Research on Analysis and Optimization Mathematical Model of 356 Day Charge and Discharge Data of User Side Energy Storage Based on Least Squares Function Fitting

Shiling Zhang*, Qiang Xiao, Haoyu Wang, Qian Zhou
State Grid Chongqing Electric Power Company Economic and Technical Research Institute, Chongqing, 401121, China

ABSTRACT

User-side energy storage power stations are widely used, and their historical operating data will have a strong correlation with the operating data of energy storage batteries. By obtaining charging and discharging power data points of energy storage power stations every 15 minutes, the centralized/user side energy storage power station charging and discharging curve is formed. The energy storage power station charging and discharging curve can be effectively obtained through the least squares fitting method. Through the quantitative analysis of the 34228 data points, it was found that the typical charging and discharging types of typical six centralized energy storage power stations include "1 charge, 1 discharge", "2 charge, 2 discharge" and other typical charging and discharging curves. And the charging time is mainly concentrated in the time zone from 0:00 to 8:00 in the morning, followed by discharge during the peak period between 12:00 and 2:00, and discharge during the peak period from 8:00 to 10:00 in the evening. Generally speaking, for independent centralized energy storage power plants, the entire charging and discharging process can be completed within 2 to 3 hours. In on-site analysis of the energy storage power stations, there is significant difference in the SOC (State of Charge) between power charging and discharging, as well as power following the depth of battery charging and discharging. The range of SOC variation during power charging and discharging is between 20% and 100%, while during power following, the range of SOC variation is between 70% and 80%. This article takes actual 356 day operation data of centralized energy storage power stations as the research object, quantitatively analyzes the characteristics of charge and discharge data, and the research results have good guiding value for the operation and maintenance of user side energy storage power stations.

Keywords: User-side energy storage power stations, energy storage batteries, 34228 data points, SOC (State of Charge) , charging and discharging process

1. INTRODUCTION

The multi level power grids can be classified into the substation level power grids, 10kV feeder level power grids, and 35kV(or higher voltage level) substation level power grids based on the voltage level and capacity of distributed power sources, the energy storage equipment, and related controllable loads, which are classified as the station line station grid connected multi-level power grids. The control center at the each level receives the dispatching instructions at the upper level, and decomposes the instructions or strategies through edge computing, and then transmits control instructions to local controlled objects[1-3]. The multi level coordination is used to achieve the goal of regional control. Figure 1 shows the station line platform grid connected multi-level power grid collaborative interaction[4,5].

Regarding future development form and evaluation index methods of distribution networks, scholars at home and abroad have mainly conducted research from the aspects of form classification, form connotation, development path, and index evaluation. At present, the research is based on respective research environments and soils, without the specifically considering factors such as the distributed resource endowment, development trends of electric vehicles, and the current status of planning and development of primary and secondary systems in the power grid in Chongqing. Therefore, this article aims to conduct research from three aspects: the coordinated development form and evolution path of smart distribution network, the coordinated planning of the primary and secondary systems of the distribution network, and the comprehensive evaluation index system of smart distribution network. It proposes the future development form of the distribution network in Chongqing that adapts to the widespread access of distributed power sources and electric vehicles,

*526793305@qq.com

The International Conference Optoelectronic Information and Optical Engineering (OIOE2024), edited by Yang Yue, Lu Leng, Proc. of SPIE Vol. 13513, 135133O · © 2025 SPIE · 0277-786X · © The Authors.

constructs a framework for the coordinated planning of primary and secondary distribution network, and establishes the comprehensive evaluation index system from the multiple levels such as energy consumption, power supply performance improvement, the safety and the reliability guarantee, and the energy-saving and efficient operation, effectively serving the future planning and development of Chongqing power grid[6].

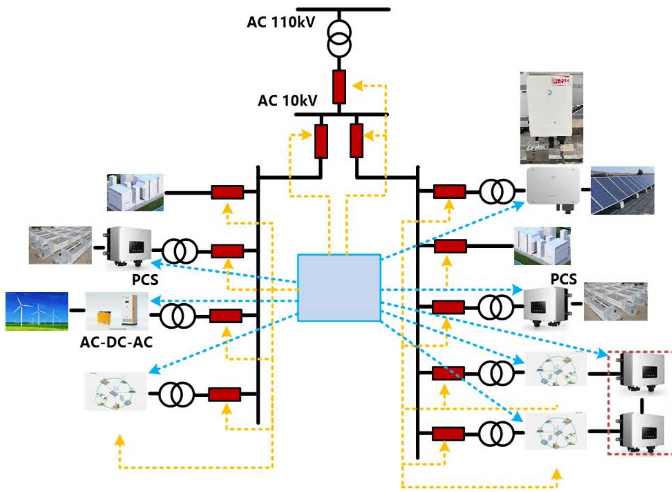


Figure 1. Multi-level power grid collaborative interaction.

