Research on the Operation Model and Strategy of Lithium Battery to Provide Frequency Regulation in the Power System

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Abstract—With the development of smart grid and energy internet, energy storage will play an important role in maintaining the power balance and providing frequency regulation in future power system. Consequently, energy storage faces a trade-off problem between the energy market and frequency regulation market. In this work, an operation model and strategy of energy storage to provide frequency regulation is proposed. Taking lithium battery as an example of energy storage, its technical feasibility to provide frequency regulation is firstly discussed. Then, a day-ahead energy market model in the power system is constructed to calculate the revenue of lithium battery. Finally, the operation strategy of lithium battery to provide secondary frequency regulation (namely AGC) is proposed based on the model of opportunity cost. Case study is conducted on a modified IEEE 6-bus system. It shows that the reduced marginal revenue of lithium battery in the energy market increases with the growth of its declared capacity for frequency regulation. Consequently, the optimal declared frequency regulation capacity for lithium battery is the amount, at which the reduced marginal revenue in the energy market is equal to the compensation price of frequency regulation.

1. Introduction

Under the development of smart grid and energy internet, the penetration level of renewable energy generation (REG) will keep increasing [1]. Currently, the proportion of coal-fired power generation has decreased to 49.1% in China. The proportion of non-fossil energy generation has reached 44.8%. REG represented by wind power and PV has greater uncertainty and volatility, which calls for more and more ancillary services such as frequency regulation and reserve in the power system.

To reduce the adverse impact of REG on the operation of the power system and ensure its safe operation, ancillary services market will further be developed. It is in favor to exploit and stimulate more ancillary service sources. Energy storage (ES), as a new type of flexible resource, has great potential in providing ancillary services. However, energy storage takes the roles of both load and generation due to its charging and discharging behavior. Thus, the analysis of cost and benefit of ES in ancillary services market becomes an urgent issue. In this regard, this paper takes the AGC as an example to investigate the cost and benefit of ES in the ancillary services market.

ES brings multiple benefits to the power system. From the perspective of generation side, it can promote the consumption of REG and reduce the curtailment of wind and PV power. From the perspective of the grid, ES contributes to peak-shaving through charging and discharging process.
From the perspective of demand side, ES can smooth the power fluctuations and provide emergency reserve to improve the quality of power supply [2].

The ancillary services from the generation side can hardly satisfy the requirements of peak shaving and reserve in modern power system. Increasing attention has been paid to the ancillary service potential of ES and flexible resources in the demand-side. The national grid in UK has clearly defined frequency response products provided by ES and load response. Relevant literature has carried out preliminary research on the operation and benefit analysis of ES participating in the ancillary service market [3]-[6].

Lit. [7] proposes a transaction model for aggregators of distributed ES participating in the ancillary services market of peak shaving. It investigates the operation mode of Data System Automation Program (DSAP) to provide peak shaving. Lit. [8] addresses the day-ahead and real-time market clearing issues considering the participation of ES and demand-side response. Lit. [9] investigates the operation strategy of ES and electricity vehicle (EV) in the frequency regulation market under the market rules for California independent system operators (ISO). Lit. [10] proposes a realization scheme for battery storage used for frequency regulation based on a distributed autonomous control. The scheme optimizes the frequency control strategy for a combined ES and REG system. Lit. [11] proposed a cooperative control framework for a wind energy conversion system (WECS) and compressed air energy storage (CAES). CAES can provide frequency regulation to release the impact of wind power on the system. Lit. [12] established a dual-objective complementary control model for ES providing frequency regulation service. The objective function consists of minimizing power deviation and frequency regulation cost.

Lit. [13] constructs a frequency regulation market considering the participation of wind, PV, hydropower, thermal power and ES. The market is cleared based on sequential bidding mode and marginal price principle. It demonstrates that the frequency regulation performance of the system is improved greatly when considering multiple types of participants. Lit. [14] proposed a control method for ES to provide frequency regulation service. The goal is to maximize the benefits of frequency regulation considering the degradation cost of ES. The frequency regulation performance of ES is compared with thermal power generators in Lit. [15]. It is concluded that ES has the advantages of fast response speed and high stability in frequency regulation. With the deepening research on ES providing ancillary services, its advantages of flexibility and rapidity have gradually become prominent. Consequently, increasing attention has been paid to ES in providing ancillary services.

In summary, technical issues of ES providing ancillary services have been studied in relevant literature from perspectives of control methods and performance analysis. However, the operation strategy of ES to provide frequency regulation service need to be further studied. Lithium battery, as a typical ES, has become an important ancillary service resource in the power system. This study takes lithium battery as an example of ES to studies its operation strategy to provide AGC frequency regulation to the power system. The modelling method and optimal strategy is proposed for lithium battery to participate in the energy market and the AGC market.

