability of the renewable energy power generation system. A grid friendly photovoltaic and battery energy storage system (PV/BESS) hybrid distributed generation (DG) was proposed based on virtual synchronization generator (VSG) grid interface [2].

Based on the above theory, this paper proposes an active support control strategy for the BESS with the third-order model of synchronous generators. The control model simulates the excitation regulator and speed regulator of synchronous generator, and provides necessary inertia and damping characteristics for grid-connected inverter of BESS .Through the design of the adjustment coefficient, and analyzes the dynamic process of the battery energy storage power station participating in the primary frequency response of the power grid, and discusses the influence of the frequency stability of the renewable energy power generation system in the frequency modulation depth of BESS. Finally, a simulation example is given to verify the effectiveness of the proposed control strategy and theory.

2. ACTIVE SUPPORT CONTROL STRATEGY BASED ON THE THIRD-ORDER MODEL OF SG

2.1 Third-order model of SG

The overall control structure of BESS based on the third-order model of synchronous generator is shown in Fig. 1.

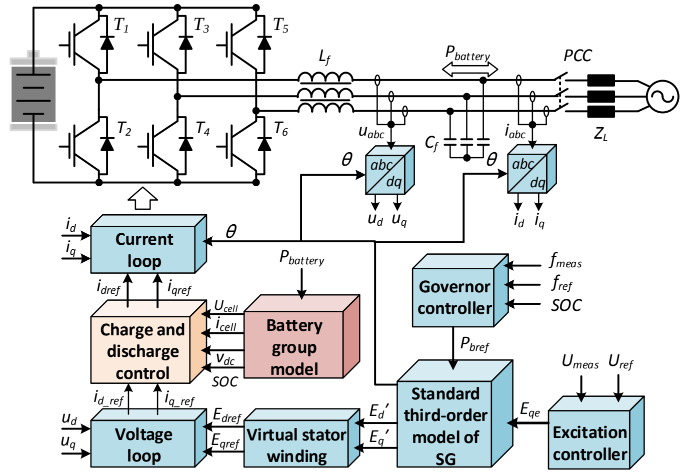

Fig 1 active support control strategy based on third-order model of SG.

In order to simulate the excitation system and the speed regulation system of SG, and make grid-connected inverters of BESS have inertia characteristics and damping characteristics. A standard third-order model of SG is established based on the second-order rotor motion equation and the first-order transient electromotive force equation. As shown in formula (1).

$$\begin{cases} 2H\dfrac{d\omega}{dt} = P_m - P_e - D\Delta\omega \\ \dfrac{d\delta}{dt} = \omega_0\omega \\ T_{d0}{}'\dfrac{dE_q{}'}{dt} = E_{qe} - E_q{}' - i_d(x_d - x_d{}') \end{cases} \tag{1}$$

For the safe operation of the grid-connected inverter, the virtual stator winding link is introduced between the internal potential of the BESS grid-connected inverter and the external node voltage. As shown in formula (2).

$$\begin{cases} E_{dref} = E_d{}' - I_d r + I_q x \\ E_{qref} = E_q{}' - I_d x - I_q r \end{cases} \tag{2}$$

The virtual stator winding can adjust the output impedance of grid-connected inverter, solve the power coupling problem caused by the resistive component in the line impedance, and satisfy the power decoupling condition of the active support control. The standard third-order model of SG is shown in Fig.2.

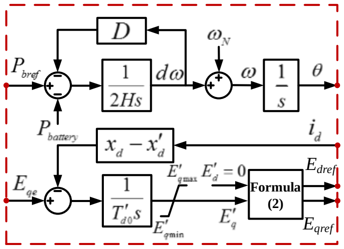

Fig 2 Third-order model of synchronous generator

2.2 *Governor controller model*

The governor controller simulates the static characteristics of SG, and realizes the automatic distribution of the active power between the multi-units in the renewable energy power generation system [4]. As shown in formula (3).

$$P_{bref} - P_{b0} = K_m (f_{meas} - f_{ref}) \tag{3}$$

In order to restrain the frequent charge and discharge of battery energy storage system, the dead zone of frequency regulation of battery energy storage power station is set at (50±0.033) Hz. Figure 3 shows governor controller model.

