A Design and Evaluation Method for the Interaction Model of Integrated Storage and Charging Stations to Improve the Comprehensive Benefits of the Station

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Abstract. In view of the existing charging station's difficulty in connecting to the grid, low utilization rate, high daytime electricity cost and impact load on the power grid, the typical operating mode of the storage and charging station was proposed and its characteristics were analyzed. Then, through calculation examples, A comparative analysis of the technical economy of the two models was conducted from four perspectives: station economics, grid economics, station service capabilities and grid resilience.The results show that the "Grid-load Synergetic" storage and charging integrated method is easy to access and more economical. It can reduce large power grid investment. In addition, it can also enhance the stability of the entire power system, so it is more promotional.

Keywords: Electric vehicle charging; Electrical engineering; Storage and Charging Stations;Economic and technical Analysis

1 Introduction

As China puts forward the goal of carbon peaking and carbon neutrality, electric vehicles (EVs) have been vigorously promoted in the field of transportation electrification due to their advantages such as electric energy drive, high energy density, and low driving noise, and are also reducing dependence on fossil energy , play a positive role in reducing carbon emissions and promoting new energy consumption [1-3].

However, the large-scale promotion of EVs faces many problems in its current development. The demand for public charging will increase rapidly, and fast charging stations will also face many new challenges. First, with the introduction of overcharging technology, grid connection has become more difficult [4]; second, the utilization rate is low and capacity costs are high [5]; third, the cost of electricity during the day is high [6]; Fourth, the impact load during the initial period of the trough will increase, which will have new impacts on the power grid [7].

In order to cope with factors such as insufficient transformer capacity due to the increased charging demand at fast charging stations, difficulty in increasing capacity, and an increase in the proportion of capacity to electricity charges, fast charging stations can be upgraded in two

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directions in the future. The first is to increase energy storage and form an integrated storage and charging station to reduce grid-connected capacity and replace peak power through energy storage [8]; the second is to use ALM(Active Load Management) flexible grid connection technology to allow charging stations to share power distribution capacity with other loads and increase the capacity limit during valley periods. In addition, by building a certain amount of energy storage, the charging load during peak hours is reduced to ensure that the peak hours do not exceed the limit requirements of the power grid.

2 Two typical operating modes of storage and charging sites

As the scale of electric vehicles increases, the demand for charging at fast charging stations will also increase rapidly. How to ensure that the growing demand for charging can be met while not exceeding the limits in station, the model of fast charging stations can develop in two directions. The first is the direction of "Station Autonomous " storage and charging integration, and the second is the "network load collaborative " direction of storage and charging integration.

2.1 "Station Autonomous" Storage and Charging Integrated Fast Charging Station

"Station Autonomous" refers to the fast charging station adding energy storage to form an integrated storage and charging station, which uses energy storage to reduce grid-connected capacity and replace peak power.Assume that by 2025, the charging demand at public fast charging stations will be twice the current level. If the installed capacity of charging piles is increased, the charging station cannot expand the capacity if it maintains the original capacity.By configuring a certain proportion of energy storage, the charging load during the peak hours and the beginning of the trough during the day is reduced to ensure that the transformer does not exceed the limit, and the maximum charging power of the station can be increased without increasing the capacity of the station area.According to the maximum load situation, the simulated charging load and grid-side load curves are shown in Figure 1, and the simulated energy storage charge and discharge situation is shown in Figure 2.

