Provision of Two-area Automatic Generation Control by Demand-side Electric Vehicle Battery Swapping Stations

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Abstract – Application of demand-side resources to automatic generation control (AGC) has a great significance for improving the dynamic control performance of power system frequency regulation. This paper investigates the possibility of providing regulation services by demand-side energy storage in electric vehicle battery swapping stations (BSS). An interaction framework, namely station-to-grid (S2G), is presented to integrate BSS energy storage into power grid for giving benefits to frequency regulation. The BSS can be regarded as a lumped battery energy storage station through S2G framework. A supplementary AGC method using demand-side BSS energy storage is developed considering the vehicle user demand of battery swapping. The effects to the AGC performance are evaluated through simulations by using a two-area interconnected power grid model with step and random load disturbance. The results show that the demand-side BSS can significantly suppress the frequency deviation and tie-line power fluctuations.

Keywords: Automatic generation control, Battery swapping station, Demand-side response, Electric vehicle, Energy storage

1. Introduction

Automatic generation control is an essential mechanism in electric power system which regulates the output of generation units in response to the load fluctuations in order to maintain the system frequency and tie-line power at their scheduled values. With the integration of higher levels of renewable energy sources such as wind power generation in future power systems, performing frequency regulation using only conventional generators may become technically difficult because of the rapid power imbalances and the insufficient regulation reserve capacity [1-3].

Increasing power system flexibility by responsive demand may become one of the solutions to this problem. Recently, the utilization of demand-side resources such as refrigerators, freezers, heat pump water heaters and air-conditioning loads for providing the needed fast-response regulation services has been shifting into focus [4-7]. One of the reasons why this has not been done is the perceived difficulties in dealing with many small loads rather than a limited number of generating units. In particular, the costs associated with the two-way communications appear to be insurmountable obstacles.

The anticipated electrification of transportation via electric vehicles (EVs) may offer another vast potential of new forms of responsive demand. In China, the cumulative

sales of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are expected to reach five million in 2020 [8]. The large-scale implementation of EVs will provide sufficient battery energy storage for power grid. Integration of EVs into AGC will change the conventional control strategies and improve the performance of power system frequency control.

The existing research about EVs providing frequency regulation is mainly based on the vehicle-to-grid (V2G) [9-11] framework, which is to manage and control the EVs plugged in the charging outlets. Most of the technical issues are limited to the interaction of the individual vehicle and the power grid in the form of decentralized charging strategies [12] or autonomous V2G control [13]. In [14], an efficient scheduling method for each vehicle regarding the V2G frequency regulation service has been studied. The system frequency fluctuations are evaluated in [15] based on dynamic simulation of applying V2G to AGC system. In [16], the method for dispatching the control signal is presented according to the response speed and controllable capability. Some studies have also addressed the V2G control strategies for plugged EVs supporting primary frequency regulation [17-19]. However, the basic premise of V2G control is that EVs can connect to grid for a long time in order to ensure a sufficient regulation capacity. If there are not enough EVs, the randomness of user mobility will affect the controllable capacity.

Some countries like Israel, Australia, Denmark and China have presented the business model of battery swapping to recharge EVs. The batteries are charged and managed in the centralized battery swapping stations (BSS).

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The energy storage in BSS will provide a new responsive resource for power system. Published literatures have addressed the benefits of BSS to EV owners and utilities [20-22]. In [23], an optimal recharging strategy for BSS to buy and sell the electricity through the day-ahead market in France has been studied. For considering the interaction between BSS and power grid, the operation cost can be significantly reduced [24, 25]. However, the application of BSS to the system frequency regulation has rarely been studied.

This paper intends to evaluate the effects of BSS energy storage on the dynamic performance of AGC under step and random load disturbance. Section 2 gives a description of the station-to-grid (S2G) concept for the interaction of BSS and power grid. An aggregated S2G model considering the swapping demand of EVs and the available regulation reserve is proposed in section 3. The contributions of S2G to AGC are verified through a two-area interconnected system simulation in section 4. Finally, the conclusions are made in section 5.

2. Station-to-Grid

2.1 The concept of S2G

At a BSS, the automated swapping platform will replace the depleted battery with a fully-charged one. This process can be realized in less than 5 minutes. There will be more and more BSSs in the future to provide swapping services for the increasing EVs. Integrating the BSS batteries into power systems for providing ancillary services has a great significance in power system operation and control. To achieve this goal, it needs to present a new conceptual framework for the application of BSS energy storage. In this paper, we call it station-to-grid (S2G).