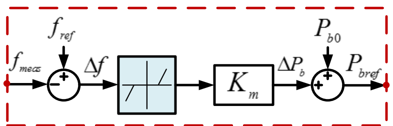

Fig 3 Governor controller model

The relationship between frequency deviation and power deviation of renewable energy power generation system is shown in formula (4).

$$\frac{\omega - \omega_0}{P_{b0} - P_{bref}} = -\frac{1}{J\omega_0 s + D\omega_0 + K_m} \tag{4}$$

2.3 *Excitation controller model*

The automatic regulating excitation system of synchronous generator is simplified to an equivalent first-order inertia link expressed by the deviation quantity. As shown in formula (5).

$$(U_{meas} - U_{ref}) \times \frac{K_e}{1 + T_e s} = \Delta u_f \tag{5}$$

The relationship between excitation voltage and no-load EMF is shown in formula (6).

$$E_{qe} = \frac{x_{ad}}{r_f} u_f = K_f u_f \tag{6}$$

Thus, the relationship between the inverter terminal voltage deviation and the no-load electromotive force is obtained, as shown in formula (7).

$$\frac{\Delta E_q{}'}{U_{meas} - U_{ref}} = \frac{K_e K_f}{(1 + T_e s) T_{d0}{}' s} \tag{7}$$

Figure 4 shows the excitation system controller model.

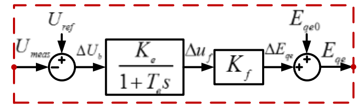

Fig 4 Excitation system controller model

The inner loop controller adopts a voltage and current double closed loop control structure based on dq decoupling, and is divided into voltage outer loop control and current inner loop control, and the energy storage power station is equivalent to a synchronous voltage source.

3. FLEXIBILITY ANALYSIS OF BESS

3.1 *Flexibility indicators of BESS*

As shown in figure 5, flexibility of BESS can be characterized along three dimensions: first, the absolute power output capacity range (MW); second, the speed of power output change, or ramp rate (MW/min); and third, the duration of energy levels (MWh). Figure 4 illustrates these three dimensions [3].

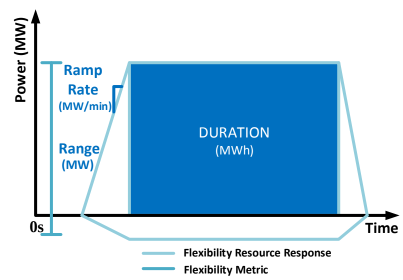

Fig 5 Illustration of three dimensions for flexibility: range, ramp rate, and duration.

3.2 *Flexible configuration of BESS*

It can be seen from the control model that the primary frequency output of BESS is divided into two parts, namely, the droop control component and the damping component. As shown in Equation (8).

$$\Delta P_{battery} = -(K_m \Delta f - D\Delta\omega) \tag{8}$$

Then the Unit power regulation of BESS can be expressed as formula (9).

$$K_{battery} = -\frac{\Delta P_{battery}}{\Delta f} = (K_m - D) \tag{9}$$

Difference coefficient of BESS can be expressed as formula (10).

$$\sigma_{battery}\% = \frac{1}{K_{battery}} \times 100 = \frac{1}{K_m - D} \times 100 \tag{10}$$

BESS distributes part of power support according to its own difference coefficient when the load of power system fluctuates, and contributes to frequency modulation output. Then frequency modulation output of BESS is shown in Formula (11).

$$\Delta P_{battery} = -\frac{\Delta f P_N}{f_N \sigma_{battery}\%} \tag{11}$$

The normal steady-state frequency change of the power system does not exceed ±0.2Hz of the frequency reference value, and the maximum frequency-modulated output is the absolute power output capacity range of BESS, as shown in Equation (12).

$$P_{battery-N} = -\frac{\Delta f P_N}{f_N \sigma_{battery}\%} = -\frac{\pm 0.004}{\sigma_{battery}\%} P_N \tag{12}$$

According to the power system frequency modulation duration (including primary frequency regulation and secondary frequency regulation) is about 30min, the duration of energy levels configuration is:

$$E_{battery} = P_{battery-N} * 0.5h \tag{13}$$

Considering that the primary frequency response time of the system is 10s to 15s, BESS needs to complete the power output before the end of primary frequency modulation. The speed of power output change or ramp rate of BESS should satisfies constraint as shown in Equation (14).

$$\eta_{battery} = \frac{\Delta P_{battery-\max}}{10s} \tag{14}$$

4. PARTICIPATE IN PRIMARY FREQUENCY RESPONSE PROCESS ANALYSIS OF BESS

Battery energy storage system participating in power system dynamic frequency modulation process will be divided into two stages, namely inertia response stage and primary frequency response stage. In the inertia reaction stage, the virtual inertia of BESS and the actual inertia of SGs together provide inertia support to reduce RoCoF at the initial time of load fluctuation. In the primary frequency response stage, BESS has similar static frequency characteristic as SG. According to unbalanced power absorbed or released by $K_{battery}$ in power system. Traditional units recover their rotational kinetic energy by absorbing the frequency modulation output of BESS, so that steady frequency deviation of power system can be obtained.

