SMES Device Charged by Renewable Energy Used to Regulate Frequency of Interconnected Power System

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Abstract: - Development and utilization of renewable energy source (RES) is an important content of global energy development strategy. Being restricted by natural conditions, the output characteristic of renewable energy generation is stochastic. If renewable energy generator units be connected with public grid directly, it will result in the instability of power grid. In this paper, apply wind power as an example, using renewable energy as charge power supply for Superconducting Magnetic Energy Storage (SMES) systems. SMES device possesses some advantages of high efficiency, fast response and good capability of exchange active and reactive power independently with power system. It is a new idea for developing renewable energy. SMES can regulate output depending on load changing on time, which can stabilize fluctuation of frequency and reduce unnecessary power flow among tie lines. Simulation result proved that SMES not only can improve frequency effectively, but also can resolve the defect of inadequate spinning reserve.

Key-Words: - renewable energy, SMES, reserve capacity, primary frequency modulation. Automatic generation control (AGC)

1 Introduction*

For saving energy and controlling emission, in 2007, the policy of *energy conservation power generating and distribution code (trail)* [1] was pushed by State Council General Office of China. During the last few years, development and utilization of renewable energy source (RES) is an important content of China's energy development strategy too [2-3]. Compared with traditional generation technology, RES overcomes some weak of conditional generation technology. It will reinforce practice power grid. It also provides a new approach to use RES. So, in [1], in the order of every kind of generation units, wind energy source, solar energy source and other renewable energies source are on the first place to generate electric power.

The ability of primary frequency (PF) regulation of power grid is an important indication of system security. If all of generator units connected with public grid quit their PF devices, the 'self-adjustment' character of whole system would become deterioration. In China, the reason that PF device input rate is very low is as following. First, many operation staff do not realize the importance of PF. Secondly, when generator units throw in PF device, once frequency fluctuates frequently, it will wear out generator units. Last, there is not perfect incentive policy about PF regulation, so positivity of throwing in PF device can not be mobilized. Many PF devices were quit or were set big dead-band value to escape PF regulation [4-5]. These measures attempting to escape PF regulation will increase burden of generation units which are assigned to automatic generation control (AGC) system. In normal, there are two kinds of AGC policies. One policy is based on super-short-term load forecasting [6]. The other one is lag control [7]. No matter lead or lag control policy, there must be disparity on time comparing with disturbance of load happening. So, regulation of generation output always overshoots or undershoots. Furthermore, if spinning-reserve of local-area is insufficient, it needs support from external area. So, it will result in not only the increase of burden of tie-line, but also fee of auxiliary-service to be paid.

Among all renewable energies, because of its economy, wind energy possesses the best prospect.

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The exploitation of wind energy is development strategic of China and one of measures used to regulate the power configuration. Wind energy is characteristic with clean, renewable and low cost. But, the stochastic characteristic of wind power output can not be ignored too. It will result in the fluctuation of power output. Therefore, if the wind power is connected with power system directly in large scale, it will be possible to cause the affect on the peak-load regulation, frequency regulation, power quality, electric network power flow and transient stability [8-10].

Based on these factors showed above, we apply wind energy as an example for analysing the practical problems which exist in the wind power supply. Differing with the conventional ideas, we propose that renewable generation units were not connected to the power grid directly, but applying them as the charge source supply for storage equipments. These storage equipments may be used as spinning reverse of primary frequency regulation and AGC regulation [11]. In this paper, wind energy, the renewable energy, is used as the charge power supply of SMES device, this application not only provide the charge power supply, but also may eliminate the direct impact on the power grid while wind generation units are connected public grid directly. The advantage of quick response of SMES device may be exploited for regulating the system frequency, and that avoiding the excess wearing, simultaneously, the SMES device may make up deficiency of system reverse and improve the power quality.

