

Article

Operation Strategy for Electric Vehicle Battery Swap Station Cluster Participating in Frequency Regulation Service

Fan Zhang ¹, Senjing Yao ¹, Xiankai Zeng ², Ping Yang ^{2,*}, Zhuoli Zhao ³, Chun Sing Lai ^{3,4,*}  and Loi Lei Lai ³ 

¹ Digital Grid Research Institute of China Southern Power Grid, Guangzhou 510640, China; zhangfan1@csg.cn (F.Z.); yaosj2@csg.cn (S.Y.)

² Guangdong Key Laboratory of Clean Energy Technology, South China University of Technology, Guangzhou 510640, China; 202021015113@mail.scut.edu.cn

³ Department of Electrical Engineering, School of Automation, Guangdong University of Technology, Guangzhou 510006, China; zhuoli.zhao@gdut.edu.cn (Z.Z.); l.l.lai@gdut.edu.cn (L.L.L.)

⁴ Brunel Interdisciplinary Power Systems Research Centre, Department of Electronic and Electrical Engineering, Brunel University London, London UB8 3PH, UK

* Correspondence: eppyang@scut.edu.cn (P.Y.); chunsing.lai@brunel.ac.uk (C.S.L.)

Abstract: Idle batteries in the battery swap stations (BSSs) of electric vehicles (EVs) can be used as regulated power sources. Considering the battery swap service and the frequency regulation (FR) service, this paper establishes a model of BSS cluster participating in the FR service and formulates a two-stage operation strategy. The day-ahead strategy arranges the battery charging plan and FR plan with the goal of the optimal operating economy on the next day. The intra-day strategy aims at maximizing the satisfaction degree of battery swap, minimizing the loss of planned revenue and ensuring the coordination of battery swap service and FR service by regulating the charging and discharging status of each battery in real-time. The simulation case shows that, under the prerequisite of gratifying the battery swap demand, the strategy improves the operating economy by making full use of idle batteries which bear a part in the FR service.



Citation: Zhang, F.; Yao, S.; Zeng, X.; Yang, P.; Zhao, Z.; Lai, C.S.; Lai, L.L. Operation Strategy for Electric Vehicle Battery Swap Station Cluster Participating in Frequency Regulation Service. *Processes* **2021**, *9*, 1513. <https://doi.org/10.3390/pr9091513>

Received: 6 July 2021

Accepted: 24 August 2021

Published: 26 August 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: battery swap station; frequency regulation service; battery swap service; idle batteries

1. Introduction

Compared with charging mode, battery swapping mode of electric vehicles (EVs) has many conveniences [1], but the fundamental causes of unpopularity are its high investment and operating costs and low economic benefits. After the initial investment of the BSS is determined, how to improve the operating economy is a key issue that needs to be considered. Enabling battery swap stations (BSSs) clusters to participate in the frequency regulation (FR) service can make full use of idle batteries to gain revenue, thereby improving the operating economy of BSSs and promoting the popularization of battery swapping mode [2,3].

At present, improving the efficiency of the battery swap business is the main solution to the economic problems of BSSs, which mainly include battery charging optimization and battery swap scheduling optimization. In [4], charging period and charging power were taken as decision variables, which were researched to reduce network loss, peak-to-valley difference and power purchase costs. The authors of [5,6] used the battery in BSSs to solve the problem of photovoltaic power generation surplus, which could reduce the battery charging costs, while solving the consumption of new energy. The authors of [7] built an operating model of a centralized distribution model based on the closed-loop supply chain, established a battery logistics model using time-space network technology and optimized the management of battery charging and distribution.

To further enhance the economics of operation, some scholars have broadened the scope of research to the construction of the entire battery swap service and the relationship

between the BSS operator and other entities. For example, [8] proposed a nano-grids-based charging and swapping system for EVs to improve the cleanliness of energy supply and the electrification of transportation, while [9] studied the joint control of BSSs and batteries in a dynamic energy pricing environment and proposed an optimization framework to reduce costs and energy consumption. The above-mentioned research papers only focused on the internal optimization of the service network of BSSs and did not fully consider and utilize the external environment of BSSs. The authors of [10] used reasonable control and scheduling to provide battery charging and swapping stations as active power stations to provide peak-shaving service for the power grid, whereas [11] aggregated the battery fast-charging station, BSS and energy storage system in the micro-grid into a whole and proposed a multi-time scale optimization operation strategy.

The FR market brings great profitability to industries containing energy storage technologies such as EVs [12]. The key issues are the aggregation of battery resources, the estimation of FR capabilities and the allocation of PR power. The authors of [13,14] separately studied the forecasting of disposable capacity and the development of aggregation modules for EVs to participate in the FR service, while [15] considered the uncertainty of battery charging demand and proposed a vehicle-to-grid control strategy that coordinated the development of the FR service and battery charging service. The authors of [16] proposed an aggregation model and a calculation method of disposable capacity for EVs to participate in the FR service in the electricity market and proposed a bidding strategy that considers risks. In [17], the authors proposed a two-stage self-dispatching model that took into account the day-ahead electricity market and the FR market to realize the day-ahead formulation of battery swap plans and bidding strategies. To improve the mileage score of BSS, [18] considered the uncertainty of electricity prices and FR signals and proposed a robust control model for EVs based on FR performance evaluation. The authors of [19] used Lyapunov optimization for the FR control strategy considering various factors, such as the travel demand of EVs, the cost of batteries and the access to energy to realize the optimization of decision-making without historical data. Considering the applicability of battery energy storage to participate in FR, some scholars have recently carried out research based on battery degradation. A refined model of the battery degradation principle is given in [20,21]. Based on this, the FR control strategy to minimize the degree of battery degradation is proposed and the accurate calculation method of the battery energy storage FR cost is given, both of which can promote the application of battery energy storage in the FR market.

Based on the above research inspiration, a BSS operation strategy for the collaborative development of the battery swap business and the FR service business is proposed. Under the premise of meeting the battery swap demand, it obtains benefits by making full use of idle batteries to participate in the FR service and provides a more cost-effective and efficient operation mode for BSSs.

The contributions of this article are listed as follows:

1. The unified model of BSS cluster participating in the FR service is designed and established, which clearly describes the multi-time scale behavior of BSSs. The key items that determine the economic effect are systematically given, including battery degradation costs, power purchase costs, FR service income and battery swap service income.
2. The optimization problem constructed in this paper is based on fewer assumptions and is more in line with engineering reality than existing research. Processes such as the battery swap service and FR service are accurately described by only integer variables and linear functions, which can avoid solving complex optimization problems and can obtain more detailed results, including charge and discharge power profiles, SOC, charger plug-in status and battery swap state.
3. The index that characterizes the busyness of the battery swap service of BSSs is defined and, in the FR service, the FR power is optimally allocated based on it, which

realizes the power support between the BSSs and minimizes the impact of the FR service on the battery swap service.

This paper is organized as follows: Section 2 introduces the model of BSS cluster participating in FR services and analyzes its operating economics. Section 3 proposes the day-ahead and intra-day two-stage strategy. Section 4 presents the case studies and analysis to verify the correctness and effectiveness of the proposed model and strategy. Section 5 concludes this paper.

