Control Strategy of Microgrid Switching Station based on B2G Mode of Fully Charged Battery

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Abstract. After the electric vehicle exchange station is connected to the microgrid, the battery in the exchange station can be used to stabilize the output fluctuation of renewable energy or provide auxiliary services such as frequency modulation and rotary standby through battery to grid (B2G), so as to reduce the construction cost of microgrid and improve the operation profit of the power station. In this context, the following work has been done: (1) A scheme of battery swapping to participate in B2G service is proposed, which solves the problems of insufficient available power and difficult charging plan when selecting batteries to be charged and batteries being charged; (2) Considering the service reliability of power exchange station and the power fluctuation of tie line interaction, a day ahead charging scheme is proposed and the operation cost of the power station is reduced by making the plan and scheduling the battery within a day; (3) The effectiveness of the proposed control strategy is verified by a simulation example. The control strategy of battery scheduling effectively participates in the B2G service of microgrid, which improves the power supply reliability of microgrid and gains some benefits.

1. Introduction
In recent years, electric vehicles and new energy power generation have been vigorously promoted in the world due to their environmental protection[1]. At present, the long charging time, limited driving range and shortage of charging facilities restrict the development of electric vehicles to some extent. However, due to its convenience and rapidity, the power station is welcomed by users. Electric vehicle owners can go to the nearby power station to complete energy replenishment within minutes[2]. As an effective way to connect distributed generation into power system, microgrid increases the flexibility of grid operation mode, and can operate independently in case of power system failure, thus improving the reliability of power supply[3-4]. However, due to the uncertainty of new energy output in microgrid, the interactive power fluctuation between large power grid and micro grid is too large, which may lead to "peak on peak" of large grid load, which has a negative impact on the stable operation of large power grid. The common solution is to install energy storage system in the microgrid to suppress the fluctuation of wind power output, but it increases the construction cost of microgrid. Therefore, the exchange station can be considered as a special energy storage system, which can not only reduce the construction cost of the microgrid, but also increase the operating profit of the exchange station.

At present, in the aspect of B2G of power station, the existing literatures usually choose the battery to be charged or the battery being charged to participate in B2G service. In the aspect of battery control strategy in the power station, domestic and foreign scholars have carried out the following research. In reference[5], a load demand forecasting method for electric vehicle swap station based on Monte Carlo
simulation is proposed, which provides a basis for the formulation of charging plan. Reference [6] proposed an ordered charging model with the number of batteries in each state in each period as the control variable, which solved the problem that the traditional charging and discharging power of the charger was difficult to realize flexibly in reality. Reference [7] regards the exchange station as an energy storage unit connected to the microgrid, and establishes a battery scheduling strategy for the exchange station with the goal of maximizing the response to the microgrid dispatching signal. However, the service reliability of the exchange station after participating in the microgrid dispatching response is not analyzed.

Under the above background, this paper proposes a scheme to select the battery to participate in B2G, which solves the problems of insufficient available power when selecting the battery to be charged and the battery being charged, and the difficulty in formulating the charging plan, and at the same time, it ensures the service satisfaction of the swapping station to the greatest extent. Secondly, based on the scheme, the method of making the day ahead charging plan and the strategy of day battery scheduling are proposed. At the same time, it can ensure the service reliability of the exchange station even when the forecast error of the power exchange demand is large, and reduce the power fluctuation of the tie line between the microgrid and the large grid, so as to achieve a win-win situation between the operator of the exchange station and the power grid company.

2. B2G Mode and Operation Rules of Battery

After the power station is connected to the microgrid, the idle batteries in the station can obtain additional benefits by participating in B2G service. Therefore, the reliability of B2G should be determined with a reasonable number of batteries in service.

According to the working state, the battery of power station can be divided into three types: charging battery, battery to be charged and battery changing battery. When choosing the battery to be charged or the battery being charged to participate in B2G service, there are some problems such as insufficient available power and difficult charging plan. When choosing the battery to be charged, the above problems can be solved, but the user will actually get the battery that is not fully charged. To solve this problem, based on the participation of battery exchange in B2G service, the classification and conversion of batteries in the exchange station are optimized, as shown in Figure 1.

![Conversion diagram of various types of batteries in the battery swapping station](image)

**Figure 1.** Conversion diagram of various types of batteries in the battery swapping station

As shown in the figure above, on the basis of the original classification of batteries, a class of batteries only used for participating in B2G services is added, that is, B2G batteries in the figure. However, the battery for battery replacement is no longer used for B2G service. According to a certain dispatching strategy, the operator can transfer the idle battery into B2G battery. At the same time, B2G battery can be used as a backup battery for battery replacement, which can be provided to users when the battery is insufficient in the station.