The basic concept of S2G is that BSS provides services to the grid. BSS can charge during low-demand time and discharge when power is needed by the grid. Its difference with the conventional storage is that BSS needs to meet the swapping demand for EVs.

Fig. 1 schematically illustrates the connections among vehicles, BSS and the electric power grid. The power energy flows from power plant through the grid to electricity users, and flows back to the grid from BSS when it is needed. The EV operation and management center (OMC) is responsible for communicating with the grid operator, managing the BSS batteries and guiding EVs to charge or recharge. The grid control center collects data from EV OMC, power plant and grid, then it sends control signals to BSS through the communication network. The EVs and batteries can be integrated into the internet of things with the wireless communication technologies such as ZigBee, RFID and 3G/GPRS, so that EV OMC can know the vehicle location and battery state, and guide the EVs to the nearest BSS for swapping.

Fig. 1. Illustrative schematic of proposed S2G connections

2.2 S2G participating in AGC

The batteries in BSS are very suitable for frequency regulation because of the rapid response capability. When a disturbance occurs in the control area, the AGC will order the BSSs to change their power consumption or output by sending set-points to the EV OMC under its domain. Then, the EV OMC will distribute these set points among the BSSs according to their SOC's at that time. The difference between BSS and conventional battery energy storage (BES) is that the BSS storage is located in the demand side. The S2G power must be limited by the swapping demands.

3. Frequency Analysis Model with S2G

3.1 Available regulation reserves (ARR)

In order to determine the regulation reserves available from BSS in the electricity market, the OMC needs to forecast the EV swapping demand of the second day ahead. It is usually calculated from the historical data. Unless EVs have been implemented in a large scale, it will be hard to get the actual operating data. This paper uses the queuing theory [26] to determine the available regulation reserves (ARR) for simplicity.

It is assumed that each BSS manage its batteries separately, i.e. not considering the exchange between BSSs. The transition process of battery in BSS can be described as follows:

- 1) EV arriving for recharge, a depleted battery is replaced with a fully charged one;
- 2) The depleted batteries wait to be recharged until an arbitrary recharging device becomes available;
- 3) The depleted batteries start to be recharged as soon as

Fig. 2. State transition diagram of BSS

the recharging device is available;

- 4) After the batteries are fully recharged, they will be transported to the stock zone to set aside for being swapped into next EVs.

It can be seen that there will be three kinds of battery states, i.e., waiting to be charged, charging on the device, and being fully charged. We define that the total number of batteries in a station is N , the number of charging device is c (it means that c batteries can be simultaneously charged in the station), and the number of batteries need to be recharged (i.e. sum of the waiting and charging batteries) is n . Then, the number of batteries in each phase is described as follows:

$$\{N_w, N_c, N_f\} = \begin{cases} \{n-c, c, N-n\} & (c \leq n \leq N) \\ \{0, n, N-n\} & (0 \leq n \leq c) \end{cases} \quad (1)$$

where N_w is the number of batteries waiting to be recharged, N_c is the number of batteries being recharged, and N_f is the number of batteries that have been fully recharged. Note that N and c are both constants. We can confirm the state of BSS if n is determined. Assumed that EVs arrive into BSS according to a homogeneous Poisson process with the average arrival rate λ , and charging time follows exponential distribution whose service rate is μ , the state transition diagram of BSS can be depicted as Fig. 2.

This transition process is a one-dimensional birth and death process. In the steady state, the system equilibrium equation is:

$$\begin{cases} \lambda p_0 = \mu p_1 & (n=0) \\ (\lambda + n\mu)p_n = \lambda p_{n-1} + (n+1)\mu p_{n+1} & (1 \leq n < c) \\ (\lambda + c\mu)p_n = \lambda p_{n-1} + c\mu p_{n+1} & (c \leq n < N) \\ c\mu p_N = \lambda p_{N-1} & (n=N) \end{cases} \quad (2)$$

It can be seen that EVs at a BSS can be regarded as queuing customers to be served in an $M/M/c/N$ queue, where M/M denote the inter-arrival time of customers and the service time of a customer following the exponential distribution respectively, c denotes the maximum customer number (i.e. the number of swapping devices) being served at the same time, and N denotes the maximum number of batteries. The system state probability can be calculated as:

$$p_0 = \left(\sum_{n=0}^c \frac{(c\rho)^n}{n!} + \frac{c^c}{c!} \sum_{n=c+1}^N \rho^n \right)^{-1} \quad (3)$$

$$p_n = \begin{cases} \frac{(c\rho)^n}{n!} p_0 & (n \leq c) \\ \frac{c^c}{c!} \rho^n p_0 & (c \leq n \leq N) \end{cases} \quad (4)$$

$$\rho = \frac{\lambda}{c\mu} \quad (5)$$

where p_i ($i=0, 1, \dots, n$) is the probability of each state and ρ is the occupation rate per swapping device.