The configuration of this paper is as follows. In Section 2, we will introduction SMES and discuss technical characteristic of SMES. Action control and power release characteristics of SMES will be discussed in this section too. In Section 3, based on the feasibility analysis of Section 2, how SMES devices coordinating with frequency modulation units will be analyzed. Both primary frequency regulation and AGC regulation will be considered. In Section 4, simulation model will be described. In order to consider complexity of interconnected power system, triple-area primary and AGC regulation model will be adopted. In the following Section 5 and 6, simulation results and conclusions will be described.

2 Introduction of SMES

In 1975, Superconducting Magnetic Energy storage (SMES) was discussed in reference [11] already. The reference point out, as the cost of fossil fuel had increased and the load factors on electric utilities had decreased, the need for efficient, reliable energy storage systems increased. With the technical development, smart grid concept was put forward. Where, how to combine stochastic renewable energy source with storage device is an important point.

2.1 Technical characteristic of SMES

High speed development of Flexible AC Transmission Systems (FACTS) makes significant pole in enhancing the stability, reliability and safety of power system. SMES device is energy storage equipment which the energy was stored in the coil of SMES. This technology is an active combination of the FACTS and superconducting power technology [12-16].

SMES exploit the coil manufactured from superconductor to storing magnetic energy. When power was transported, the energy type is not needed to be changed, moreover, the energy conversion has the advantage of high response speed, high conversion efficiency and large specific capacity (1-10Wh/kg)/specific power (104-105kW/kg), it is very convenient for transporting large capacity of energy from SMES devices to power grid and power compensation. From the technical viewpoint, SMES device is uncomplicated, besides the vacuum and cooling system, the device has no rotating components. Therefore, SMES device has the advantage of long service lifetime, the installation location is not restricted. Moreover, the maintain procedure is simple and free-pollution. Nowadays, the 1-5MJ/MW low temperature of SMES device has been manufactured as products in the worldwide, 100MJ of SMES device has be running in the high voltage power system, feasibility and technology analysis on 5GWh of SMES device has been completed. SMES device may satisfy with these requirements from voltage stability of transmission and distribution system, power compensation, frequency regulation, and that it can improve the stability of power system and enhance the transmission capacity [17].

Based on those advantages mentioned above, SMES device become an important research subject which many researchers were interest in. US, Japanese and Russian have made comprehensive research. Adopting US as example, since 1971, some researchers found out that the storage equipment of power energy can sufficiently suppress the oscillation of power system, which consists of superconductor inductance coil is characteristic with the high response speed.. By 1982, LASL and BPA (Bonneville Power Administration) work together to building the 30MJ/10MW of SMES system, this system suppressed the low frequency of 0.35Hz spontaneous oscillation on the 500 kV, double-loop line of 1500kM from the North-West Region in the Pacific Ocean to the South Galifornia [18]. In China, researching on low temperature superconducting technology began at the last 1950. In recent 40 years, a number of studying works have established the basis of superconductor material and technology. Tsinghua University and Electrician Institute of China have developed corporately the controllable storage equipment of 20kJ/15 kW superconductor. This device can ensure the total harmonic wave distortion at about 9% from the total output of AC current [19]. 35kJ/7 kW of direct-cooling high temperature SMES specimen had been developed corporately by Technology University of Huazhong and many companies. Moreover, dynamic simulation test was implemented on the sample. Test results showed that SMES device can restrain the power oscillation caused from the short-circuit fault and improve the stability of power system effectively [20].

2.2 Action control and power release characteristics of SMES

Numerous studying shows that the transform efficiency of SMES up to above 96%, the release speed of power is fast, and commonly several tens milliseconds be needed only. Based on the demand of large power system, we can control the trigger angle for implementing the control of active and/or reactive power from the SMES for large power system, and that can control the active or reactive power separately. From this viewpoint, SMES device can be considered as a FACTS device which can exchange active or reactive power with power system. Setting the reasonable control law, the stability of power system can be improved effectively. The passive stability of power system was changed as the initiative stability.