In B2G process, charging process and discharge process will occur frequently. In order to reflect the backup of B2G battery, it is necessary to ensure that its power level is at a high level. The operation rules of B2G battery are proposed as follows:
1) If the minimum SOC acceptable to the vehicle owner is $SOC_{\text{min}}$, all batteries in B2G battery should always meet the following requirements:

$$SOC_{\text{min}} \leq SOC_i \leq 1$$  \hspace{1cm} (1)

Among them, $SOC_i$ represents the state of charge of the $i$th power battery in B2G battery, and $SOC_{\text{min}}$ can be taken according to the actual situation, which should not be less than 0.8.

2) In the process of B2G, when charging the battery, the battery with low SOC shall be charged first; when discharging the battery, the battery with high SOC shall be discharged preferentially, so as to avoid the decrease of the actual number of B2G batteries due to the SOC of individual battery at the upper and lower limits of formula (1). At the same time, when the battery is used to suppress the fluctuation of renewable energy output or provide amplitude modulation service, the required discharge amount and charging amount are usually not different, which can make the battery SOC tend to the center value of $SOC_{\text{min}}$ and 1, and the average power of B2G battery is at a high level, which improves the service satisfaction.

3) When the number of batteries in the power station is not enough to meet the demand, the power battery with the highest SOC in B2G battery should be given priority to the vehicle owner, and the owner should be compensated according to the SOC.

### 3. Day Ahead Charging Plan and Intra Day Battery Scheduling Strategy

On the basis of battery B2G mode, the control strategy of the exchange station mainly includes two parts: day ahead charging plan formulation and day battery scheduling. The flow chart is shown in Figure 2. Among them, the day ahead charging plan should reduce the charging cost on the premise of ensuring service reliability; the purpose of daily battery scheduling is to control the number of battery replacement and B2G in real time according to the prediction error, so as to obtain the maximum benefit.

![Flow chart of control strategy for battery swapping stations](image)

**Figure 2.** Flow chart of control strategy for battery swapping stations
3.1. Day Ahead Charging Plan

In order to improve the operation efficiency of large-scale power grid and the stable operation of microgrid, the power fluctuation of tie line interaction between microgrid and large power grid should be controlled within a reasonable range when making charging plan.

3.1.1. SOC discretization of battery to be charged. In order to determine the type and quantity of batteries to be charged at each time of the next day, the SOC of the battery to be charged should be discretized before making the battery plan. In reference [14], a discretization method is proposed, in which the charging process of the battery is approximately regarded as constant power charging. If the number of periods for an empty battery to be fully charged is K, then it can be known that the SOC increment per unit period of the battery should be. Therefore, the battery to be charged can be divided into K charge levels, as shown in Table 1, then the number of periods required for the battery with charge level K to be fully charged should be K\(\cdot k+1\).

| Charge level | 1 | ... | k | ... | K |
|-------------|---|-----|---|-----|---|
| SOC interval| \([0, \frac{1}{K})\) | \(...\) | \([k-1, k)\) | \(...\) | \([K-1, 1]\) |

3.1.2. Objective function. From the operator's point of view, the main goal of charging plan is to minimize the daily charging cost of the exchange station. Considering the time of use price, taking the number of new batteries charged in each period as the control variable, the expression of the objective function is as follows:

\[
\min F = \sum_{t=1}^{T} c(t) \cdot N_c(t) \cdot p \cdot \Delta t
\]  

(2)

Among them, \(c(t)\) is the unit price of microgrid at time \(t\); \(N_c(t)\) is the total number of batteries being charged in the primary power station at time \(t\); \(p\) is the charging power of batteries; \(\Delta t\) is the length of unit time period; \(T\) is the total number of segments in a day.

3.1.3. Constraint condition

1) The limit of the number of batteries to be charged:

\[
0 \leq n_{c,k}(t) \leq n_{w,k}(t)
\]  

(3)

Among them, \(n_{c,k}(t)\) is the total number of batteries with charge level of \(k\) in the initial charging pool at time \(t\); \(n_{w,k}(t)\) is the number of batteries with charge level of \(k\) newly put into charge at time \(t\).

2) Service reliability constraint: in order to ensure the service satisfaction, the battery number \(N_f(t)\) and B2G battery number \(N_g(t)\) in any period of time should not be less than \(a\) times of the predicted value of the power change demand in that period.

\[
N_f(t) + N_g(t) \geq a \cdot N_{dem}^\text{pre}(t)
\]  

(4)

Where \(a\) is the battery reserve factor, which is not less than 1.