In order to provide a sufficient service level, there should be a safety stock in BSS. We define that the number of batteries that are fully charged and set aside to be swapped into EVs is N^* ($c < N^* \leq N$). When the number of EV waiting for swapping has reached N^* , the service demand of new EV will be refused. Then, the loss of customer probability ($LOCP$) due to the service refusal is:

$$LOCP = \frac{c^c}{c!} \rho^{N^*} \left(\sum_{k=0}^c \frac{(c\rho)^k}{k!} + \frac{c^c}{c!} \cdot \frac{\rho(\rho^c - \rho^{N^*})}{1 - \rho} \right)^{-1} \quad (6)$$

The safety stock N^* can be obtained by reducing $LOCP$ to a certain targeted level δ (i.e. make $LOCP \leq \delta$). For EV OMC, it can be regarded as the stationary demand of EV swapping because the allowable loss probability has been considered.

Only the batteries connected to the grid can participate in frequency control. It can be assumed that the N^* batteries scheduled for EV swapping demand will not provide the regulation reserves (stacked in swapping zone and not connected to grid). The positive reserve ARR^+ and negative reserve ARR^- then can be calculated as:

$$ARR^+ = (N_t - N^*) \cdot C_{b_inv} - P_{ini} \quad (7)$$

$$ARR^- = -(N_t - N^*) \cdot C_{b_inv} - P_{ini} \quad (8)$$

where N_t is the total number of batteries, C_{b_inv} is the battery inverter capacity, and P_{ini} is the initial set-point for BSS.

3.2 Aggregated S2G model

While in aggregating the BSS to an equivalent resource, the dispatch method of AGC signal must be considered. In this paper, we use the *SOC* synchronous control method [27] to dispatch the AGC signal from the grid control center, as shown in Fig. 3. It is assumed that there are i batteries in the BSS that can provide regulation service. The grid control center sends AGC signal to BSS every one second. The charge and discharge of the controllable batteries are restricted by their inverter capacity and their *SOC* limit. Each battery informs the BSS whether it is

Fig. 3. Dispatching method of AGC signal in BSS

Fig. 4. Aggregated S2G model

controllable or not, and sends its SOC every 30 seconds. After receiving the signal from the grid control center, the BSS dispatches the control signal as follows. The charging and discharging states of batteries are determined according to their SOC s. The charging signal is dispatched to the batteries in the ascending order of SOC , while the discharging signal is dispatched to the batteries in the descending order. As a result, the SOC s of the controllable batteries can be synchronized and the BSS can be designed as one large aggregated model.

Fig. 4 shows the aggregated S2G model considering the constraints of ARR. The input of this model is AGC signal for BSS and the output is the total charging/discharging power of BSS, which is controlled based on the ARR at that time. The communication delay is approximated by the first order model with time delay denoted by T_d . The Thevenin-based battery model [15] which consists of an open circuit voltage source in series with an internal resistance and a parallel RC network is used to compute the output of battery. In view of the real battery protection to avoid damage of the battery and to preserve battery life, the battery power is limited to ARR dynamically according to the allowable SOC range and demand of EV swapping. In particular, if the battery SOC goes out of the range $[SOC_{min}, SOC_{max}]$, ARR will be set to zero to avoid the overcharging or over discharging. That means the battery will not take part in AGC services.

3.3 Modeling of two-area AGC with S2G

To investigate the effects of S2G regulation, a two-area

Fig. 5. Two-area interconnected system AGC model

interconnected AGC model is used in this paper. The two-area interconnected power system linearized around an operating reference point can be described by the standard state space equation as

$$\dot{X} = AX + MU + \Gamma P \quad (9)$$

where X , U , and P are the state, control and disturbance vectors, respectively, and A , M , and Γ are constant matrices of appropriate dimensions which in turn depend on the system parameters and the operating point. For a two-area AGC system with S2G,

$$X = [\Delta f_1, \Delta f_2, \Delta P_{tie}, \Delta P_{g1}, \Delta P_{g2}, \Delta P_{S2G1}, \Delta P_{S2G2}]^T \quad (10)$$