The AC/DC converter device of controllable SMES device has voltage-type and current-type. Main circuit structure of current-type converter can be equivalent to a controllable current source. Amplitude and phase angle of Output current can be regulated by changing the modulation ratio of pulse width modulation (PWM) and trigger angle of switch component, so active and reactive power regulation can be implemented in four quadrants conveniently [13]. Comparing to voltage-type converter, the current-type converter possesses more capacity to provide reactive power, so the voltage fluctuation on SMES device was decreased effectively. Moreover, it is feasible to implement multi-bridge parallel in high power application case. Voltage-type converter was applied widely, and can be used to compensating the bus-bar voltage [21]. The reference [22] shows that when applying current-type converter of multi-pulse, the voltage fluctuation of superconductor coil can be restricted, at the same time, the power loss was decreased successfully, so the current-type converter is the optimal choice for high power of SMES device. During discharging, whether voltage-type or current-type converter, they can continue to supply power for some certain time, so the stability of power output is assured.

2.3 Charging power source of SMES device

This paper presents applying the wind energy as the charging power source of SMES device for making up a deficiency of spinning reserve of primary and secondary frequency regulation. When the SMES device was installed at the bus-bar of outlet of wind farm, it is convenient to regulate the frequency of power system quickly. Besides, like the wind farm, the large-sized of SMES device may also be installed at the bus-bar of outlet of the pumping water stored energy plant, heat power plant, garbage power plant and tidal power station. When the generating capacity is instable or excess, may charge the SMES device, as well as avoiding the direct impact. While the system stability and power quality needed to be improved, the SMES device may play important pole.

3 SMES device coordinates with frequency modulation units

Mentioned above, SMES device may regulate active and reactive power separately by controlling the trigger angle. When the range of dead-band of governor is overlarge, the units can't to join into primary frequency regulation. However, when the units operate with full load, the units will lost the capacity of frequency modulation. At this condition, system frequency modulation can be implemented by exploring the advantage of quick transform of SMES device, injecting or absorbing power what may be used to make up a deficiency of the inadequate spinning reserve.

3.1 SMES device coordinates with the primary frequency regulation

When the SMES device acts for coordinating with the units of primary frequency regulation, the best way is to installing the SMES device at the bus-bar side of units needed to coordinate. Because of the SMES device act time, the order of milliseconds, is less than the act time of units of primary frequency regulation, the act time of frequency regulation may be decreased. At the same time, when the units are lack of capacity of primary frequency regulation, SMES device may be used as the spinning reserve.

To aiding primary frequency regulation, the frequency bias was used as the act criterion. For example, when the frequency bias is more than the act value of dead band of primary frequency regulation, SMES device may be switched on for exchange power with system. While the frequency bias is less than the setting value of dead band, the SMES device would be quit.

3.2 SMES device coordinates with AGC

Not only the performance of frequency regulation of the thermal units is different from hydro units, but also the great difference occurs among thermal units. At the same time, when the AGC with different behaviour were put into operation, it is difficult to reach to synchronization adjustment, so the adjustment effect is not ideal. Specially, while thermal units act frequently, the cost and units wear will rise. Lead-control of AGC can be implemented by applying super-short-term load forecast to calculate the bias of generation plan and distribute the plan on AGC unit which adjustment speed is slow. Ahead-control period commonly is 5 minutes. Lag-control period of AGC is only several tens of seconds, so the conflict is not caused from control time. If applying the SMES device to replace partial AGC units, not only the ahead-control of SMES device may be implemented, at the same time, power unbalance may be improved on time.

SMES device can beforehand adjust active output by receiving super-short-term load forecast alone. Based on AGC unit condition which SEMS devices cooperate with, SMES device can supply the inadequate of spinning reserve. . When applied in lag-control, ACE can be used as the action signal of SMES.

4 Description of simulation model

In this paper, simulation model of primary frequency modulation and AGC modulation was based on typical tipple-area interconnection power system, as showed in Fig.1.