3) Tie line interaction power fluctuation constraint: the maximum allowable power fluctuation of tie line is taken as artificial constraint to prevent excessive power fluctuation from affecting the stable operation of large power grid.

\[
\left| P_g(t+1) - P_g(t) \right| \leq s\% \cdot S_n
\]  

(5)

\(s\%\) is the ratio of the maximum allowable fluctuation value of interactive power to the rated capacity of microgrid, and \(S_n\) is the rated capacity of microgrid.

In addition, the number of chargers, microgrid power balance and tie line transmission capacity should be considered.
The charging plan is an integer linear programming problem, which can be solved by intlinprog function in MATLAB R2017A.

3.2. Intra Day Battery Scheduling Strategy
Dynamic scheduling of battery replacement is to increase the number of B2G batteries as much as possible under the premise of ensuring service reliability, so as to obtain the maximum benefit. Assuming that the initial total number of batteries in the exchange station is $N$, then the total number of batteries in the exchange station is $N$ at any time. If the power station is charged according to the proposed charging plan, the number of batteries newly put into charge at the initial replacement station $n_c(t)$ at time $t$ is as follows:

$$n_c(t) = \sum_{k=1}^{K} n_{c,k}(t)$$

According to formula (6), the number of batteries $n(t)$ that just completed charging at the time $t$ should meet the following requirements:

$$n(t) = \sum_{k=1}^{K} n_{c,k}(t - K - 1 + k)$$

At the beginning of time $t$, the number of all batteries in the exchange station should be the sum of the number of remaining batteries and $n(t)$ after deducting the actual demand for power change in the previous period. In order to increase the number of B2G batteries as much as possible, at the beginning of time $t$, the reserved battery number $n(t)$ should meet the following formula, and the remaining batteries are classified as B2G batteries:

$$N_{r}(t) = \begin{cases} \min \left( \left\lfloor a \cdot N_{\text{dem}}(t) \right\rfloor, n(t) \right), & N_{r}(t - 1) \leq N_{\text{dem}}(t - 1) \\ \min \left( \left\lfloor a \cdot N_{\text{dem}}(t) \right\rfloor, n(t) \right) + N_{r}(t - 1) - N_{\text{dem}}(t - 1), & N_{r}(t - 1) > N_{\text{dem}}(t - 1) \end{cases}$$

Where, $N_{\text{dem}}(t)$ and $N_{\text{dem}}(t)$ are the predicted value and the actual value of the power change demand at time $t$; $\left\lfloor \cdot \right\rfloor$ are the rounding up; $a$ has the same meaning as $a$ in equation (4). The larger $a$ is, the more standby batteries are, the less B2G batteries are.

On the basis of formula (8), the number of B2G batteries $N_{g}(t)$ in the power station at time $t$ can be obtained as follows:

$$N_{g}(t) = N_{g}(t - 1) + N_{r}(t - 1) - N_{\text{dem}}(t - 1) + n(t) - N_{r}(t)$$

At time $t$, the number of rechargeable batteries and the number of batteries to be charged in the initial power station shall be $N_{c}(t)$ and $N_{w}(t)$ respectively

$$N_{c}(t) = N_{c}(t - 1) + N_{r}(t - 1) - N_{\text{dem}}(t - 1) + n(t) - N_{r}(t)$$

$$N_{w}(t) = N - N_{g}(t) - N_{r}(t) - N_{c}(t)$$

There may be some error between the predicted value and the actual value, so there may be insufficient battery in the station when the above battery scheduling strategy is adopted. In order to evaluate the impact of the above scheduling strategies on service reliability, a service reliability evaluation index $\delta$ is defined

$$N_{\text{dem}}(t) = \begin{cases} N_{\text{dem}}(t) - N_{g}(t) - N_{r}(t), & N_{g}(t) + N_{r}(t) - N_{\text{dem}}(t) < 0 \\ 0, & N_{g}(t) + N_{r}(t) - N_{\text{dem}}(t) \geq 0 \end{cases}$$

$$\delta = \frac{\sum_{t=1}^{T} N_{\text{dem}}(t) - \sum_{t=1}^{T} N_{\text{dem}}(t)}{\sum_{t=1}^{T} N_{\text{dem}}(t)} \times 100\%$$
\(N_{\text{wait}}(t)\) refers to the number of electric vehicles that can not be replaced due to insufficient batteries in the power station during \(T\) period. It can be seen from formula (12b) that the value of \(\delta\) is between 0% and 100%. The higher the actual service reliability is, the higher \(\delta\) is. When the reliability is the highest, that is, all electric vehicles can replace batteries immediately, \(\delta\) is 100%.