2. Model for Battery Swap Station Cluster Participating in Frequency Regulation Service

The model for a BSS cluster participating in the FR service is designed in this section and the corresponding model is established.

2.1. Model for Battery Swap Station Cluster Participating in Frequency Regulation Service

The EV battery swapping modes include centralized charging mode and battery-swapping mode [22]. The charging and battery-swapping modes are the research object in this paper. BSS operators provide battery leasing service and battery swap service for EVs and use idle batteries to participate in the FR service to increase revenue [23]. The business model of the BSS cluster participating in the FR service is shown in Figure 1. The BSS operators are located in the middle of the industrial chain, providing a battery swap service for EVs and the FR service for the power system. EV users pay battery rental fees and battery swap service fees through BSSs to obtain batteries swap service; the power sector organizes and supervises the FR service market [24].

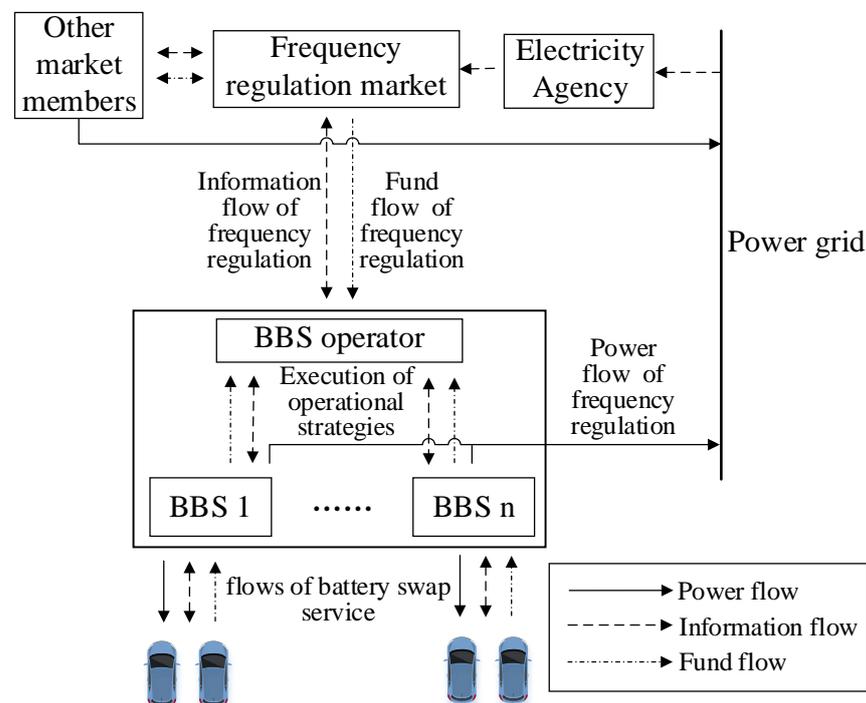


Figure 1. The business model of BSS cluster participating in FR service.

2.2. Model for Battery Swap Station Cluster Participating in Frequency Regulation Service

Under the model of a BSS cluster participating in the FR service, the costs borne and benefits obtained by BSS operators are analyzed in this section and the model of a BSS cluster participating in the FR service is established.

2.2.1. Operating Costs

The investment costs [25] and annual financial costs [26] of BSSs can be determined in the initial construction stage. The operating costs mainly consist of operation and maintenance costs, power purchase costs and degradation costs.

$$\begin{cases} Z_{total}^{day} = Z_1 + Z_2 + Z_3 \\ Z_1 = \sum \alpha_i \cdot P_i + \varepsilon \cdot n \\ Z_2 = \sum \frac{E_i}{\eta_{i,ch}\eta_{i,j}} \cdot P_{grid} \\ Z_3 = \max(\pi_{ess} C_{cap} / T_{float}, C_{ess}^{cycle}) \end{cases} \quad (1)$$

where Z_{total}^{day} is the daily operating costs (USD), Z_1 is the daily maintenance costs (USD), α_i is the industry operation and maintenance rate of the i th equipment, P_i is the investment costs of the i th equipment (USD), ε is the average daily wage of the employee (USD/person), n is the number of employees (person), Z_2 is the daily power purchase costs (USD), E_i represents the charging demand of the i th BSS on that day (kWh), $\eta_{i,ch}$ is the charging efficiency of the i th BSS, $\eta_{i,j}$ is the power utilization efficiency of the i th BSS, P_{grid} is the power purchase price of the BSS (USD/kWh), Z_3 is the daily degradation cost (USD), π_{ess} is the investment cost per unit capacity of the battery (USD/kWh), C_{cap} is the battery capacity (kWh), T_{float} is the floating charge life of the battery (day) [27] and C_{ess}^{cycle} is the average daily cycle costs of the battery (USD) [28].

$$\begin{cases} C_{ess}^{cycle} = \sum_{t=1}^T \frac{1}{2N_{eq,t}} \pi_{ess} C_{cap} \\ N_{eq,t} = \frac{N_0}{[\frac{1}{C_{cap}} (\frac{1}{\eta_{dis,i}} P_{dis,i}(t) + \eta_{ch,i} P_{ch,i}(t))]^{k_p}} \end{cases} \quad (2)$$

where $N_{eq,t}$ is the equivalent number of full cycles of energy storage in the t th period, $P_{ch,i}(t)/P_{dis,i}(t)$ is the actual value of charge/discharge power of the i th battery in the t th period [29], $\eta_{ch,i}/\eta_{dis,i}$ is the charge/discharge efficiency of the i th battery and k_p is the fitted energy storage characteristic parameter, generally 0.8–2.1.

2.2.2. Operating Income

Under the mode of BSS cluster participating in the FR service, the operating income of the BSS operator mainly comes from the battery swap business and the FR service business.

$$\begin{cases} S_{total}^{day} = S_1 + S_2 + S_3 \\ S_1 = \sum Q_{max,i} \cdot (SOC_{m,i} - SOC_i) \cdot P_{sell} + \mu \\ S_2 = \sum (A_j \cdot k_j \cdot P_{grid,j} + Q_j \cdot P_j) \\ S_3 = \sum \pi_{ess} C_{cap} \sigma \cdot C_i / C_{i,M} \end{cases} \quad (3)$$

where S_{total}^{day} is the daily operating income (USD), S_1 is the income from daily battery swap service (USD), $Q_{max,i}$ is the maximum battery capacity of the i th EV (kWh) [30], $SOC_{m,i}$ is the state of charge (SOC) requirement of the i th EV, SOC_i is the SOC of the i th EV before swapping the battery [31], P_{sell} is the price of the battery swap service (USD/kWh), μ is the fixed charge for the battery swap service (USD), S_2 is the revenue from the daily FR service (USD), A_j is the signal mileage of the BSS operator in the trading cycle of the j th FR service (kW), k_j is the average of the composite FR score [32] for the j th trading cycle, $P_{grid,j}$ is the mileage settlement price of the j th trading cycle (USD/kW), Q_j is the FR capacity awarded in the j th trading cycle (kWh), P_j is the FR capacity compensation pricing (USD/kWh), S_3 is the daily residual value return (USD), C_i is the charging and discharging times of the i th battery (times), $C_{i,M}$ is the maximum charge–discharge times of the i th battery (times) and σ is the residual value yield, that is, the proportion of the residual value income when the fixed asset is scrapped to its original value.