$$U = [\Delta P_{Thr1}, \Delta P_{Thr2}, \Delta P_{BSSr1}, \Delta P_{BSSr2}]^T \quad (11)$$

$$P = [\Delta P_{L1}, \Delta P_{L2}]^T \quad (12)$$

where Δf_1 and Δf_2 are the frequency deviation of area 1 and area 2, ΔP_{tie} is the tie-line power deviation, ΔP_{g1} , ΔP_{g2} , ΔP_{S2G1} , and ΔP_{S2G2} are the outputs of thermal generators and BSS in area 1 and area 2, respectively, ΔP_{Thr1} , ΔP_{Thr2} , ΔP_{BSSr1} , and ΔP_{BSSr2} are the reference set-points from the AGC control center, and ΔP_{L1} , ΔP_{L2} are the load disturbance in the two areas, respectively.

The area control error (ACE) of area i which reflects the power imbalance is given by the equation $ACE_i = \Delta P_{tie} + B_i \Delta f_i$ ($i=1, 2$), where B_i is the frequency bias factor. The AGC operation is accomplished by tie-line bias control (TBC) in the two areas to restore the frequency and tie-line power to the scheduled values.

Fig. 5 shows the block diagram of an AGC model integrating the thermal generation units and the aggregated S2G. This model is used to evaluate the dynamic performance of AGC, including an aggregated BSS in each area. The models of thermal generators are those used in [28], which consider the governor dead-band and generation rate constraint. It is assumed that the discharging power of BSS is positive.

Fig. 6. Coordinated control of thermal units and BSS

3.4 Coordinated control scheme

The coordinated control scheme is depicted in Fig.6. The control signal is firstly passed through a low-pass filter and a high-pass filter. The low-pass filter with a time constant of 10 min is used to filter out the long-cyclic component of the control signal. The high-pass filter with a time constant of 10 s is used to filter out the fast-cyclic component of the control signal. These two components are not entered to the conventional generators and BSSs. By using this method, only the short-cyclic component whose range is several ten seconds to several minutes is responded by the regulation units. The AGC order of the thermal units are found by subtracting the insufficiency of S2G power.

4. Simulation Analysis

It is assumed that there is a BSS in each area and the number of controllable batteries are 1000. The maximum charging/discharging power and average capacity of each battery is 10kW, 40kWh, respectively.

The system base power is 2000MW. It is assumed that EVs go to BSS for battery swapping every two minutes (i.e. $\lambda=0.5$) and the average service time is seven minutes (i.e. $\mu=0.14$). The number of service window is four (i.e. $c=4$) in each BSS. The EV OMC obtains the scheduled reserves for batteries swapping by reducing $LOCP$ below 0.001 (i.e. $\delta=0.001$). Then ARR can be calculated according to (1)-(7). As a result, ARR^+ is 0.0018 p.u.MW, and ARR^- is -0.0038 p.u.MW. The batteries that are needed to meet the swapping demand have been fully charged and set aside for swapping in advance. Under this assumption, the ARR will keep constant at the simulation time scale.

It is assumed that the initial current is 4.426 kA, and the initial SOC of batteries is 0.85. The other parameters are listed in Table 1. The parameters of area 1 and area 2 are assumed to be identical. The simulation is conducted under the step load disturbance and random load disturbance in order to evaluate the short term and long term frequency control performance.

4.1 Step load disturbance

It is assumed that a step increased load of 0.5% occur at the initial time in area 1. The simulation results are shown

Table 1. Simulation Parameters

Parameters	Values
Inertia constant M_i (s)	0.1667
Load damping D (p.u.MW/Hz)	0.008333
Synchronized coefficient T_{12} (p.u.MW/radian)	0.545
Units droop R_i (Hz/p.u.MW)	2.4
Frequency bias coefficient B_i (p.u.MW/Hz)	0.425
Time constant of governor T_{gi} (s)	0.08
Time constant of turbine T_{ti} (s)	0.3
Time constant of low-pass filter T_{LFI} (s)	600
Time constant of high-pass filter T_{HFI} (s)	10
SOC_{min}	0.8
SOC_{max}	0.9
Initial set-point for BSS. P_{ini} (p.u.MW)	0.001
BSS control delay T_d (s)	0.026
Battery internal resistance R_θ (Ω)	0.013
Polarized resistance R_p (Ω)	0.001
Polarized capacitance C_p (F)	1

Fig. 7. Frequency deviation of area 1

Fig. 8. Frequency deviation of area 2

as Fig. 7-12.