4. Example Analysis
In this paper, a power station in the microgrid is taken as the research object. Under the background of selecting battery B2G mode, reasonable day ahead charging plan and day battery scheduling strategy are studied to ensure service reliability, optimize charging cost and optimize microgrid operation.

4.1. Relevant Parameters of Microgrid and Power Station
The rated capacity of a microgrid is 6MW, of which the total installed capacity of wind power and photovoltaic power are 4MW and 2MW respectively. The microgrid is connected with the large grid, and the maximum transmission capacity of tie line is 3000kW. Figure 3 shows the output of wind power and photovoltaic power in a typical day; Figure 4 shows the basic load of microgrid; table 2 shows the time of use price of microgrid.

Assuming that the average daily service times of a power exchange station in a microgrid is 200, according to the reference [8], the number of self owned batteries of the exchange station should be 120 sets. Assuming that all batteries are of the same specification, the specific parameters of the exchange station are shown in Table 3.

4.2. Forecast Demand and Actual Demand
According to the method of power exchange demand prediction in reference [6], the SOC of the battery entering the exchange station obeys the normal distribution with parameters of \((0.2,0.12)\). Through the Monte Carlo simulation method to simulate the 200 electric vehicles in the region, we can get the status of battery entering stations at each time.
The mean absolute percentage error (MAPE) is usually used to reflect the size of prediction error. In this paper, case I and case II correspond to two cases of small prediction error (MAPE = 15%) and large prediction error (MAPE = 30%). The predicted value and actual value of electricity exchange demand are shown in Figure 5. In this paper, one hour is taken as the unit scheduling time, so the SOC increment per unit period is 0.2, and the battery should be divided into five charge levels.

Figure 5. Forecast and actual value of the battery swapping demand

4.3. Optimization Results and Analysis

4.3.1. Analysis of day ahead charging plan. In this section, the battery reserve factor \( a \) is set as 1.3, which is used to analyze the influence of the maximum allowable value of interconnection line interaction power fluctuation on the formulation of charging plan. The optimization results under different \( s\% \) are shown in Table 4.

Table 4. Relationship between \( s\% \) and charging cost

| \( s\% \) | Charging cost/yuan |
|----------|--------------------|
| Lower than 13 | No optimal solution |
| 14       | 702.18             |
| 15       | 683.57             |
| 16       | 667.32             |
| 17       | 658.86             |
| 18       | 658.86             |
| 19       | 658.86             |

Among them, "No optimal solution" means that the maximum value of interactive power fluctuation cannot be less than 0.13 of the rated capacity of microgrid. With the increase of the maximum allowable fluctuation value of the interactive power, the charging cost of the charging station decreases. When it reaches a certain value (17%), the charging charge does not change.

Taking \( s=17\% \) as an example, Fig. 6 shows the charging schedule of the swapping station, and Fig. 7 shows the comparison between the ordered charging plan and the disordered charging. In Fig. 7 (c), the interactive power fluctuation ratio refers to the ratio of the interactive power fluctuation value to the rated capacity of the microgrid.

Figure 6. Charging schedules in coordinated charging
It can be seen from Fig. 7 that the charging plan can transfer part of the charging load during the day to the night, which has the effect of "peak shaving and valley filling". When the microgrid load drops rapidly, more batteries will be put into the exchange station for charging to alleviate the rapid change of interactive power caused by the rapid load drop of microgrid, such as 22:00-24:00.

Table 5 shows the comparison of several key indicators between orderly charging plan and disordered charging. It can be seen from the table that the charging cost of the orderly charging plan is 39.12% lower than that of the disordered charging, which has obvious advantages. The load peak and peak valley difference and the interactive power fluctuation of microgrid are significantly reduced, which improves the stability of microgrid and large grid. In the actual operation process, $s\%$ can be determined according to the tolerance of large power grid to disturbance.

**Table 5. Comparison of key indexes**

| Project                      | Disorderly charging | Orderly charging |
|------------------------------|---------------------|------------------|
| Charging charge/yuan         | 1082.18             | 658.86           |
| Peak load/kW                 | 6218.23             | 5860.54          |
| Load peak valley difference/kW| 3591.12             | 2878.79          |
| Peak interactive power/kW    | 3000                | 2747.27          |
| Maximum value of interactive power fluctuation ratio/% | 23.57%             | 16.65%           |
| Average value of interactive power fluctuation ratio/% | 6.44%              | 5.75%            |

4.3.2. Analysis of battery scheduling results within a day. The battery reserve factor $a$ set in the daily battery scheduling will directly affect the service reliability of the exchange station. This section sets $s\%$ to 17%, and figure 8 shows the relationship between $a$ and charging cost and service reliability $\delta$.