2.2.3. Model for Battery Swap Station Cluster Participating in Frequency Regulation Service

Therefore, a day-ahead and intra-day dual time scale model is established to formulate an FR plan and power allocation plan meeting the demand for power exchange. The details are as follows.

$$\begin{cases} \mathbf{Q}_{1 \times n}^{da} \cdot \mathbf{A}_{n \times m}^{da} = \mathbf{Q}_{1 \times m}^{grid} \\ \mathbf{P}_{1 \times n}^{rt} \cdot \mathbf{A}_{n \times 1}^{rt} = P^{grid} \end{cases} \quad (4)$$

where $\mathbf{A}_{n \times m}^{da}$ is the FR capacity distribution coefficient matrix of n BSSs in m periods of the next day, which is the output matrix of the model in the day-ahead stage, $\mathbf{Q}_{1 \times m}^{grid}$ is the tendered FR capacity (kWh), which is the input matrix of the model in the day-ahead stage, $\mathbf{Q}_{1 \times n}^{da}$ represents the maximum available capacity of each BSS (kWh), $\mathbf{A}_{n \times 1}^{rt}$ is the power distribution coefficient matrix of a single FR signal for n BSSs in the intra-day stage, which is the output matrix of the model in the intra-day stage, P^{grid} is the single FR signal in the intra-day stage (kW), which is the input matrix of the intra-day stage model, and $\mathbf{P}_{1 \times n}^{rt}$ is the maximum adjustable power of BSSs (kW).

Given that uncertainty [33] affects operations, some studies adopt the robust optimization framework for system scheduling and control [34], which can lead to stable and reliable solutions, but the solutions are often conservative, that is, the system capabilities cannot be fully utilized. So, in this paper, some parameters in the model are treated as random variables, which mainly include the battery swap demand that obeys the normal distribution and the time when the battery swap demand arises that obeys the uniform distribution [35]. Further, the impact of the uncertainty on the system is reduced through the day-ahead plan and intra-day adjustments.

3. Two-Stage Strategy for Battery Swap Station Cluster Participating in Frequency Regulation Service

In order to ensure that the battery swap service and FR service are carried out cost-effectively, this chapter proposes an optimal operation model which includes two parts, day-ahead and intra-day operation.

In the day-ahead stage, an operation plan is made with the goal of maximizing the net income of the next day; it includes a battery charging plan and an FR plan. In the intra-day stage, when the BSS operator receives the FR signal, the FR power is allocated with the goal of maximizing the satisfaction degree of battery swap service and minimizing the loss of planned income, so the charging and discharging status of each BSS is regulated. The detailed optimal model described in this paper is as follows.

3.1. Day-Ahead Operation

A BSS cluster participating in the FR service needs to coordinate the operation plan of each station in the day-ahead stage. It specifically includes the following:

1. Determining the available FR capacity of each station on the next day;
2. Arranging a battery charging plan. In order to achieve the above goal, it is necessary to optimize the solution based on the predicted value of battery swap demand and the FR demand issued by the power sector.

Therefore, for each battery in each period, its charging power (real), discharging power (real), charge–discharge state variable (integer), charger plug-in state variables (integer), state variable indicating whether the battery is fully charged (integer) and state variable of battery swap (integer) are used as decision variables to construct an optimization model.

3.1.1. Objective Function

In the model for a BSS cluster participating in the FR service, batteries are used for the FR service, so the average number of daily cycles increases, resulting in more degradation costs and potential power purchase costs, but obtains the FR service income and some

residual value income. The optimization goal of the day-ahead stage is to maximize the net income of the next day, as described in the following formula:

$$\max RS = S_1 + S_2 + S_3 - Z_1 - Z_2 - Z_3 \quad (5)$$

where RS is the daily net income of the BSS operator (USD).

3.1.2. Constraints

When optimizing the operation plan for the next day, it is necessary to comprehensively consider the constraints of battery energy constraints, FR service rules and battery swap demand.

1. Battery energy constraints

The charge and discharge power of the battery at any time is less than its maximum limit.

$$\begin{cases} 0 \leq \eta_{i,ch} P_{i,ch}(t) \leq I_i(t) P_{ch,i,max} \\ 0 \leq \frac{P_{i,dis}(t)}{\eta_{i,dis}} \leq (1 - I_i(t)) P_{dis,i,max} \end{cases} \quad \forall t \in T \quad (6)$$

where $P_{ch,i,max}/P_{dis,i,max}$ is the maximum limit of the charge/discharge power of the i th battery and $I_i(t)$ is the charge–discharge state variable, which takes 1 to indicate that the i th battery is charged, otherwise it is discharging.

The SOC of the battery remains within the allowable range at any time to avoid a sharp drop in life and the battery SOC has a quantitative relationship with its charges and discharges power.

$$SOC_{i,min} \leq SOC_i(t) \leq SOC_{i,max} \quad (7)$$

$$SOC_i(t + \Delta t) = SOC_i(t) + (P_{i,ch}(t) - P_{i,dis}(t))\Delta t / E_{i,0} \quad (8)$$

where $SOC_{i,min}/SOC_{i,max}$ is the lower/upper limit of the i th battery SOC, $SOC_i(t)$ is the SOC of the i th battery in the t th period and $E_{i,0}$ is the i th battery rated capacity (kWh).

To ensure that the optimization strategy is continuously executed, the electricity stored in each station needs to be equal at the beginning and end of each day. The battery swap process is treated as a quick discharge that rapidly reduces the SOC of the battery to the level of the inbound battery in this paper.

$$\sum SOC_{i,first} = \sum SOC_{i,final}, \quad \forall i \in N \quad (9)$$

where $SOC_{i,first}$ is the SOC at the beginning of the next day of the i th battery, $SOC_{i,final}$ is the SOC at the end of the next day of the i th battery and N is the collection of batteries in the N th power station.

2. FR service rules

In this paper, we assume that, in the FR service, the BSS operator declares the equivalent upward and downward FR capacity and that the FR signals issued by the power dispatch agency in each transaction cycle are electrically neutral.

$$\begin{cases} Q_t \leq \sum_i (Q_{i,max} - Q_{i,t,ev} - Q_{i,t,ch}) \\ Q_t \leq \sum_i ((Q_{i,rate} - Q_{i,max}) - \bar{Q}_{i,t,ch}) \\ Q_t \leq Q_{grid,t} \end{cases} \quad (10)$$

where Q_t is the tendered FR capacity for the t th period (kWh), $Q_{i,max}$ is the total battery power for the i th power change in the t th period (kWh), $Q_{i,t,ev}$ is the power needed for the battery swap service of the i th BSS in the t th period (kWh), $Q_{i,t,ch}$ is the remaining charge of the battery that needs to be continuously charged during the t th period (kWh), $Q_{i,rate}$ is the total capacity of all batteries for the i th BSS (kWh), $\bar{Q}_{i,t,ch}$ is the amount of charge that can be obtained by the battery that needs to be continuously charged in the i th BSS in

the t th period (kWh) and $Q_{grid,t}$ is the maximum amount of FR service that an FR service provider can tender during the t th period (kWh).