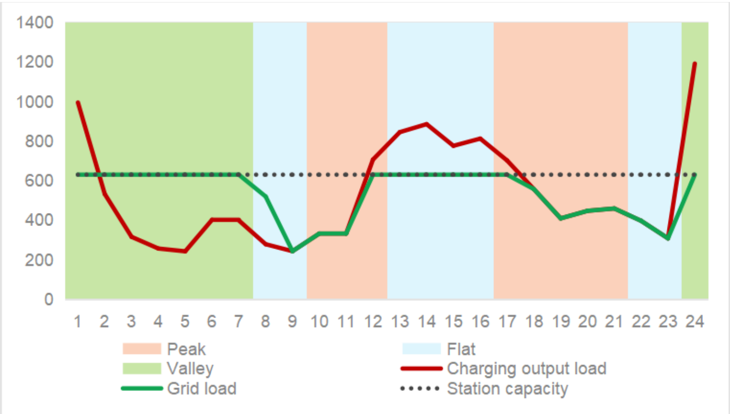

Figure 1 Simulation of "Station Autonomous" charging load and grid side load

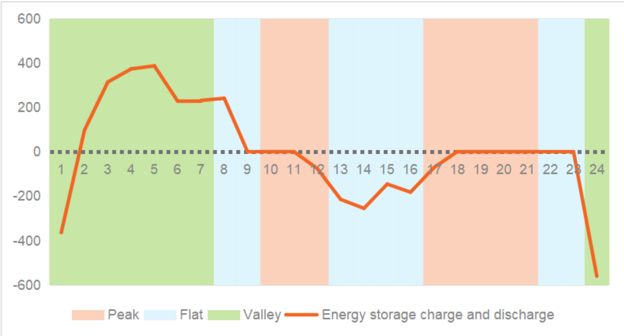

Figure 2 Simulates the energy storage charging and discharging situation of "Station Autonomous "

This "Station Autonomous" integrated storage and charging fast charging station model still has two problems. First, due to the high proportion of energy storage operating conditions of "low valley charging and low valley discharge", the economics of energy storage have significantly deteriorated. Second, during valley periods, the transformer load factor is very high, and the load curve from the grid side becomes flatter, and the load adjustability of fast charging stations is reduced.

2.2 "Grid-load Synergetic " integrated storage and charging fast charging station

"Grid-load Synergetic" mainly meets the operator's demand for doubling charging power through transformer expansion and energy storage, try to use the rich capacity of the power grid to supply power during valley periods, and energy storage is mainly used to solve the problem of insufficient power supply capacity during peak and flat periods of the power grid.In this mode, the transformer capacity is expanded and a certain capacity of energy storage is configured. At the same time, the operator and the power grid agree on the upper limit of the transformer load in peak, flat and valley sections. The simulated charging load and grid-side load curves are shown in Figure 3, and the simulated energy storage charging and discharging conditions are shown in Figure 4.

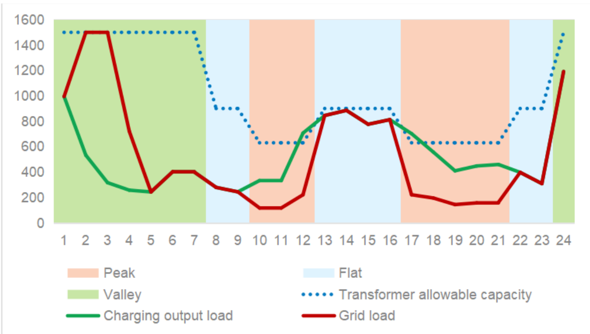

Figure 3 Simulates "Grid-load Synergetic " charging load and grid-side load

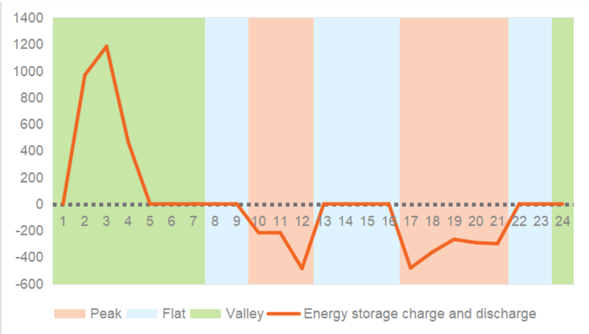

Figure 4 Simulates the charging and discharging situation of "Grid-load Synergetic " energy storage

Compared with the "Station Autonomous" station, the "Grid-load Synergetic " integrated storage and charging station model has the following advantages. First, although the transformer capacity is expanded after the charging demand increases, by limiting the peak and flat transformer power, the load rate of the corresponding distribution network access line will not be increased, and there is no need to expand the capacity of the upper-level power grid. Second, during valley periods, the abundant capacity of access lines can be fully utilized to provide direct power supply to the grid, thus avoiding the uneconomical operating conditions of "valley charging and valley discharge" while also improving facility utilization during valley periods.Third, energy storage equipment works more under the economic operating conditions of "charging at valleys and discharging at peaks", which is expected to achieve more stable arbitrage through peaks and valleys and improve economic efficiency.

The characteristics of each mode are shown in Table 1.