The work of this paper is organized as follows. Section 2 analyses the frequency regulation performance of ES. Section 3 constructed the operation model of ES. The optimal operation strategy of lithium battery to provide AGC service is proposed in Section 4. Case studies are conducted in Section 5, followed by conclusions in Section 6.

2. Technical Feasibility of Lithium Battery to Provide Frequency Regulation to Power System

2.1. Frequency regulation principle of lithium battery

Lithium battery realizes frequency response control through the power control of its grid-connected converter. The frequency control is realized through two steps of control process [15].
2.1.1. DC/AC converter control

DC/AC converter control consists of two parts: inner loop control and outer loop control. The inner loop control realizes the decoupling control of inner loop currents. The outer loop control realizes integrated inertia control and droop control.

In the control methods for lithium battery when responding to system frequency deviation, active power-frequency droop control is a commonly used control method. The active power increment and frequency deviation satisfy the following relationship:

\[ \Delta P_{st} = -\Delta f_t / \delta_s \]  

where \( \Delta P_{st} \) is the active power increment of lithium battery at time \( t \); \( \Delta f_t \) is the system frequency deviation at time \( t \); \( \delta_s \) is frequency regulation coefficient of lithium battery.

The input or output active power of lithium battery is determined by system frequency deviation and the frequency regulation coefficient. When the frequency deviation of the system exceeds the set limit, the corresponding active power input or output of the lithium battery will change. In the operation the state of charge (SOC) of lithium battery is required to be restricted within a safety range, for example [10%, 90%].

2.1.2. Operation status control of lithium battery

For conventional generators, the power regulation range is within their minimum and maximum technical outputs. For lithium battery, the theoretical adjustment range in frequency regulation process is the full power range, namely \([-P_{max}, P_{max}]\), where \( P_{max} \) is the maximum charging and discharging power.

2.2. Frequency regulation performance of lithium battery

Lit [15] tested the frequency regulation response speed of a thermal power unit and an ES with the same installed capacity. The test found that under the same disturbance, the time required for the ES to respond to frequency deviation and reach a stable output is about 1 s. While the time required for the thermal power unit is about 6 s. It indicated that the frequency regulation response speed of ES is faster than that of the thermal power unit.

Due to the fast response capability, ES can provide a certain amount of active power compensation for the power system in the early stage of frequency fluctuations. Thus, the power system can respond quickly to frequency deviations and reduces the maximum system frequency deviation.

3. Operation Model of and Profit Analysis for Lithium battery in Day-ahead Energy Market

3.1. Operation model of lithium battery

The operation of lithium battery is restricted by its maximum charging/discharging power and the boundary of SOC. Since lithium batteries has a relatively fast adjustment rate, the ramping constraint is generally not considered. Power and SOC constraints of lithium battery are constructed as follows:

\[ 0 \leq P_{ch,t}^{es} \leq P_{ch,max}^{es} \]  
\[ 0 \leq P_{dch,t}^{es} \leq P_{dch,max}^{es} \]  
\[ Soc_t^{es} = Soc_{t-1}^{es} + P_{ch,t}^{es} \eta_{ch} T - P_{dch,t}^{es} / \eta_{dch} T \]  
\[ Soc_{min}^{es} \leq Soc_t^{es} \leq Soc_{max}^{es} \]  

where \( P_{ch,t}^{es}, P_{dch,t}^{es} \) is the charging and discharging power of lithium battery, respectively; \( P_{ch,max}^{es}, P_{dch,max}^{es} \) is the maximum charging and discharging power respectively; \( Soc_t^{es} \) represents the SOC of lithium battery, \( Soc_{min}^{es}, Soc_{max}^{es} \) is the lower and upper limit of SOC; \( \eta_{ch}, \eta_{dch} \) is the charging and discharging efficiency, respectively; \( T \) if the length of a dispatch interval.

Since the battery cannot be charged and discharged simultaneously, two "0-1" variables and their mutual exclusion constraint are introduced. Eq. (2~3) are then replaced by Eq. (6~7).
where $b_{ch,t}, b_{dch,t}$ represents the charging and discharging state of the battery.

### 3.2. Profit modelling of lithium battery in the energy market

Lithium battery has charging and discharging states in the energy market. In order to maximize its profits, it will charge when energy price is low and discharge when energy price is high. The net income of lithium battery is the discharge income minus charge cost and its operation costs.