3. Battery swap demand

Carrying out the battery swap business requires that the number of available batteries in each station at each period is greater than the battery swap demand.

$$Q_j C_{j,t} \leq Q_{0,j} + \sum_{t=1}^k (P_{c,j,t} - P_{d,j,t}) - \sum_{t=1}^k D_{j,t} (Q_{h,i}) \leq Q_j (C_{j,t} + 1), \forall k \in T \quad (11)$$

$$\sum_{j=1}^N C_{j,t} \geq dem_{n,k+1} \quad (12)$$

$$D_{j,t} \leq C_{j,t} \quad (13)$$

where Q_j is the rated capacity of the j th battery (kWh), $C_{j,t}$ is the state variable indicating whether the battery is fully charged, which takes 1 to indicate that the j th battery is full at the end of the t th period, otherwise, it is not fully charged, $D_{j,t}$ is the state variable of battery swap, taking 1 means that the j th battery was swapped out of the station in the t th period, otherwise, it was not swapped out, $Q_{h,i}$ is the difference in battery power before and after the i th battery swap (kWh) and $dem_{n,k+1}$ is the predicted value of the battery swap demand of the n th BSS in the $k + 1$ th period (pc).

3.2. Intra-Day Operation

The uncertainty of the battery swap demand and the FR demand make the operation plan unable to be fully implemented in the intra-day stage. To ensure the stable operation of BSSs in the intra-day stage, it is necessary to regulate the charging and discharging status of each power station in real-time to ensure the reasonable distribution of FR power.

Therefore, for each battery, when the FR signal is received, its charging power (real), discharging power (real) and response degree of the FR signal (real) are used as decision variables to construct an optimization model.

3.2.1. Objective Function

The goal of power allocation decision-making on the FR signal based on real-time data is to ensure the coordination of the battery swap service and FR service to maximize battery swap satisfaction and minimize planned revenue loss. Its objective function is described in the following formula:

$$\min KZ = Z_{3k} - S_{2k} - S_{3k} - \sum_n B_n (P_{n,k} \Delta t) \quad (14)$$

where Z_{3k} is the degradation cost corresponding to the k th FR (USD), S_{2k} is the mileage revenue for the k th FR (USD), S_{3k} is the residual value income for the k th FR (USD), B_n is the battery swap saturation indicator for the n th BSS, $P_{n,k}$ is the FR power provided by the n th station in k times of FR (kW), positive means downward FR, and Δt is the FR signal duration (s).

$$B_n = \frac{x_{n,t,k} + dem_{n,t}}{2 \times dem_{n,t}} \quad (15)$$

where $x_{n,t,k}$ is the number of battery swap demands that occurred in the t th period when the k th FR signal was issued.

3.2.2. Constraints

When the intra-day operating strategy is formulated, it is necessary to comprehensively consider the constraint conditions of the loss of revenue and the power balance of the grid and battery.

(1) Loss of revenue

$$S_{2k} = v_k \cdot A_k \cdot k_j \cdot P_{\text{grid},j} \quad (16)$$

$$S_{3k} = \sum \left(\frac{C_{st,i,k}}{C_{st,i,M}} \cdot P_{st,i} \right) \cdot \sigma \quad (17)$$

$$Z_{3k} = \sum \left(\frac{C_{st,i,k}}{C_{st,i,M}} \cdot P_{st,i} \right) \quad (18)$$

where v_k is the response degree of FR signal, the value range is [0,1], A_k is the FR signal value (kW), $C_{st,i,k}$ is the total number of charge and discharge times of the batteries in the i th BSS in the k th FR (times), $C_{st,i,M}$ is the sum of the maximum charge and discharge times of each battery in the i th BSS (times) and $P_{st,i}$ is the sum of the prices of each battery in the i th BSS (USD).

(2) Power constraints of the grid and battery

$$\left| \sum \left(\frac{P_{i,\text{ch}}}{\eta_{i,\text{ch}}} - \eta_{i,\text{dis}} P_{i,\text{dis}} \right) \right| \leq P_{D,\text{max}}, i \in D \quad (19)$$

$$v A_k = \sum A_{st,n,k} \quad (20)$$

$$|P_{n,k}| \leq |A_k| \frac{Q_{t,n} + \sum Q_{t,n}/n}{\sum Q_{t,n}} \quad (21)$$

where $P_{D,\text{max}}$ is the maximum transmission power limit for the point of common coupling (PCC) D (kW) [36], $A_{st,n,k}$ is the FR power of the n th BSS in k th FR (kW) and $Q_{t,n}$ is the available FR capacity of the n th BSS in the t th period (kWh).

In addition, the optimization problem should meet Equations (6)–(8).

3.3. Two-Stage Strategy for Battery Swap Station Cluster Participating in Frequency Regulation Service

The solution sequence of the above optimization model is to solve the day-ahead stage first, then solve the intra-day stage. The specific solution process is shown in Figure 2. The scale of the optimization problem at each stage is shown in Table 1 below.

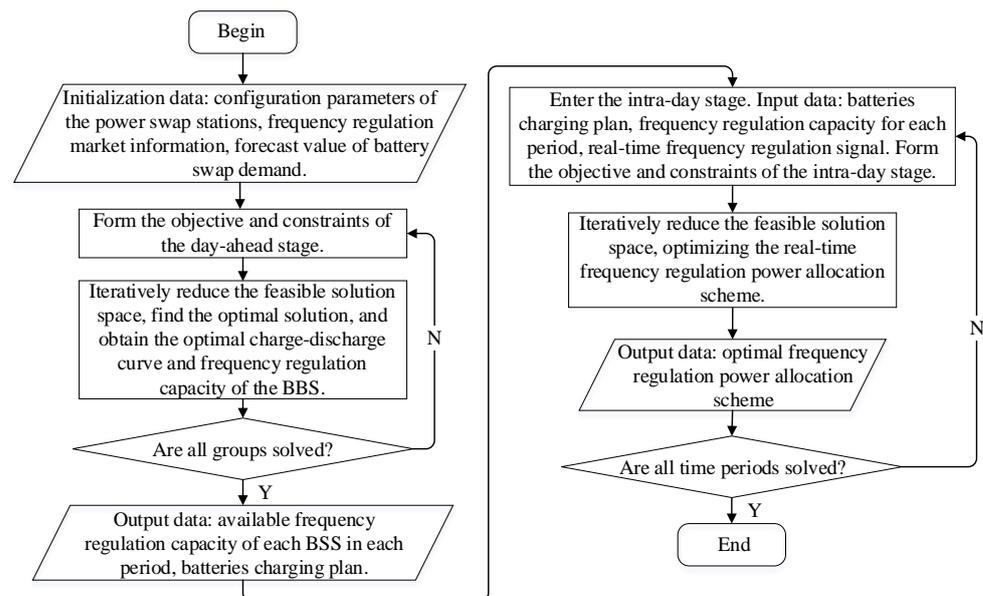


Figure 2. Two-stage strategy solution process for BSS cluster participating in FR service.

Table 1. The scale of each optimization problem.