Table 1 Characteristics of each mode

Plan	Expansion situation	Energy Storage Situation	Advantage	Disadvantage
Existing Sites,	✖	✖	Improved utilization	①Loss of customers; ②Fast charging upgrade is limited
"Station Autonomous" Storage and Charging Integrated Fast Charging Station	✖	✔	Increased output power with almost no loss of customers	① The "valley charge and valley discharge" working conditions of energy storage account for a relatively high proportion, causing a significant deterioration in the economics of energy storage; ②The load rate of the transformer is very high during the valley period, and the load adjustability of the fast charging station is reduced.

"Grid-load Synergetic" integrated storage and charging fast charging station	✔	✔	① During the low period of the power grid, the maximum output of the transformer is allowed to meet the maximum charging load of the charging pile; ② Limit the output power of the transformer and configure energy storage to solve the problem of insufficient power supply capacity in peak and flat sections of the power grid.	——

3 Technological and economic comparative analysis methods

There are many evaluation methods for electric vehicle charging. Literature [9][10] defines the evaluation index of peak and valley electricity prices on residents' charging load. Aiming at the technical economy of storage and charging stations and establishes a two-level evaluation index system from four dimensions: station economy, grid economy, station service capability, and grid resilience, as shown in Table 2.

Table 2 Evaluation indicators

Primary indicators	Secondary indicators
Station economy	Renovation investment cost
	Internal Rate of Return
Grid economy	Low voltage power distribution investment
	Medium, high voltage and secondary system investment
Station service capabilities	Service capabilities
	Ratio of peak load change to feeder capacity
	Changes in peak charging load
Grid Resilience	The length of time that power can be supplied during a power outage

3.1 Station economics

The economics of the station are mainly considered from two parts: renovation investment cost and internal rate of return.

(1) Renovation investment cost

The investment cost of transformation mainly includes two parts: expansion cost and energy storage cost. The calculation formula of investment transformation cost is as shown in (1) ~ (3).

$$C_{i,r} = C_e + C_s \tag{1}$$

$$C_e = V_e \cdot U_e \tag{2}$$

$$C_s = Q_{s,t} \cdot U_s \tag{3}$$

Among them, $C_{i,r}$ is the transformation investment cost, C_e is the expansion cost, C_s is the energy storage cost, V_e is the expansion capacity, U_e is the expansion unit price, $V_{s,t}$ is the total energy storage power, and U_s is the energy storage unit price.

(2) Internal rate of return

The internal rate of return is based on the existing sites, and the portion exceeding the revenue of the existing sites is calculated as the return of the plan.Revenue is mainly divided into two parts: charging service fee revenue and energy storage revenue. Energy storage revenue includes valley filling revenue and peak shaving revenue.The formulas are as shown in (4)~(8).

$$I = I_{SF} + I_{ST} \quad (4)$$
$$I_{SF} = V_{c,t} \cdot U_{SF} \quad (5)$$
$$I_{S,T} = I_v + I_p \quad (6)$$
$$I_v = Q_v \cdot U_v \quad (7)$$
$$I_p = Q_{v,f} \cdot U_{v,f} + Q_{v,p} \cdot U_{v,p} \quad (8)$$

Among them, I is the station income, I_{SF} is the charging service fee income, I_{ST} is the energy storage income, $V_{c,t}$ is the total charging power of the user, U_{SF} is the unit price of the charging service fee, I_v is the valley filling income, I_p is the peak shaving income, Q_v is the valley filling electricity amount, U_v is the valley filling incentive unit price, $Q_{v,f}$ is the sum of valley charge and flat discharge, $U_{v,f}$ is the flat-to-valley price difference, $Q_{v,p}$ is the sum of valley charge and peak discharge, and $U_{v,p}$ is the peak-to-valley price difference.