Fig. 7-8 show the frequency deviation fluctuations of area 1 and area 2 with and without S2G, respectively. It can be seen that the frequency fluctuations are suppressed significantly by the S2G regulation. The peak overshoot of frequency deviation in area 1 is reduced from 0.0123Hz to 0.00534Hz, while from 0.0119Hz to 0.00491Hz in area 2. Fig. 9 shows that S2G can also suppress the tie-line power fluctuations and reduce the settling time. Fig. 10 - 12 show the outputs of BSS and thermal units. It can be seen that the outputs of units are reduced due to the S2G regulation.

Fig. 9. Tie-line power deviation

Fig. 12. Output of thermal units in area 2

Fig. 10. Output of BSS

Fig. 13. Random load fluctuation

Fig. 11. Output of thermal units in area 1

Fig. 14. Frequency deviation of area 1

The output of BSS in area 1 is up to its ARR^+ quickly, while in area 2, it tends to 0. In a steady state, the outputs of BSS and units in area 1 are 0.0018 p.u.MW and 0.0032 p.u.MW, respectively, while in area 2, they are both 0. That is because the load disturbance in area 1 will be balanced only by its owned regulation resources. Without S2G, the imbalance of power in area 1 is eliminated only by increasing the conventional thermal units. Hence, the output of thermal units in area 1 tends to 0.005 p.u.MW.

4.2 Random load disturbance

The random load fluctuation of a real interconnected system can be simulated approximately by a dynamic fluctuation load model [29]. It consists of base and fringe

components obtained from the white noise generators. Fig. 13 shows the random load fluctuation in one hour. The maximum fluctuation band is 0.005 p.u.MW.

It is also assumed that the random load fluctuation occurs in area 1. Fig. 14-15 show the simulation results of frequency deviation in area 1 and area 2, respectively. It can be seen that the fluctuations of frequency deviation in both areas has been greatly suppressed. Fig. 16 shows the simulation results of tie-line power deviation. Like the results of frequency deviation, S2G power from BSS can also suppress the fluctuations of tie-line power deviations. Fig. 17-19 show the outputs of BSS and thermal units. It can be seen that the outputs of units are reduced because S2G participating in the AGC program. The output of BSS in area 1 is limited in the range from ARR^- to ARR^+ .

Fig. 15. Frequency deviation of area 2

Fig. 17. Output of BSS

Fig. 16. Tie-line power deviation

Fig. 18. Output of thermal units in area 1

Table 2. Quality of frequency deviation

	Area 1		Area 2	
	w/o S2G	with S2G	w/o S2G	with S2G
Max [Hz]	0.00465	0.00218	0.00463	0.00203
Min [Hz]	-0.00555	-0.00227	-0.00554	-0.00213
RMS [Hz]	0.00179	0.000639	0.00178	0.00059

Table 3. Quality of tie-line power deviation

	w/o S2G	with S2G
Max [p.u.MW]	0.00165	0.00088
Min [p.u.MW]	-0.00183	-0.00072
RMS [p.u.MW]	0.00062	0.00019

In order to evaluate the suppression effects of S2G power quantitatively, some evaluation indexes such as maximum (Max), minimum (Min) and root mean square (RMS) values of the frequency and tie-line power deviations are used. The results are listed in Table 2 and Table 3. It can be seen that the values of these indexes are reduced by 46.67% -69.35% because of the S2G regulation.

5. Conclusion

This paper explores how the demand-side BSS energy storage could contribute to AGC. A conceptual framework of S2G is proposed for BSS giving benefits to power grid. The integration of S2G into AGC may change the con-

ventional control strategies that only regulate AGC units, and make the demand-side BSS energy storage participate in frequency regulation. The S2G model and control scheme are proposed to evaluate the effects on AGC. The results show that S2G can significantly suppress the frequency deviation and tie-line power fluctuations and reduce the regulation of AGC units, thus improve the dynamic performance of frequency control.

Although the business model of battery swapping is facing many challenges such as safety requirements, battery standards, and swappable design, it is still an effective measure to shorten the recharging time of EV batteries and provides a large convenience for users extremely in large cities or in densely populated regions. Once the BSS have been implemented in a large scale, they

Fig. 19. Output of thermal units in area 2

will provide new responsive resources in the demand side for supporting power grid services, especially in power system frequency and voltage regulation.

The demand for battery swapping in BSS may fluctuate significantly under a large time window (for example, one day). The dynamic fluctuation of ARR in a day will be considered in our future research.

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