Stage	Number of Real Variables	Number of Integer Variables	Number of Bounding Constraints	Number of Inequality Constraints	Number of Equality Constraints
day-ahead	$2i^1 t^2$	$4it$	$4it$	$(8i + 5)t$	$it + j^3$
intra-day	$2i + 1$	0	$4i + 2$	$6i + j + d^4$	$i + 4$

¹ i is the number of batteries; ² t is the number of periods; ³ j is the number of BSSs; ⁴ d is the number of PCC.

Among them, the intra-day stage is a linear programming model, which is easy to solve by using classic methods. The day-ahead stage involves multiple integer variables, such as charge and discharge state variables, full charge state variables and battery swap state variables. They are coupled in the battery swap service constraint. At the same time, the total number of batteries in the service area is usually large, so it is easy to form a more complex large-scale mixed-integer linear programming (MILP) problem [37]. In this paper, the basic method to solve the problem is the branch and bound method according to the grouping of BSSs. Its specific steps are as follows:

1. Divide the original problem into n MILP problems according to the number of BSSs;
2. Perform linear relaxation on the MILP problem and determine the relaxed solution space Ω_0 and the corresponding upper and lower bounds of the objective function;
3. The substitution problem, after linear relaxation, is divided into several sub-problems W_i , whose solution set is X_i and requires $\Omega_0 \in X_1 \cup X_2 \cup \dots \cup X_i$. For each sub-problem, if the optimal solution of the sub-problem is a feasible solution of the original problem, it is the optimal solution of the MILP problem and the calculation is completed; otherwise, the value of the objective function is regarded as the new upper bound U_1 of the MILP problem. The optimal solution of the sub-problem that is the feasible solution of the MILP problem is selected and its objective function is regarded as the lower bound L_1 of the MILP problem;
4. Abandon the sub-problems where the objective function value of the optimal solution is less than L_1 and keep the sub-problems where the objective function value of the optimal solution is greater than L_1 ;
5. Select the sub-problem with the largest objective function of the optimal solution and repeat 1 and 2. If the optimal feasible solution of the sub-problem is found, the maximum value of the objective function of the feasible solution and all the previously retained sub-problems is regarded as the new lower bound L_2 and d is repeated until the optimal solution is found;
6. Judge whether to traverse all the BSSs; if yes, end, otherwise, select the next BSS and go back to 2.

4. Case Study

4.1. Basic Data

In order to verify the effectiveness of the strategy, six BSSs established by a BSS operator are simulated and analyzed. The relevant parameter settings are shown in Table 2. Each BSS is located in different locations in the service area, so the battery swap demand of each station is different. The battery swap demand in 24 periods of a typical day is selected for simulation and the relevant data are shown in Appendix A. It is assumed that the SOC of the battery obeys the probability distribution of $N(0.2, 0.042)$ when the user of the EV generates the battery swap demand and the generation of the battery swap demand in each period obeys the uniform distribution. There are two peaks in the battery swap demand curve, which are 9–11 h and 15–20 h. The battery swap demand at night is little, showing a low state.

Table 2. Parameter setting of EV BSSs.

Parameter	Set Value
Number of stations/pc	6
Number of batteries/pc	40
Number of chargers/pc	30
Electricity price for battery swap service/(USD/kWh)	0.1566
Basic fee for battery swap service/USD	1.566
Operating commercial electricity price/USD	0.1181
Battery capacity/kWh	40
Single battery power upper limit/kW	12
Charger efficiency/%	95
SOC lower limit/%	20

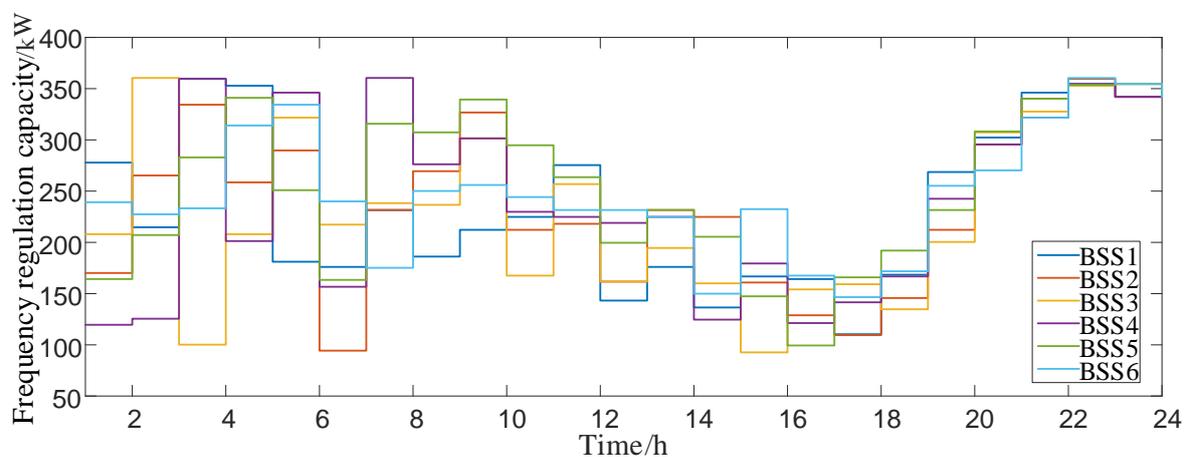
4.2. Results and Comparisons

4.2.1. Results and Comparisons of Strategy in the Day-Ahead Stage

Table 3 and Figure 3 are the simulation results of the day-ahead operation strategy for a BSS cluster participating in FR service [38]. It can be seen, from Table 3, that, under the strategy proposed in this paper, each BSS obtains some revenue from the FR service while obtaining the revenue from the battery swap service. Among them, BSS 3 has the highest daily battery swap income, because the battery swap demand of this station is the highest level on that day; BSS 5 has the least demand for batteries swap and the lowest daily battery swap income, but this station has more idle batteries for the FR service and its daily FR yield is the highest, which makes up for the overall profit of this station on that day.

Table 3. Daily revenue under the day-ahead operating strategy.

Station	Operating Costs/USD	Battery Swap Income/USD	FR Income/USD	Net Income/USD
BSS 1	429.01	780.46	268.38	619.82
BSS 2	429.39	780.83	268.95	620.39
BSS 3	452.61	826.12	261.10	634.61
BSS 4	418.27	765.49	271.39	618.60
BSS 5	386.29	697.28	286.66	597.64
BSS 6	401.91	727.59	280.65	606.33
Sum	2517.53	4577.83	1637.18	3697.46

**Figure 3.** Available FR capacity of each BSS.

It can be seen, from Figure 3, that the FR capacity provided by the BSS operator varies in 24 periods. Figure 4 shows the comparison between the FR capacity and the total battery swap demand. It illustrates that the available FR capacity curve of each BSS and the battery swap demand curve show an opposite trend. In general, the available FR capacity is low when the demand for the battery swap service is high; the available FR capacity is high when the battery swap demand is low. Moreover, the change of available FR capacity is ahead of the total battery swap demand; for example, the sharp decrease in the available FR capacity in the 5–6 periods corresponds to the surge in the total battery swap demand in the 8–9 periods, while the sharp decrease in the available FR capacity during the 13–16 periods corresponds to the surge in the total power exchange demand during the 15–18 periods. It can be seen that, under the influence of the strategy in this paper, each BSS arranges battery charging before the period of high battery swap demand to ensure the sustainability of the battery swap business, so the available FR capacity is reduced at this time.