![Figure 8. The correlation between swapping battery spare coefficient $a$ and charging cost, service reliability](image)

It can be seen from figure 8 that with the increase of $a$, the charging cost of the exchange station increases correspondingly. This is because in order to meet the constraint condition (4), the exchange station must put in more batteries for charging in the daytime, which will increase the charging cost,
but can improve the service reliability of the exchange station. Even if $a=1$ and the average absolute percentage error of the forecast is as high as 30%, the service reliability can still reach more than 94%. When $a$ reaches 3, the service reliability reaches 100%, and the corresponding charging cost is 720.29 yuan, which is 33.44% lower than that of disordered charging. To sum up, in order to ensure the satisfaction of power exchange service, the value of $a$ can be set between 2 and 3 during actual charging.

Figure 9 shows the comparison of the actual demand for battery replacement in case II and B2G battery with different values of $a$. It can be seen that even in the case of large demand forecast error, the sum of battery and B2G battery can still meet the actual demand for power exchange in most of the time. Only at 22:00 and 23:00, the shortage of batteries will be eased with the increase of $a$. At 1-15, the number of B2G batteries is large, and the sum of battery replacement and B2G battery is 3-100 times of the actual demand for power exchange, which means that if there is no B2G battery, a large number of batteries will be idle, which will reduce the benefits of power station replacement.

5. Conclusion
In this paper, based on the B2G mode of battery exchange in the power station, the day ahead charging plan and the day battery scheduling strategy are proposed.
1) Most of the time, there are a large number of idle batteries in the exchange station. These batteries can cooperate with the energy storage system of microgrid to suppress the fluctuation of wind and solar output or provide FM and rotary backup services, which can improve the quality and reliability of microgrid power supply and obtain certain benefits.

2) The simulation results show that the charging plan cost is significantly lower than that of disordered charging, and the peak load can be cut to fill the valley, and the interactive power fluctuation of tie line is controlled within a reasonable range, which improves the operation efficiency of large power grid and is conducive to the stable operation of microgrid. In the actual operation process, the value of $s\%$ can be set according to the tolerance of large power grid to disturbance.

3) The proposed intra day battery scheduling strategy can reduce the service reliability degradation caused by demand forecasting error. In actual operation, it is suggested that the value of battery reserve factor $a$ can be set between 2 and 3.

Acknowledgments
This work is supported by the Science and Technology Project of State Grid Corporation of China under Grant No. 520201190090.

References
[1] Wang S X, Chen J K, Wang H K, Wu Z W. Optimization method for two-stage flexibility enhancement of distribution network considering electric vehicle charging and energy storage and interruptible load dispatch, Electric Power Automation Equipment, 2020, PP(11):1-8
[2] Feeney K, Brass D, Kua D, et al. Impact Of Electric Vehicles And Natural Gas Vehicles On The Energy Markets, Mpra Paper, 2011:3-15.
[3] Li P, Zhang X, Li Y W, Cai Y Q, et al. Scenario analysis based two-layer optimal operation method for AC/DC hybrid microgrid, High Voltage Engineering, 2020:1-12
[4] XIAO Dingyao, WANG Chengmin, ZENG Pingliang, et al. A Survey on Power System Flexibility and Its Evaluations, Power System Technology, 2014, 38(6):1569-1576.
[5] Dai Q, Cai T, Duan S, et al. Stochastic Modeling and Forecasting of Load Demand for Electric Bus Battery-Swap Station, IEEE Transactions on Power Delivery, 2014, 29(4):1909-1917.
[6] HUANG Minli, YU Aiqing. Study on Coordinated Charging Strategy for Battery Swapping Station Based on Improved Cuckoo Search Algorithm, Proceedings of the CSEE, 2018, 38(4):1075-1083.
[7] YANG Ai-min, ZHANG Chen-xi, WEN Fu-shuan, et al . Operation strategy for battery swapping stations of electric vehicles in microgrid environment, Journal of North China Electric Power University, 2013, 40(4):19-26.
[8] ZHANG Changhua, MENG Jinrong, CAO Yongxing, et al. A Battery Swapping Requirement Adequacy Model for Electric Vehicles and Its Simulation Research, Power System Technology, 2012, 36(9):15-19.