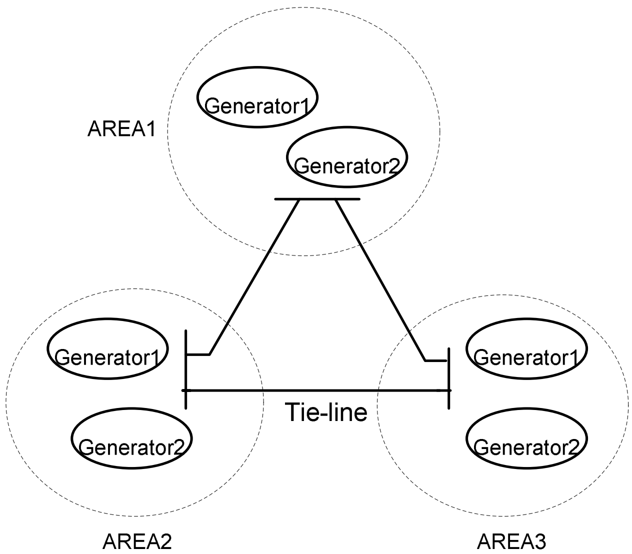

Fig.1 typical 3 area system model

This paper applies the SIMULINK to simulation. For qualitative analysis, the simulation model can be simplified, so the nonlinear factors of uint ramp control (URC) and upper and lower limit of generation rate control (GRC) aren't involved in this simulation model. The dead-band loop