3.2 Power Grid Economics

The economics of the power grid are divided into low-voltage power distribution investment and medium-voltage and secondary system investment. Among them, investment in medium and high voltage and secondary systems includes investment in increasing the load supply of the 10 kV power grid, investment in increasing the load supply of the 110 kV power grid, and investment in increasing the load supply of the secondary system. The formulas are as shown in (9)~(11).

$$I_{low} = C_{ex} \cdot P_{low} \quad (9)$$
$$I_{m,h,s} = L_{i,max} \cdot (P_m + P_h + P_s) \quad (10)$$
$$L_{i,max} = max(L_{2,16-20} - C_{p,16-20} - L_{1,16-20}) \quad (11)$$

I_{low} is the low-voltage power distribution investment, C_{ex} is the transformer expansion capacity, and P_{low} is the unit price per kilowatt of low-voltage power distribution investment. $I_{m,h,s}$ is the investment in medium and high voltage and secondary systems, $L_{i,max}$ is the maximum load increase from 16 to 20 points, $L_{2,16-20}$ is twice the charging demand load from 16 to 20 points, $C_{p,16-20}$ is the peak clipping corresponding to 16 to 20 points, $L_{1,16-20}$ is the doubled charging demand load corresponding to 16 to 20 points, P_m is the unit price per kilowatt of the 10 kV power grid unit's additional load investment, P_h is the unit price per kilowatt of the 110 kV power grid unit's additional load investment, P_s is the unit price per kilowatt of additional load investment in the secondary system unit.

3.3 Station service capabilities

Station service capability indicators are used to evaluate the performance and reliability of the power grid to cope with changing demands and loads to meet consumer demands while ensuring the reliability and quality of power supply. It includes three parts: service capacity, the ratio of peak load change to feeder capacity, and peak charging load change. The calculation formula is as shown in Equations (2-12) ~ (2-14).

$$F_s = \frac{V_i}{V_s} \tag{12}$$

$$R_{p,f} = \frac{L_t - L_s}{V_f} \tag{13}$$

$$R_p = \frac{L_t}{L_s} - 1 \tag{14}$$

Among them, F_s is the service capacity, V_i is the installed capacity, V_s is the station capacity; $R_{p,f}$ is the ratio of the peak load change to the feeder capacity, L_t is the peak load of the mode, L_s is the peak load of the existing station,V_f is the feeder capacity; R_p is the change in peak charging load.

3.4 Grid Resilience

The resilience of the power grid is reflected by the duration of power supply during a power outage, indicating the stability and reliability of the power grid, which is especially important in the face of natural disasters, failures or other emergencies. This metric takes into account the grid's backup capacity to cope with power outages, which not only benefits consumers but also helps maintain the continuity of charging station operations. Its calculation formula is shown in Equation (15).

$$T_{a,o} = \frac{C_S \times 24}{\sum_{t=1}^{24} L_{c,t}} \tag{15}$$

$T_{a,o}$ is the duration of power supply in case of power outage, C_s is the energy storage capacity, and $L_{c,t}$ is the charging load at time t.

4 Example analysis

Taking a typical fast charging station with a transformer of 630kVA, a charging pile installed capacity of 660kW, and a maximum simultaneous rate of 0.8 as an example. The feeder capacity is 5MW. When the charging demand of the fast charging station increases to 2 times, the two models are compared and analyzed. The "Station Autonomous" integrated storage and charging solution has a charging pile installed capacity of 1,560kW.The transformer capacity of the "Grid-load Synergetic " storage and charging integrated solution is expanded to 1500kVA, assuming that it is also configured with 600kW/4.4 hours of energy storage. At the same time, the operator and the power grid agreed that the transformer load should not exceed 630kW during peak periods, 1200kW during flat periods, and 1500kW during valley periods.

4.1 Economic analysis of stations

The income from valley filling is 0.1 yuan/kWh, the flat-valley price difference is 0.4 yuan/kWh, and the peak-to-valley price difference is 0.8 yuan/kWh; the energy storage pricing is 2,000 yuan/kWh and 1,200 yuan/kWh respectively, and the unit price for capacity expansion is 1,000 yuan/kW; the public charging service fee is estimated at 0.5 yuan/kWh.The economic comparison of stations is shown in Table 3.