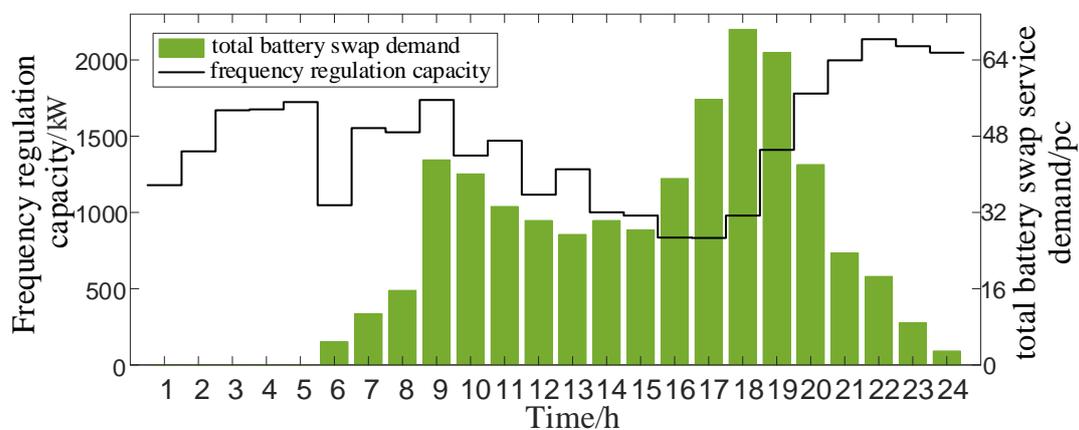


Figure 4. Comparison between the FR capacity and the total battery swap demand.

4.2.2. Results and Comparisons of Strategy in the Intra-Day Stage

Based on the simulation design in Section 4.1, the intra-day operation strategy simulation is carried out and the strategy proposed in this paper is compared with the traditional distribution based on capacity strategy.

After the BSS operator receives the FR signal, it allocates the FR power intending to take into account the coordination of the FR service and battery swap service and realizes the response of the FR signal. The total output power of 6 stations in 24 periods is shown in Figure 5.

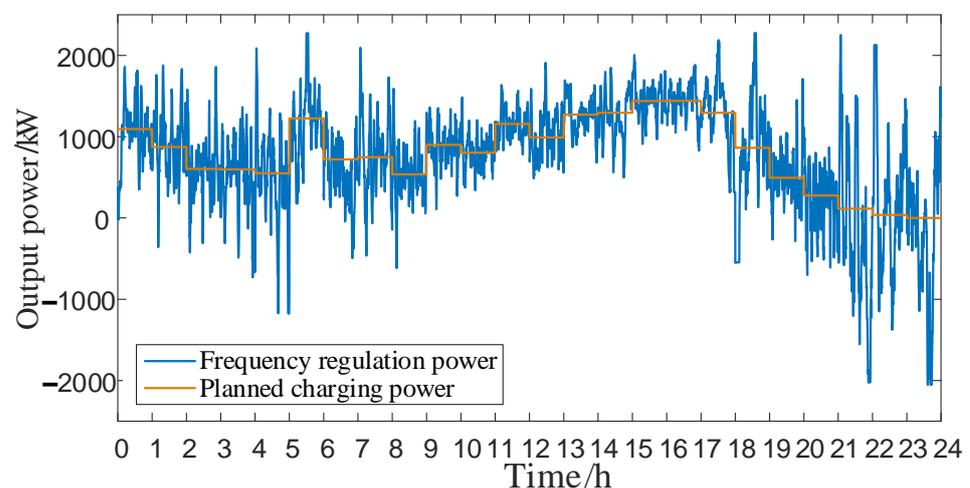


Figure 5. Overall output power.

Among them, the FR power in the 8th period is shown in Figure 6 and the distribution of the battery swap demand is shown in Table 4. The red circle representing the battery swap demand generated at this time makes the actual battery swap demand in this period greater than the predicted value. From Table 4, the battery swap saturation level of each station can be calculated when the FR signal is issued, which affects the FR power distribution. For example, the BSS cluster responds to the upward FR signal at 7:15, that is, the overall system needs to reduce the charging power. BSS 3 and BSS 6 have the highest battery swap saturation; they provide the largest FR power and reduce the minimum charging power, so that they have more sufficient power to meet possible battery swap demand. The BSS cluster responds to the downward FR signal at 7:50, that is, the overall system needs to increase the charging power. At this time, the battery swap saturation is the lowest in BSS 4 and 6, so they provide the smallest FR power, that is, their increased charging power is the smallest, which, in turn, makes the BSS with a higher degree of battery swap saturation have a higher charging power to cope with the possible battery swap demand.

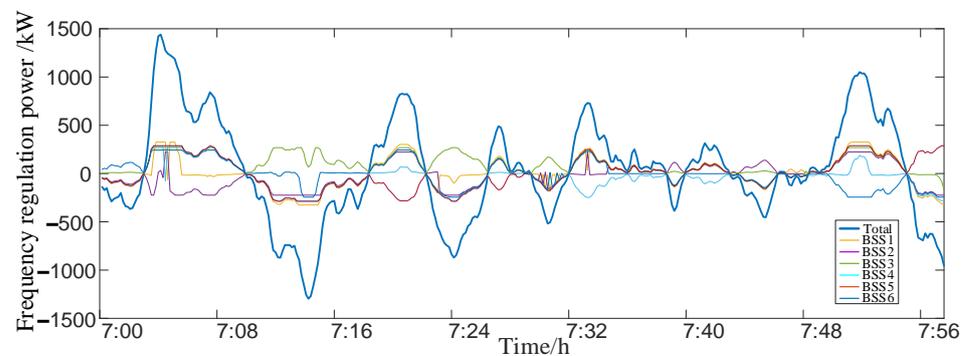


Figure 6. FR power in the 8th period.

Table 4. Distribution of battery swap demand from 7:00 to 8:00.

Station	Prediction of the Number of Battery Swap Demand/pc	When the Battery Swap Demand Arises
BSS 1	4	7:00, 7:12, 7:24, 7:36, 7:48, 8:00
BSS 2	2	7:00, 7:20, 7:40, 8:00
BSS 3	3	7:00, 7:08, 7:16, 7:50, 8:00
BSS 4	3	7:00, 7:43, 7:51, 8:00
BSS 5	2	7:00, 7:33, 7:40, 7:53, 8:00
BSS 6	2	7:00, 8:00

Figure 7 shows the comparison of the FR power of BSS 3 in the 8th period under the strategy of this paper and the strategy of capacity allocation. It can be seen that the FR power of BSS 3 under the strategy of this paper is basically positive and the FR power under the capacity allocation strategy is determined by the positive or negative value of the FR power of the system. According to Table 4, it can be seen that the battery swap demand predicted value for this period is reached at 7:16 and the battery swap demand predicted value is exceeded at 7:50. Compared with the capacity allocation strategy, the strategy in this paper can make BSS 3 have more sufficient power at 7:50 to meet the exceeded battery swap demand.