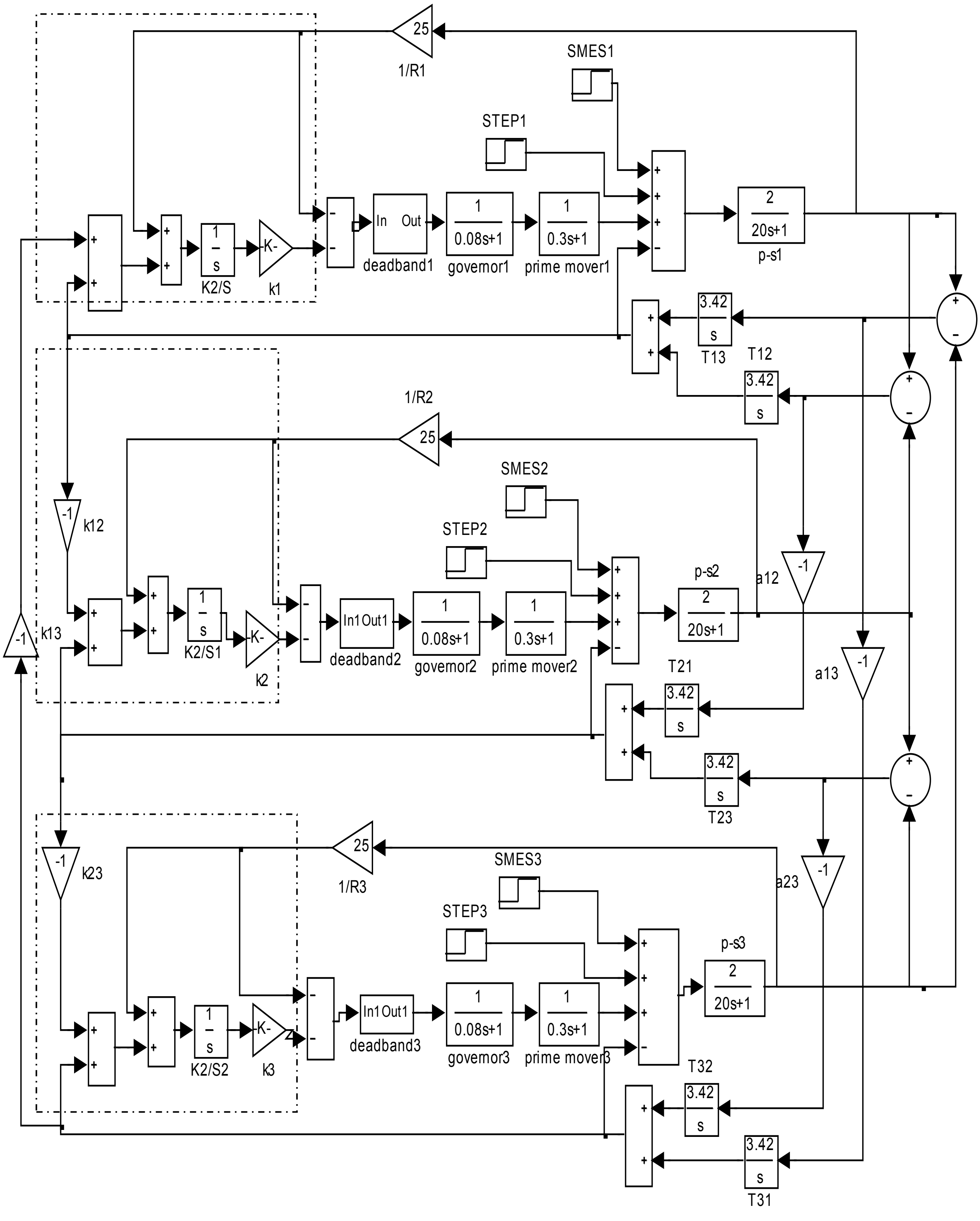

Fig.2 triple-area model of primary frequency regulation and AGC regulation was only considered [23]. The other parameters setting can be seen from Fig.2 and Table.1. Among them, k_{12} , k_{13} represents the tie-line direction of area 1 with area 2 and 3 respectively. AGC regulation part was marked in dashed border of Fig.2.

Table.1 System parameters for the triple-area model

T_g	0.08s
T_t	0.3s
T_p	20s
R	2.4Hz/pu
K_p	120Hz/pu
T_{ij}	0.545
k_{ij}	-1
a_{ij}	-1
k_i	0.23
Dead-band	0.033Hz

4.1 Effect from SMES device on primary frequency regulation

Secondary frequency regulation mainly was used to adjusting the load of slowly change, specially, it is applicable to control forecast load: certainty load. But primary frequency modulation is a quick regulation process of simple feedback loop of generation units to load change. It was only started up while secondary frequency regulation was too late to regulate the high-speed change of load. So as to underline the primary contradiction, the affect of secondary frequency regulation wasn't considered in the analysis of primary frequency regulation. When SMES device was installed in power system, power flow of tie-line and frequency change curves were showed in Fig.3. Among them, curve 1 represents the affect from primary frequency regulation only under the condition without SEMS device. Curve 2 shows when SMES device was installed in the area of load disturbance, response time is 30ms after load disturbing happening. In fact, this condition is an ideal time of SMES device action. Curve 3 represents that SMES device was installed in the area of load disturbance, but the response time is 4s after load disturbing. During simulation, load disturbance value of 0.02 p.u is supposed, at the same time, 0.01p.u of power output will be supplied by SMES device.

The parameters of this system are taken from [24]. The relevant parameters are given in Table 1.

5 Simulation result

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Curves given in Fig.3 (a) showing SMES device is useful for further modification of frequency bias, as seen from curve 2 showed in Fig.3 (a). As known from comparing curve 1 and 2 of Fig.3 (a), when SMES device acts at 30ms after load disturbing, SMES device action not only is useful for quick recovery of frequency, but also useful for restricting frequency fluctuation. Fig.3 (b) shows the condition of power flow change of tie-line, curve2 represents it is benefit to reducing power flow among tie-line, when SMES device quickly acts at the time of load disturbance. At the same time, power support from outer-area was reduced effectively.