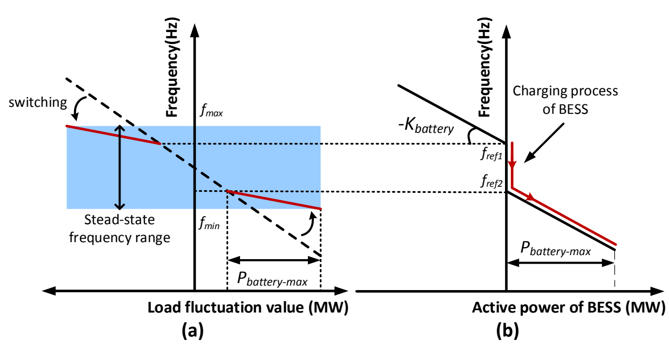

Fig 6 Power-frequency characteristic curve

When frequency rise exceeds the right boundary of the frequency dead zone, BESS absorbs energy from the power system by multiplying the frequency deviation and the unit regulated power as the charging power energy; When the system frequency drops beyond the left boundary of the frequency dead zone, BESS releases energy to the power grid by multiplying the frequency deviation and the unit regulated power as the discharge power energy. The static frequency characteristic curve of BESS is shown in Fig. 6(b), the expression is as shown in the formula (15).

$$P_{battery} = \begin{cases} -K_{battery}(f_{meas} - f_{ref}) & f_{meas} \geq f_{ref1} \\ 0 & f_{ref2} < f_{meas} < f_{ref1} \\ -K_{battery}(f_{meas} - f_{ref}) & f_{meas} \leq f_{ref2} \end{cases} \tag{15}$$

The characteristic curve of relationship between load fluctuation and frequency of BESS is shown in Fig. 5(a). When the frequency fluctuation exceeds the dead zone, BESS begins to participate in the primary frequency response of power system, and the load fluctuation and frequency relation curve are switched in the range beyond frequency dead zone. Steady-state frequency of BESS can be stabilized in range of (f_{min}, f_{max}) by reasonable allocation of flexibility and difference coefficient.

5. PARTICIPATE IN PRIMARY FREQUENCY RESPONSE CONTRIBUTION ANALYSIS OF BESS

As the static frequency characteristic of BESS is a positive adjustment process mapped by the frequency deviation to the frequency modulation output. Therefore, the frequency modulation output of BESS involved in the primary frequency response of power system caused by load fluctuation will not negatively affect the frequency change of the system.

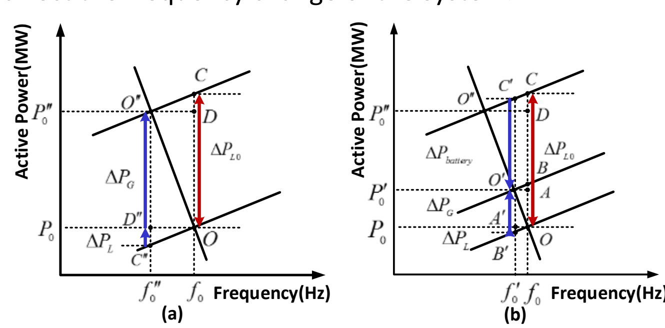

Fig 7 Primary frequency response characteristic cure of power system

The primary frequency process of BESS participating in power system is shown in Fig. 7(b). C'O' represents the active power output of the primary frequency modulation of BESS. A'O' is the primary frequency modulation active power output of SG. B'A' represents the self-regulating power of load in the primary frequency response process. The combination of BESS, traditional synchronizers and integrated loads share unbalanced power to achieve a new stable operating point for renewable energy generation systems. The system frequency decreases from f_0 to f_0', as shown in formula (16).

$$\Delta P_{L0} = \Delta P_{battery} + \Delta P_G + \Delta P_L = -(K_{battery} + K_G + K_L)(f_0' - f_0) \quad (16)$$

According to the forward static frequency characteristics of battery energy storage system, the difference coefficient of storage power station determines the active power output of BESS participating in primary frequency response of power system.