#### 3.2.1 Operation cost of lithium battery

The usage life of a lithium battery depends on the depth of discharge in each cycle. Lit. [17] proposes an operation degradation cost model for lithium battery as shown in equation (9)

$$
C_{D,t} = \frac{C_l}{2N_{life}Q_0} (p_{ch,t}^{es} + p_{dch,t}^{es})T
$$

where $C_{D,t}$ is the degradation cost of lithium battery; $C_l$ is the initial investment cost of lithium battery system; $N_{life}$ is the average cycle life of lithium battery, $Q_0$ is the rated storage capacity of lithium battery.

The operation and maintenance of lithium battery system also incurs costs. The operation and maintenance cost per unit time is related to the charging and discharging power:

$$
C_{M,t} = K_{M,t} (p_{ch,t}^{es} + p_{dch,t}^{es})T
$$

where $C_{M,t}$ is the operation and maintenance cost of lithium battery; $K_{M,t}$ is the operation and maintenance cost coefficient.

#### 3.2.2 Benefit of lithium battery

The net profit of lithium battery is the discharge income minus the charge cost and its operation costs. Taking one day as a dispatch unit with N periods, the profit in a day is expressed as:

$$
\sum_{t=1}^{N} (p_{dch,t}^{es} \lambda_t - p_{ch,t}^{es} \lambda_t - C_{D,t} - C_{M,t})T
$$

where $\lambda_t$ is the electricity price at time $t$.

### 4. Operation Strategy of Lithium Battery to Provide AGC Frequency Regulation

#### 4.1. Energy market modelling considering the participation of lithium battery

The opportunity cost of lithium battery to provide ancillary services comes from the loss of revenue in the energy market. In this reason, a market clearing model of energy market is established considering market participants including thermal power units, wind power units, lithium battery and loads.

The objective function of the energy market is to minimize the total operation cost from thermal power units and lithium battery:

$$
(P) \min f = \sum_{i=1}^{N} \sum_{t=1}^{n_g} Cost_{i,t}^g + \sum_{t=1}^{N} (C_{D,t} - C_{M,t})
$$

$$
Cost_{i,t}^g = a_i^g + b_i^g p_{i,t}^g + c_i^g p_{i,t}^{g2} + u_i^g x_{i,t}^g
$$
where, the first term in Eq. (12) represents operation cost of conventional generators, which consist of generation cost and start-up cost as expressed in Eq. (13); $p_{ij}^g$ is the power of thermal unit $i$; $u_{ij}$ is the start-up cost of thermal unit $i$; $x_{ij}^g$ represents the state of start-up; $a_i^g$, $b_i^g$, $c_i^g$ is the coefficient of the quadratic cost function of a thermal unit; $C_{O,t}$ and $C_{M,t}$ is the degradation cost and maintenance cost of lithium battery, which is given by Eq. (9) and (10), respectively.

The objective function of the market clearing problem is subjective to the following constraints.

Power balance constraint:
\[
\sum_{i=1}^{n_g} p_{ij,t}^g + p_{t}^{re} + p_{dch,t}^{es} - p_{ch,t}^{es} = L_t
\]
(14)
where $L_t$ represents system load; $p_t^{re}$ is the power of renewable energy generation.

Power boundary constraint of thermal units:
\[
b_i^g,_{P_{i,min}} \leq p_{ij,t}^g \leq b_i^g,_{P_{i,max}}
\]
(15)

Ramping constraint of thermal units:
\[
p_{ij,t}^g - p_{ij,t-1}^g \leq \Delta P_{i,max} \forall i, t
\]
(16)
\[
p_{ij,t-1}^g - p_{ij,t}^g \leq \Delta P_{i,max} \forall i, t
\]
(17)

Start-up and shut-down constraint of thermal units:
\[
b_i^g,_{x_{ij},U} \leq x_{ij,t}^g \leq b_i^g,_{y_{ij},D} \forall t
\]
(18)
\[
\sum_{t=\max\{1, t-U_i+1\}}^{t} x_{ij,t}^g \leq b_i^g,_{x_{ij},U} \forall t
\]
(19)
\[
\sum_{t=\max\{1, t-D_i+1\}}^{t} y_{ij,t}^g \leq 1 - b_i^g,_{y_{ij},D} \forall t
\]
(20)
where $b_{ij,t}$ represents the operation state of thermal unit $i$; $p_{i,min}$, $p_{i,max}$ the minimum and maximum power output of a thermal unit, respectively; $\Delta P_{i,max}$, $\Delta P_{i,up}$, $\Delta P_{i,down}$ is the maximum upward and downward ramping rate, respectively; $y_{ij,t}^g$ represents the state of shut-down of a thermal unit; $U_i$, $D_i$ is the minimum start-up and shut-down time, respectively.