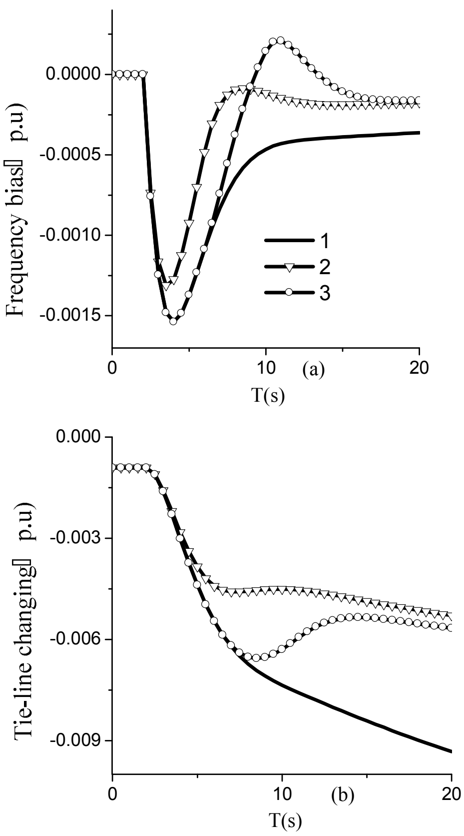

Fig.3 Primary frequency regulation status while SMES device installed

Table 2 Average of frequency bias and tie-line change based on primary frequency and SMES regulation

	Δf (pu)	Δp_{tie} (pu)
Curve1	-0.000567054	-0.00581
Curve 2	-0.000300884	-0.00335
Curve 3	-0.000337923	-0.00418

Table 2 lists the simulation result. There is the average value of frequency bias and tie-line change while only primary frequency regulation device coordinates with SMES device. Curve 2, that is, if SMES device act after load disturbance happened 30ms, the result is optimal.

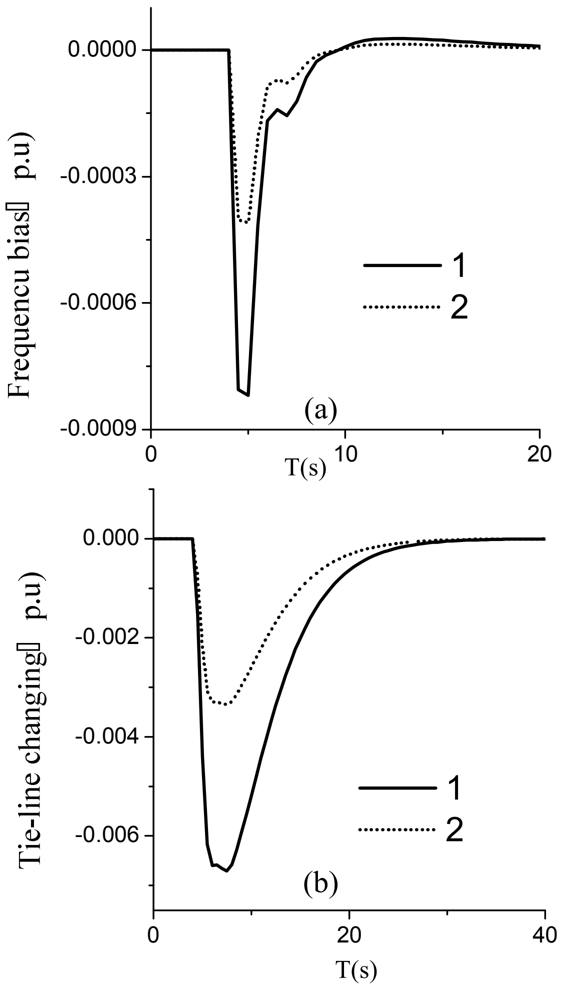

Fig.4 AGC regulations status while SMES device installed

Table 3 Average of frequency bias and tie-line change based on AGC and SMES regulation

	Δf (pu)	Δp_{tie} (pu)
Curve1	-0.000567054	-0.00581
Curve 2	-0.000300884	-0.00335

5.2 Effect from SMES device on secondary frequency regulation

When applying SMES device to supplementing partial regulation capacity of AGC, change curves of tie-line and system frequency were showed in Fig.4 and 5.

In Fig.4, curve 1 represents the case when the AGC unit was thrown in only, curve 2 descript that case when all units joint into AGC action, moreover, based on the value of load forecast, the output regulation value of SMES device was 0.01 p.u, the SMES device was installed in output-end of generator of load disturb area. i.e, regulation value of ahead-load forecast distributed to this AGC unit was complemented by SMES device.