When traditional generators and BESS participate in primary frequency response in power system, the total unit power regulation of traditional generators as shown in formula (17).

$$K_{GN} = K_{G1} + K_{G2} + \cdots + K_{Gn} = \sum_{i=1}^{i=n} K_{Gi} \quad (17)$$

The total frequency modulation output of traditional generators as shown in formula (18).

$$\Delta P_{GN} = -K_{GN}\Delta f = -\sum_{i=1}^{i=n} K_{Gi}\Delta f \quad (18)$$

The traditional generator equivalent difference coefficient as shown in the formula (19).

$$\frac{\sigma_{GN}\%}{100} = \frac{1}{K_{GN*}} \quad (19)$$

The total unit regulation power of BESS as shown in formula (20).

$$K_{batteryM} = K_{battery1} + K_{battery2} + \cdots + K_{batterym} = \sum_{j=1}^{j=m} K_{batteryj} \quad (20)$$

Formula (21) shows the total frequency modulation output of BESS.

$$\Delta P_{batteryM} = -K_{batteryM}\Delta f = -\sum_{j=1}^{j=m} K_{batterym}\Delta f \quad (21)$$

The equivalent difference coefficient of BESS as shown in formula (22).

$$\frac{\sigma_{batteryM}\%}{100} = \frac{1}{K_{batteryM*}} \quad (22)$$

The ratio of the total frequency modulation output of BESS to the total frequency modulation output of SGs is defined as the contribution factor of BESS participating in the primary frequency response of power system, as shown in the formula (23).

$$\lambda = \frac{\Delta P_{battery} / P_{bN}}{\Delta P_G / P_{GN}} = \frac{\sum_{i=1}^{n} K_{battery-i}\Delta f / P_{bN}}{\sum_{j=1}^{m} K_{G-j}\Delta f / P_{GN}} = \frac{\sigma_{GN}\%P_{GN}}{\sigma_{batteryM}\%P_{bN}} \quad (23)$$

6. RESULTS AND DISCUSSIONS

In order to verify the correctness of the proposed theory, the system structure including photovoltaic power station, BESS and synchronous generator is simulated and built. The rated power of photovoltaic power station is 50MW, that of BESS is 30MW, that of synchronous generator is 100MW, and that of comprehensive load is 110MW. The text system is shown in Fig. 8.

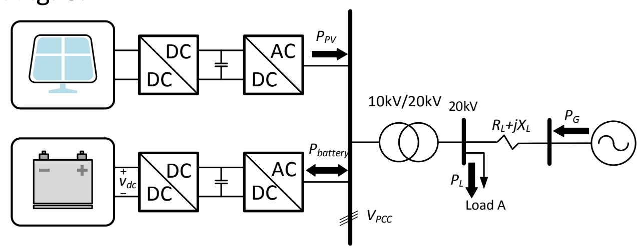

Fig 8 Text system

When the damping coefficient D=20, the comprehensive load increases 10MW suddenly at t=200s. From the Fig. 9, it can be seen that with the increase of virtual inertia H, the dynamic response overshoot with active power of BESS increases, the change rate of output power decreases, and the dynamic time of primary frequency response increases. However, due to the discharging rate characteristics of storage battery, the capacity to provide power support in inertia response stage is limited, so different virtual inertia only affect the frequency recovery process of primary frequency response.

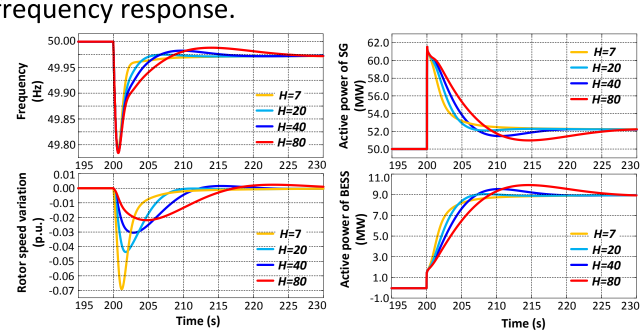

Fig 9 Primary frequency response characteristics with different virtual inertia H

Figure 10 shows that with the increase of damping coefficient D, the effect of suppressing frequency oscillation in primary frequency response is more obvious, reduction of output active power overshoot of BESS, and enhanced frequency stability of renewable energy grid-connected power generation system.

The virtual inertia J=10 and damping coefficient D=20 are selected to compare the active power output of the primary frequency response of BESS participating in the system under different difference coefficient $\sigma_{battery}\%$.

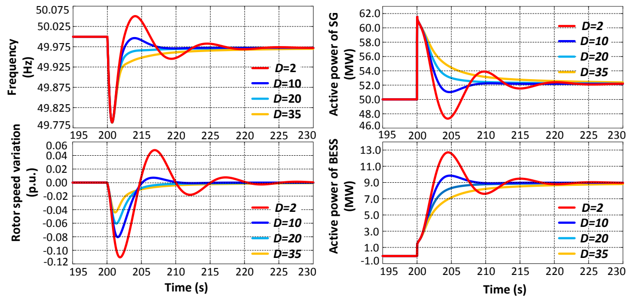

Fig 10 Primary frequency response characteristics with different damping coefficient D

Figure 11 shows that with increase of the difference coefficient, the frequency modulation output of BESS decreases, the change value of rotor speed in primary frequency response increases. The increase of frequency modulation output of SG leads to the increase of steady-state frequency deviation after primary frequency response.