Power constraints on the renewable energy generation:
\[
0 \leq p_t^{re} \leq P_t^{re}
\]
(21)
where $P_t^{re}$ is the total forecast power of renewable energy generation.

4.2 AGC opportunity cost of lithium battery to provide AGC

Opportunity cost refers to the maximum benefit that an investment or a behaviour can obtain from alternative schemes.

The opportunity cost of ES to provide AGC frequency regulation refers to the reduced revenue in the energy market. As shown in Eq. (22), the opportunity cost is equal to the difference between the revenues in the energy market before and after providing AGC frequency regulation capacity.

\[
C_{Op} = Pr_e - Pr'_e
\]
(22)
where $C_{Op}$ is AGC opportunity cost of the lithium battery; $Pr_e$ and $Pr'_e$ is the revenue of lithium battery in the energy market before and after providing AGC frequency regulation capacity.

In this work, it is assumed that the bidding strategy of lithium battery in the AGC market is symmetrical, namely provide the same upward and downward AGC frequency regulation capacity.
Under the energy market environment presented in Section 4.1, AGC opportunity cost based on simulation calculation can be obtained through the following steps:

4.2.1. Read in the parameters of generators, lithium battery, and load.

4.2.2. Construct the energy market model considering the participation of lithium battery, namely Eq. (4~10, 12~21).

4.2.3. Solve the energy market clearing problem and calculated the revenue of lithium battery in the energy market, denoted by $P_{re}$.

4.2.4. Assume lithium battery provides certain amount of AGC capacity to the system. Then, the operation boundary of lithium battery in the energy market are updated as shown by Eq. (23~26).

4.2.5. Resolve the market clearing problem after updating the operation boundary of lithium battery and obtain the revenue in the energy market, namely $P_{re}'$.

4.2.6. Calculate AGC opportunity cost, namely $P_{re} - P_{re}'$.

\[
\begin{align*}
    p_{ch,\text{max}}^{es} &= p_{ch,\text{max}}^{es} - R_D \\
    p_{dch,\text{max}}^{es} &= p_{dch,\text{max}}^{es} - R_U \\
    SoC_{\text{min}}^{es} &= SoC_{\text{min}}^{es} + R_U t_{AGC} \\
    SoC_{\text{max}}^{es} &= SoC_{\text{max}}^{es} - R_D t_{AGC}
\end{align*}
\]  

(23) \hspace{2cm} (24) \hspace{2cm} (25) \hspace{2cm} (26)

where $R_U$ and $R_D$ is the upward and downward AGC bidding capacity of lithium battery.

4.3 Operation strategy of lithium battery to provide AGC to the power system
Lithium battery can participate in the energy and AGC market simultaneously. For each unit of capacity, it has two options, namely i) participating in the energy market to make profits by charging and discharging at different periods, ii) participating in the AGC market to obtain compensation benefits. To maximize the profits, the decision can be made by comparing the opportunity cost of unit battery capacity and the AGC compensation price. For example, when AGC compensation price is 0.16 yuan/kW in the power system, and the calculated opportunity cost of per unit battery capacity is 0.2 yuan/kW, it indicates that the profit of lithium battery through providing AGC service is lower than the reduced cost in the energy market. Thus, it prefers to participate in the energy market.

In this study, AGC opportunity cost of lithium battery is calculated successively. Then, decisions are made according to the opportunity cost and the AGC compensation price. As long as the opportunity cost of per unit AGC capacity is less than AGC compensation price, lithium battery can make more profits by providing AGC service. Therefore, the optimal AGC bidding capacity can be obtained through the simulation process shown in Fig. 1.
Start

Initialize AGC bidding capacity: \( R=0 \)

Increas AGC bidding capacity: \( R=R+\Delta R \)

Calculate AGC opportunity, and record the current value of \( R \)

R<P_{\text{max}}

Yes

Select the maximum value of \( R \) in conditions of the opportunity cost being lower than AGC compensation cost and take as the final AGC bidding capacity

No

End

Fig. 1. Decision-making process for lithium battery in the market

5. Case Studies

5.1 Introduction to the test case
Simulation is conducted on a modified IEEE 6-bus system, as shown in Fig. 2. The system contains three conventional units: G1, G2 and G3, connected to bus 1, 2 and 6, respectively; one wind power connected to bus 4; and one lithium battery with a capacity of 20MW/100MWh connected to bus 5. The parameters of the three conventional units are shown in Table 1, including the maximum and minimum technical output, the quadratic function coefficient of the generation cost, the fuel price.