From Fig.4 and table 3 we can see, while SMES device coordinates with AGC, SMES will be benefit to frequency and tie-line recovery quickly.

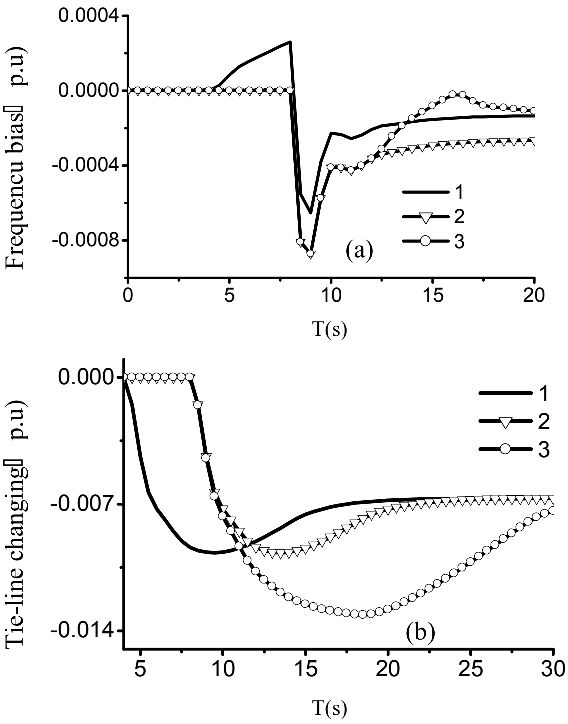

Fig.5 comparing SMES-in-advanced control with SMES-in-lag control

Fig 5 provides that comparison results of ahead and lag-control. Among them, curve 1 presents the 0.01p.u active power output provided by SMES device basing on super-short time load forecast. After one period (4s), the load rise to 0.02p.u, curve 2 shows that AGC units action only, SMES device doesn't act. Curve 3 was obtained basing on the size of ACE, applying lag-control of SMES device, i.e, SMES device acts at one period (4s) behind disturb appearance.

It is may be seen from the simulation results of Fig. 5 (a), under this condition of super-short time load forecast and lag-control of ACE, the action of SMES device may reduce frequency fluctuation effectively, speeding up the frequency recovery to allowed arrange.

From Fig. 5 (b) we can obtain that ahead-control is benefit to reduce tie-line power flow. Lag-control will increase burden of tie-line. So, ahead-control based on super-short time load forecast will benefit to recover frequency fluctuation and to reduce tie-line power flow.

Table 4 lists the average value of frequency bias and tie-line power flow change on three kinds of control mode. These values can be used to prove that ahead-control is optimal control method.

Table 4 ahead-control comparing with lag-control based on SMES controlling

	Δf (pu)	Δp_{tie} (pu)
Curve1	-9.44899E-05	-0.0060743
Curve 2	-0.0002168	-0.006487907
Curve 3	-0.000148222	-0.00711

6 Conclusion

Basing on all analysis and simulation mentioned above, following results can be summarized:

1) If renewable energy was stored and used as the supply source of SMES device, not only the direction impulse on power system may be avoided, but also may be used as system reservation, so it can play active pole for stability of power grid.
2) Applying SMES device to frequency regulation, not only frequency fluctuation can be reduced, but also the system stability was improved. At the same time, decreasing the power flow

among tie-lines. So avoiding the increase of power exchange caused from non-consciousness.
3) Adopting renewable energy to charge storage energy device, will give an new research subject of smart grid.
4) It is possible to cause further line blocking due to different installation location of SMES device. It is also possible to reducing the power flow among tie-lines. These problems are worthy of further studying.

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Appendix

Table 5 Nomenclature

SMES	Superconducting Magnetic Energy Storage
AGC	Automatic generation control
RES	Renewable Energy Source
PF	primary frequency
BPA	Bonneville Power Administration
FACTS	Flexible AC Transmission Systems
URC	Uint Ramp Control
GRC	Generation Rate Control
PWM	pulse width modulation