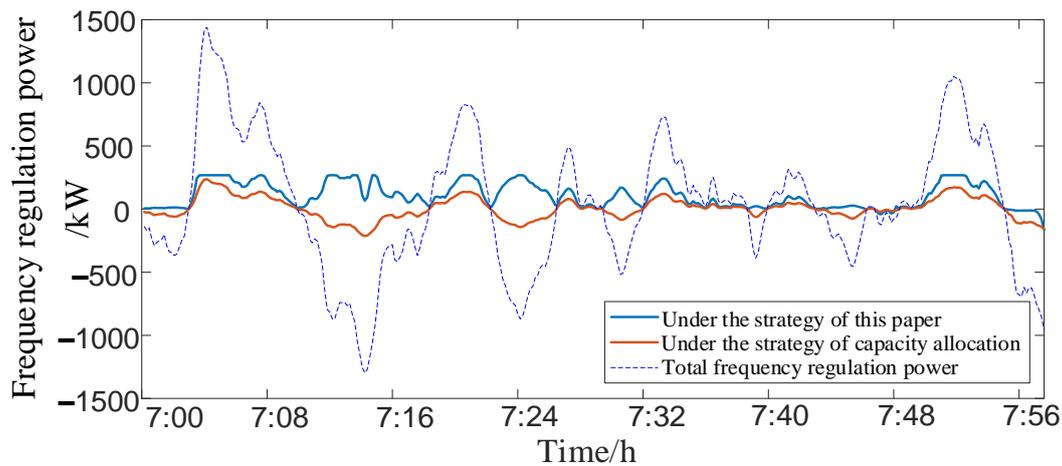


Figure 7. Comparison of FR power of BSS 3 under the strategy of this paper and the strategy of capacity allocation distribution based on capacity.

The case of the intra-day operation strategy was performed by multiple optimization calculations using CPLEX/MATLAB 2016b. The longest time for a single optimization is 1.0431 s (problem-construction time + problem-solving time); the time to solve the problem is within 60 ms, which can give enough time for other links, such as data communication.

5. Conclusions

To increase the operating income of BSSs, a day-ahead and intra-day two-stage strategy for a BSS cluster participating in the FR service is proposed. The following conclusions are drawn through simulation analysis:

1. This work has a two-fold contribution. In theory, it provides a systematic and achievable method for a BSS cluster to participate in the FR service. In practice, it makes full use of idle batteries to participate in the FR service, which can improve the operating economy of BSSs. In addition, different from the conservativeness of other methods, such as robust optimization [39], the method in this paper is more conducive to improving the economy, while still maintaining a certain level of robustness through the power support and the planned use of limited resources.
2. From the results of optimized operations, it can be seen that the battery swap income and FR income are complementary. When the battery exchange income is high/low, FR income is low/high. By using limited resources in a planned way, the FR service can bring great economic benefits to BSS operators, especially when the battery swap demand is low.
3. FR power is allocated based on the busyness of the battery swap service, which realizes the power support between the BSSs. Numerical experiments using a realistic battery swapping project date and including comparison with the traditional method show that this method is more economical and synergistic, while still maintaining fast calculation speed, which is conducive to real-time regulation.

Author Contributions: Conceptualization F.Z.; methodology, P.Y.; software, S.Y.; validation, F.Z. and S.Y.; formal analysis, L.L.L.; investigation, C.S.L.; resources, F.Z.; data curation, Z.Z.; writing—original draft preparation, X.Z.; writing—review and editing, C.S.L. and L.L.L.; visualization, Z.Z.; supervision, S.Y.; project administration, P.Y.; funding acquisition, P.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Research Project of the Digital Grid Research Institute, China, Southern Power Grid under Grant YTYZW20010 and in part by the National High Technology Research and Development Program of China (863 Program) under Grant 2014AA052001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Battery swap demand on a typical day.

Station Number	1	2	3	4	5	6
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	1	1	2	1	0
	3	1	2	1	1	3
	4	2	3	3	2	2
Battery swap demand/pc	8	8	10	7	6	5
	9	7	7	5	5	8
	6	6	8	6	4	4
	4	6	5	7	4	5
	4	5	6	4	5	4
	6	5	5	5	4	6
	5	5	4	6	5	4
	7	7	8	6	7	5
	12	10	9	8	9	9
	11	12	12	13	12	12
	10	11	10	12	11	13
	6	7	9	7	8	6
	4	4	4	4	4	4
	3	4	3	4	1	4
	1	2	2	1	2	1
	0	0	1	0	1	1

References

1. Yang, J.; Yang, H.; Zhang, X. A Charging Optimization Strategy on Charging and Swapping Station for Electric Buses Based on Optimization of Switching Rules and Matching of Buses and Batteries. *Proc. CSEE* **2019**, *39*, 2337–2346.
2. Liang, Y.; Cai, H.; Zou, G. Configuration and system operation for battery swapping stations in Beijing. *Energy* **2021**, *214*, 118883. [[CrossRef](#)]
3. Wang, X.; Wang, J.; Liu, J. Vehicle to Grid FR Capacity Optimal Scheduling for Battery Swapping Station Using Deep Q-Network. *IEEE Trans. Ind. Inform.* **2021**, *17*, 1342–1351. [[CrossRef](#)]
4. Worley, O.; Klabjan, D. Optimization of battery charging and purchasing at electric vehicle battery swap stations. In Proceedings of the 2011 IEEE Vehicle Power and Propulsion Conference (VPPC), Chicago, IL, USA, 6–9 September 2011; pp. 1–4.
5. Deilami, S.; Masoum, A.S.; Moses, P.S. Real-time coordination of plug-in EV charging in smart grids to minimize power losses and improve voltage profile. *IEEE Trans. Smart Grid* **2011**, *2*, 456–467. [[CrossRef](#)]
6. Takagi, M.; Iwafune, Y.; Yamamoto, Y.; Yamaji, K.; Okano, K.; Hiwatari, R.; Ikeya, T. Energy Storage of PV using batteries of battery-switch stations. In Proceedings of the 2010 IEEE International Symposium on Industrial Electronics, Bari, Italy, 4–7 July 2010.
7. Liu, X.; Zhao, T.; Yao, S.; Soh, C.B.; Wang, P. Distributed Operation Management of Battery Swapping-Charging Systems. *IEEE Trans. Smart Grid* **2019**, *10*, 5320–5333. [[CrossRef](#)]
8. Ban, M.; Zhang, Z.; Li, C.; Li, Z.; Liu, Y. Optimal scheduling for electric vehicle battery swapping-charging system based on nanogrids. *Int. J. Electr. Power Energy Syst.* **2021**, *130*, 106967. [[CrossRef](#)]
9. Wang, L.; Chen, S.; Pedram, M. Optimal joint management of charging and battery swapping service for electric vehicles. In Proceedings of the 2017 9th Annual IEEE Green Technologies Conference (GreenTech), Denver, CO, USA, 29–31 March 2017; pp. 328–333.
10. Chu, H.; Xie, D. Charging/discharging control strategy of EV charging-discharging-storage integrated station considering operational status of power grid. *Electr. Power Autom. Equip.* **2018**, *38*, 96–101.