![Fig. 2. Single-line diagram of IEEE 6-bus system](image)

| UNIT | Min output MW | Max output MW | Quadratic cost function coefficient | Fuel price $/MBtu |
|------|--------------|---------------|------------------------------------|-------------------|
|      |              |               | \( a \) Mbtu | \( b \) MBtu/MWh | \( c \) MBtu/MWh² |                |
| G1   | 90           | 220           | 176.9     | 13.5       | 0.0004       | 5               |
| G2   | 10           | 100           | 129.9     | 32.6       | 0.001        | 5.5             |
| G3   | 10           | 20            | 137.4     | 17.6       | 0.005        | 5.2             |
5.2 Energy market clearing results
The energy market results and clearing price is shown in Fig. 3 and Fig. 4. The clearing prices in the energy market are determined by the marginal generation cost of the conventional units. The higher is the output of the conventional units, the higher is the market clearing price. The lithium battery is charged during the low price hours and discharged during the peak price hours. It arbitrages the price spread between the charging and discharging period in the energy market to make profits.

5.3 Operation results and revenue of lithium battery after providing AGC service
The opportunity cost of providing AGC for Lithium battery is obtained through a simulation method. The trend of the SOC of lithium battery when providing different AGC capacities is shown in Fig. 5. The trend of SOC can also reflect its revenue in the energy market to certain extent. When the AGC capacity is 0 MW, i.e. when lithium battery only participates in the energy market, it has the highest revenue in the energy market. The utilisation rate of its capacity reaches maximum, with the maximum SOC close to 100 MWh and the minimum SOC close to 22 MWh. When the AGC capacity increases to 10 MW, the maximum amount of electricity stored in lithium battery is less than 80 MWh. When AGC capacity increases to 12 MW, the highest SOC of lithium battery is less than 70 MWh, indicating that the utilization rate of lithium battery in the energy market is further reduced. When the AGC capacity increases to 18 MW, the SOC of lithium battery changes between 20~40 MW. The corresponding profits in the energy market become even low.
Fig. 5. SOC of energy storage under different AGC bidding price

Fig. 6 illustrates the profit changes of lithium battery in the energy market against different AGC capacities. The reduced revenue is the AGC opportunity cost of lithium battery. As the AGC bidding capacity increases, the revenue of lithium battery in the energy market decreases. Its opportunity cost increases faster and faster. The slope of the opportunity cost curve can be regarded as the marginal opportunity cost, which also increases as the bidding capacity getting larger, indicating that the AGC resources become more and more scarce.

Fig. 6 Profit and reduced revenue of lithium battery in the energy market after providing AGC frequency regulation capacity

The market strategy for lithium battery is to reasonably allocate its capacity in the energy market and AGC market to maximize the total profits. The opportunity cost per unit of AGC capacity is calculated and shown in Fig. 7. It shows that the larger AGC bidding capacity is, the higher is the opportunity cost per unit of AGC capacity. When the value is higher than the revenue per unit of capacity in the AGC market, the total revenue obtained by lithium battery begins to decrease.

As shown in Fig. 7, if the AGC compensation price is at 0.8 yuan/MW and AGC bidding capacity reaches 12 MW, the opportunity cost per unit of AGC capacity is equal to the AGC compensation price. In this condition, the total revenue from lithium battery in the energy market and AGC market reaches the maximum. If the AGC bidding capacity is higher than 12 MW, the total revenue of the lithium battery will decrease.
6. Conclusions
In this paper, an operation model and strategy of lithium battery to provide frequency regulation is proposed. The technical feasibility lithium battery to provide frequency regulation is analysed. An day-ahead energy market clearing model with the participation of lithium battery storage is established. The reduced revenue in the energy market, namely the opportunity cost of lithium battery to provide frequency regulation is obtained through successive simulations. Through comparing the opportunity cost with the AGC compensation price, an operation strategy is proposed for lithium battery to allocate its charging and discharging capacity in day-ahead energy market and the AGC frequency regulation market.

After lithium battery provides AGC frequency regulation capacity, its upper power limit in day-ahead energy market will decrease. While the available range of its SOC in the energy market also becomes smaller. As a result, its revenue in the energy market decreases.

The marginal reduced revenue, namely the opportunity cost of lithium battery in day-ahead energy market increases as it provides more and more AGC frequency regulation capacity. Consequently, optimal frequency regulation capacity for lithium battery is the amount, at which the marginal reduced marginal revenue in the energy market is equal to the compensation price of frequency regulation.

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