Table 3 Comparison of station economics

Plan		Transformer expansion capacity (kVA)	Energy storage configuration	Renovation investment (10,000 yuan)	Internal Rate of Return
"Station Autonomous" Storage and Charging Integration	Energy storage costs are high	0	600kW@3h	394	-4%
	Energy storage costs are low	0	600kW@4.6h	332	11%
"Grid-load Synergetic" storage and charging integration	minimum investment strategy (Energy storage costs are high)	870	100kW@1.5h	118	29%
	Energy storage costs are low (Peak-cutting priority strategy)	870	600kW@4.4h	418	21%

In terms of site economics, the "Station Autonomous" integrated storage and charging solution does not require transformer expansion. The investment scale is large, the investment return rate is negative, and the business is unsustainable. The "Grid-load Synergetic" capacity expansion, distribution and storage combination solution can solve the problem of insufficient access capacity at a lower cost and has greater peak-cutting potential.When the battery cost is high, the investment scale is lower than that of the "Station Autonomous "; when the battery cost is low, energy storage investment can be expanded. For example, in the case of peak shaving of 65%, the internal rate of return can reach 16%, which can be promoted.

4.2 Analysis of power grid economics

The investment in low-voltage power distribution is calculated as 15,000 yuan/60kW; the investment in increased load supply of 10 kV power grid unit is calculated as 1959 yuan/kilowatt; the investment in additional load supply for the 110 kV power grid unit is estimated at 1,441 yuan/kilowatt, and the investment for additional load supply per unit of the secondary system is estimated at 457 yuan/kilowatt.The comparison of grid economic analysis is shown in Table 4.

Table 4 Analysis and comparison of power grid economics

Plan		Low voltage power distribution investment (10,000 yuan)	Medium, high voltage and secondary system investment (10,000 yuan)
"Station Autonomous" Storage and Charging Integration		0	96.48
"Grid-load Synergetic" storage and charging	minimum investment strategy (Energy storage costs are high)	21.75	96.48

integration	Energy storage costs are low (Peak-cutting priority strategy)	21.75	-23.53

Using "Grid-load Synergetic" storage and charging integration, when the energy storage cost is low, the increased investment in medium and high voltage and secondary systems "does not rise but falls", which can achieve higher benefits.

4.3 Analysis of station service capabilities

In terms of site service capabilities, the "Grid-load Synergetic" storage and charging integrated solution can increase the service capability to 2.5 times. It is more flexible in energy storage configuration, will not increase the line load during peak hours, and has lower line access requirements. The comparison of service capabilities of stations is shown in Table 5.

Table 5 Comparison of station service capabilities

Plan		Station Capacity （kVA)	Service capabilities	Ratio of peak load change to feeder capacity	Changes in peak charging load
Existing Sites		630	2.48	0%	0%
"Station Autonomous" Storage and Charging Integration		630	1.04	0%	0%
"Grid-load Synergetic" storage and charging integration	minimum investment strategy (Energy storage costs are high)	1500	2.48	0%	0%
	Energy storage costs are low (Peak-cutting priority strategy)			-8.2%	-65%

4.4 Grid Resilience Analysis

In terms of grid resilience, the "Station Autonomous" storage and charging integrated solution can continue to supply power for about 4 hours after a power outage. Adopting "Grid-load Synergetic" storage and charging integration, when the energy storage cost is high, the power supply can continue for about 3 hours after a power outage; when the energy storage cost is low, the power supply can continue for about 6 hours after a power outage.The resilience comparison of the power grid is shown in Table 6.

Table 6 Comparison of power grid resilience

Plan		Duration of power supply in case of power outage (h)
"Station Autonomous" Storage and Charging Integration		3.94
"Grid-load Synergetic" storage and charging integration	minimum investment strategy (Energy storage costs are high)	2.83
	Energy storage costs are low (Peak-cutting priority strategy)	6.2

5 Conclusions

Based on the typical operation mode of storage and charging stations, this paper comparatively analyzes the technical and economic capabilities from four perspectives: station economics, grid economics, station service capabilities and grid resilience. From the comprehensive result analysis, the following conclusions can be drawn.

In terms of economics, the "Grid-load Synergetic" is more economical than the "Station autonomous " regardless of the cost of energy storage. In terms of power grid economics, the "Grid-load Synergetic" can reduce the investment in large power grids. In addition, in terms of field station service capabilities, both "Station Autonomous " and "Grid-load Synergetic" can meet user needs, but ALM has greater peak-shaving potential and improves the reliability of power supply.In terms of grid resilience, both modes can effectively alleviate problems that may be caused by power outages. When the cost of energy storage is low, power supply can continue for up to 6 hours after a power outage, providing longer power support, thus enhancing the stability and coping capabilities of the entire power system.Taken together, the "Grid-load Synergetic" solution is more popular.

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