11. Yuan, H.; Wei, G.; Zhu, L. Optimal scheduling for micro-grid considering EV charging-swapping-storage integrated station. *IET Gener. Transm. Distrib.* **2018**, *14*, 1127–1137. [[CrossRef](#)]
12. Habibifar, R.; Aris Lekvan, A.; Ehsan, M. A risk-constrained decision support tool for EV aggregators participating in energy and frequency regulation markets. *Electr. Power Syst. Res.* **2020**, *185*, 106367. [[CrossRef](#)]
13. Han, S.; Han, S.; Sezaki, K. Estimation of Achievable Power Capacity from Plug-in Electric Vehicles for V2G Frequency Regulation: Case Studies for Market Participation. *IEEE Trans. Smart Grid* **2011**, *2*, 632–641. [[CrossRef](#)]
14. Han, S.; Han, S.; Sezaki, K. Development of an optimal vehicle-to-grid aggregator for Frequency Regulation. *IEEE Trans. Smart Grid* **2010**, *1*, 65–72.
15. Liu, H.; Qi, J.; Wang, J.; Li, P.; Li, C.; Wei, H. EV Dispatch Control for Supplementary Frequency Regulation Considering the Expectation of EV Owners. *IEEE Trans. Smart Grid* **2018**, *9*, 3763–3772. [[CrossRef](#)]
16. Lv, L.; Gao, C.; Li, H.; Shen, T.; Wei, X.; Liu, L. Estimation of plug-in electric vehicles schedulable capacity. In Proceedings of the 2016 3rd International Conference on Systems and Informatics (ICSAI), Shanghai, China, 19–21 November 2016; pp. 223–229.
17. Wu, C.; Lin, X.; Sui, Q. Two-stage self-scheduling of battery swapping station in day-ahead energy and Frequency Regulation markets. *Appl. Energy* **2020**, *283*, 116285. [[CrossRef](#)]
18. Yao, E.; Wong, V.W.S.; Schober, R. Robust Frequency Regulation Capacity Scheduling Algorithm for Electric Vehicles. *IEEE Trans. Smart Grid* **2017**, *8*, 984–997. [[CrossRef](#)]
19. Sun, S.; Dong, M.; Liang, B. Real-time welfare-maximizing regulation allocation in dynamic aggregator-EVs system. *IEEE Trans. Smart Grid* **2014**, *5*, 1397–1409. [[CrossRef](#)]
20. Scarabaggio, P.; Carli, R.; Cavone, G.; Dotoli, M. Smart Control Strategies for Primary Frequency Regulation through Electric Vehicles: A Battery Degradation Perspective. *Energies* **2020**, *13*, 4586. [[CrossRef](#)]
21. Yan, G.; Liu, D.; Li, J.; Mu, G. A cost accounting method of the Li-ion battery energy storage system for frequency regulation considering the effect of life degradation. *Prot. Control Mod. Power Syst.* **2018**, *3*, 4. [[CrossRef](#)]
22. Gao, H.; Wu, X. A Survey on Battery-Swapping Mode of Electric Vehicles. *Power Syst. Technol.* **2013**, *37*, 891–897.
23. Zhao, Z.; Yang, P.; Wang, Y.; Xu, Z.; Guerrero, J.M. Dynamic Characteristics Analysis and Stabilization of PV-Based Multiple Microgrid Clusters. *IEEE Trans. Smart Grid* **2019**, *10*, 805–818. [[CrossRef](#)]
24. Wang, M.; He, Y.; Yang, T.; Jia, Y.; Xu, Z. Cascaded Voltage Control for Electric Springs with DC-Link Film Capacitors. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *8*, 3982–3994. [[CrossRef](#)]
25. Schneider, F.; Thonemann, U.W.; Klabjan, D. Optimization of Battery Charging and Purchasing at Electric Vehicle Battery Swap Stations. *Transp. Sci.* **2017**, *52*, 1211–1234. [[CrossRef](#)]
26. Zhe, L.; Ouyang, M. The pricing of charging for electric vehicles in China—Dilemma and solution. *Energy* **2011**, *36*, 5765–5778.
27. Carli, R.; Dotoli, M. A Distributed Control Algorithm for Optimal Charging of Electric Vehicle Fleets with Congestion Management. *IFAC-Pap.* **2018**, *51*, 373–377. [[CrossRef](#)]
28. Wu, X.; Feng, Q.; Bai, C.; Lai, C.S.; Jia, Y.; Lai, L.L. A novel fast-charging stations locational planning model for electric bus transit system. *Energy* **2021**, *224*, 120106. [[CrossRef](#)]
29. Lai, C.S.; Jia, Y.; Dong, Z.; Wang, D.; Tao, Y.; Lai, Q.H.; Wong, R.T.; Zobia, A.F.; Wu, R.; Lai, L.L. A review of technical standards for smart cities. *Clean Technol.* **2020**, *2*, 290–310. [[CrossRef](#)]
30. Zhao, Z.; Guo, J.; Lai, C.S.; Xiao, H.; Zhou, K.; Lai, L.L. Distributed Model Predictive Control Strategy for Islands Multimicrogrids Based on Noncooperative Game. *IEEE Trans. Ind. Inform.* **2021**, *17*, 3803–3814. [[CrossRef](#)]
31. Symeonidou, M.M.; Zioga, C.; Papadopoulos, A.M. Life cycle cost optimization analysis of battery storage system for residential photovoltaic panels. *J. Clean. Prod.* **2021**, *309*, 127234. [[CrossRef](#)]
32. Wang, Z.; Zhong, J.; Li, J. Design of performance-based frequency regulation market and its implementations in real-time operation. *Int. J. Electr. Power Energy Syst.* **2017**, *87*, 187–197. [[CrossRef](#)]
33. Nassourou, M.; Blesa, J.; Puig, V. Robust Economic Model Predictive Control Based on a Zonotope and Local Feedback Controller for Energy Dispatch in Smart-Grids Considering Demand Uncertainty. *Energies* **2020**, *13*, 696. [[CrossRef](#)]
34. Sortomme, E.; El-Sharkawi, M.A. Optimal power flow for a system of microgrids with controllable loads and battery storage. In Proceedings of the 2009 IEEE/PES Power Systems Conference and Exposition, Seattle, WA, USA, 15–18 March 2009; pp. 1–5.
35. Wang, H.; Zhang, Y.; Mao, H. Load forecasting method of EVs based on time charging probability. In Proceedings of the 2018 International Conference on Power System Technology, Guangzhou, China, 6–8 November 2018; p. 1731.
36. Wang, M.; He, Y.; Jia, Y.; Xu, Z. A Power-Decoupled Current Source Inverter for PV Energy Harvest and Grid Voltage Regulation. *IEEE Trans. Ind. Electron.* **2020**, *68*, 9540–9549. [[CrossRef](#)]
37. Tomasz, P.P.; O'Neill, M. Grammatical evolution for constraint synthesis for mixed-integer linear programming. *Swarm Evol. Comput.* **2021**, *64*, 100896.
38. Pjm-Data Miner 2. Available online: https://dataminer2.pjm.com/feed/reg_market_results/definition (accessed on 13 January 2016).
39. Hosseini, S.M.; Carli, R.; Dotoli, M. A residential demand-side management strategy under nonlinear pricing based on robust model predictive control. In Proceedings of the 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC), Bari, Italy, 6–9 October 2019; pp. 3243–3248.