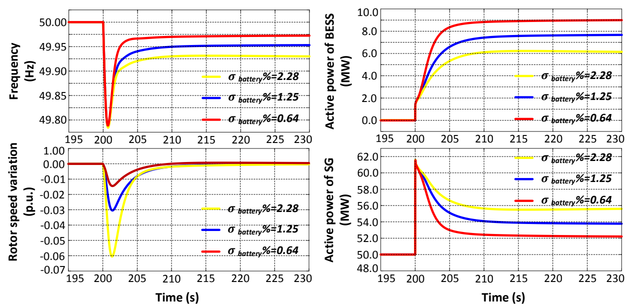

Fig 11 Primary frequency response characteristics with different difference coefficient $\sigma_{battery}\%$

Table 1 shows the contribution factors of BESS participating in primary frequency response of power system under different difference coefficients. Contribution factor characterizes the contribution of BESS to primary frequency modulation.

Table 1 Primary frequency response comparison of BESS with different $\sigma_{battery}\%$

$\sigma_{battery}\%$	Δf/Hz	ΔP_G/MW	$\Delta P_{battery}$/MW	λ
0.64	0.029	2.08	8.98	4.317
1.25	0.048	3.35	7.51	2.242
2.28	0.069	5.27	5.94	1.127

In order to maintain the steady-state frequency of the system in the range of 50±0.1Hz, Select the parameter H=10, D=20, $\sigma_{battery}\%$=0.64, simulate continuous load fluctuations of text system. The simulation results are shown in Figure 12. When the system is equipped with BESS, synchronous generators recover their rotor kinetic energy by absorbing the output active power of BESS. The steady-state frequency of the power system can be maintained in a stable range after multiple load fluctuations, thus providing a frequency-friendly power system environment for renewable energy grid-connected. Meanwhile, BESS can flexibly adjust unbalanced power in power system according to real-time variation.

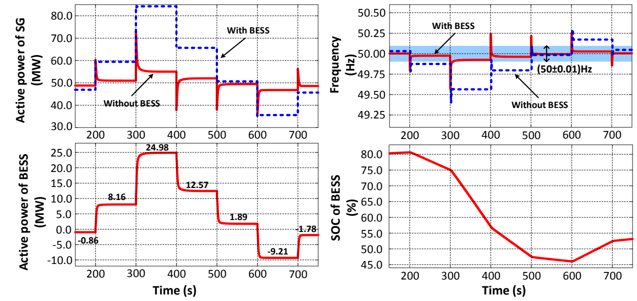

Fig 12 Primary frequency response with continuous load fluctuation

7. CONCLUSIONS

The active support control of BESS based on the third-order model of synchronous machine is proposed. The difference coefficient $\sigma_{battery}\%$ of BESS is defined. By designing $\sigma_{battery}\%$, the frequency modulation output of BESS participating in primary frequency response of the system can be controlled, and the steady frequency deviation of the system after primary frequency response can be reduced. The contribution factor of BESS is defined to measure the contribution of BESS to primary frequency response of power system. Through the rational allocation of energy storage, the capacity of BESS to provide frequency modulation auxiliary services on the grid side can be improved.

ACKNOWLEDGEMENT

Project supported by Research Program of State Grid Corporation of China (Research on Stability Control Technology for Regional Power Grid with Renewable Energy Supported by Energy Storage).

REFERENCE

[1] Wen Y, Dai Y, Daqiang B I, et al. A Grid Friendly PV/BESS Distributed Generation Control Strategy [J]. Proceedings of the C see, 2017, 37(2):464-475.

[2] Yingjie T, Muttaqi K M, Paul C P, et al. Enhanced Frequency Regulation Using Multilevel Energy Storage in Remote Area Power Supply Systems [J]. IEEE Transactions on Power Systems, 2018:1-1.

[3] Ela E, Milligan M, Bloom A, et al. Wholesale electricity market design with increasing levels of renewable generation: Incentivizing flexibility in system operations [J]. The Electricity Journal, 2016, 29(4):51-60.

[4] Serban I, Marinescu C. Control Strategy of Three-Phase Battery Energy Storage Systems for Frequency Support in Microgrids and with Uninterrupted Supply of Local Loads [J]. IEEE Transactions on Power Electronics, 2014, 29(9):5010-5020.