2. COMPREHENSIVE ANALYSIS OF CHARGING AND DISCHARGING DATA OF 356 DAY USER-SIDE ENERGY STORAGE POWER STATION

At present, for the user-side energy storage, the efficient utilization of new energy is mainly achieved through integrated operation strategies of the light, storage, and charging. The focus is on charging and the discharging curves of centralized energy storage power stations. Provide the annual charging and the discharging curves of the five energy storage power stations, namely the Songgai Energy Storage Power Station (200MW/400MWh), the Longteng Energy Storage Power Station (100MW/200MWh), Science the Valley Energy Storage Power Station (100MW/200MWh), Huaiyuan Energy Storage Power Station (100MW/200MWh), and Shuanghuai Energy Storage Power Station (240MW/480MWh), from September 1, 2023 to August 22, 2024, with one data point collected every 15 minutes. A total of the 34228 points were collected during the above time interval[7]. Among them, the 96 data points are collected every day, and the 52 points were collected on August 22, 2024.


Figure 2. Integrated operation project of light storage and charging.

In response to the large amount of data mentioned above, specialized software is needed for quantitative and qualitative analysis. Firstly, 34228 points of data from 5 energy storage stations are displayed to compare the different charging and discharging operation characteristics of the 5 energy storage stations shown in Figure 3. Figure 3 shows that the 365 day charging and discharging curves of the five energy storage stations are different. The charging and discharging curves of Science Valley Energy Storage Station (100MW/200MWh) and Shuanghuai Energy Storage Station (240MW/480MWh) are relatively symmetrical, and the each energy storage station is fully charged. Next, we will focus on daily charging and discharging curves of Shuanghuai Energy Storage Station (240MW/480MWh)[8]. The analysis process is as follows:

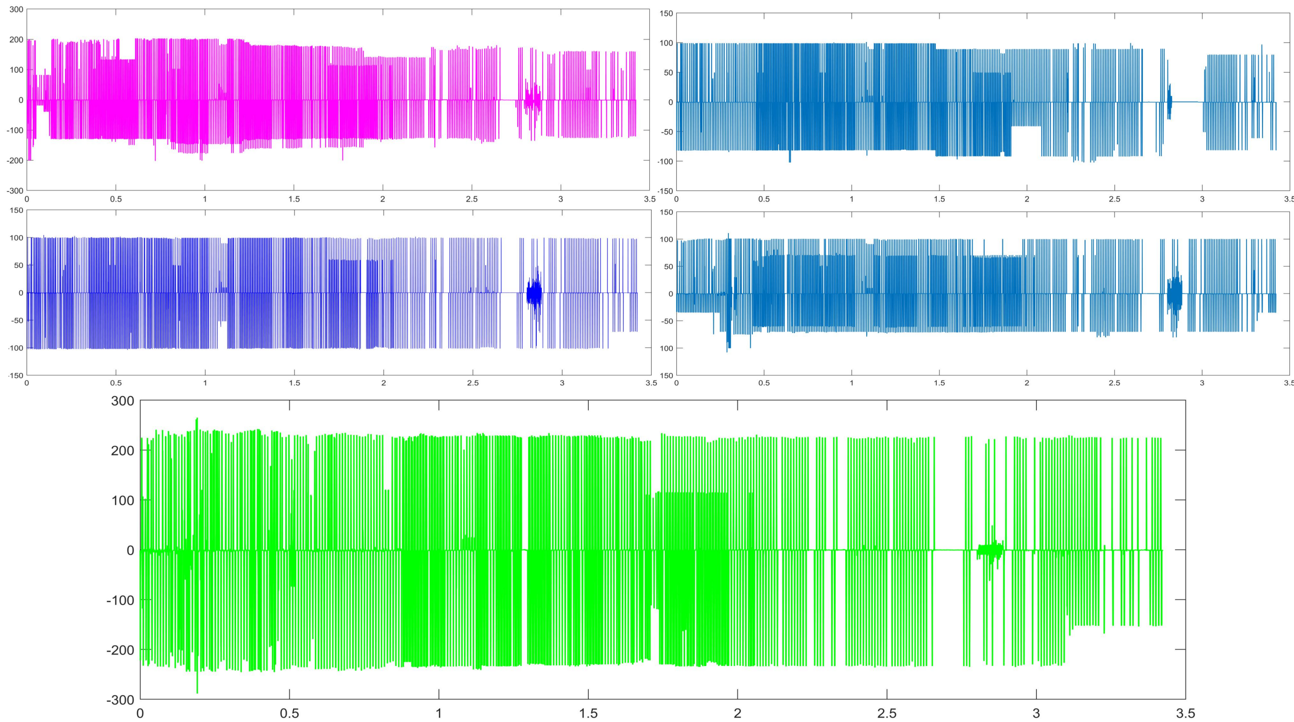


Figure 3. 356 day user-side energy storage power station.

X5=CNDZSJ(:,5)

The above program will write the data of Shuanghuai Energy Storage Station (240MW/480MWh) into column X5, and then delete the last 52 data points. The remaining 34176 data points will be arranged in a sequence of 96 to form a matrix data of 96 * 356.

Array Data=table2array(X51)

B=reshape(array Data,[96, 356])

Display its charging and discharging status through the mesh function:

[x,y]=mesh grid(1:1:356, 1:1:96)

mesh(x, y, B)

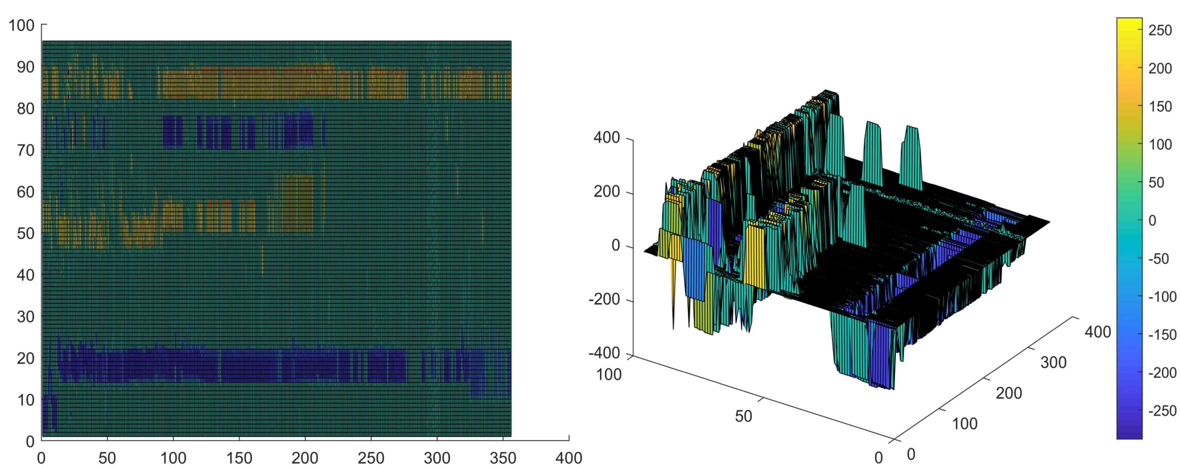


Figure 4. Shuanghuai Energy Storage Power Station (240MW/480MWh).

The above figure shows that during 356 day period of a year, charging period of the Shuanghuai Energy Storage Station is mainly concentrated in the "1 charge and 1 discharge", and there are also conditions of "2 charges and 2 discharges". Furthermore, the charging and discharging curves of one day of the energy storage power station were randomly selected from 356 days, and charging and discharging curves of the energy storage power station within 24 hours of one day were specifically studied. Taking the 100th day of Songgai Energy Storage Power Station (200 MW/400MWh) as an example. Taking day as example, the energy storage station starts charging at the 3am and charges until 6am. With the power of 150MW, it can accumulate 150*3=450MWh of electricity, totaling 450000 kWh. The discharge will start at 12 noon and be completed within 2 hours, resulting in 200*2=400MWh and a total of 400000 kWh of electricity[9].

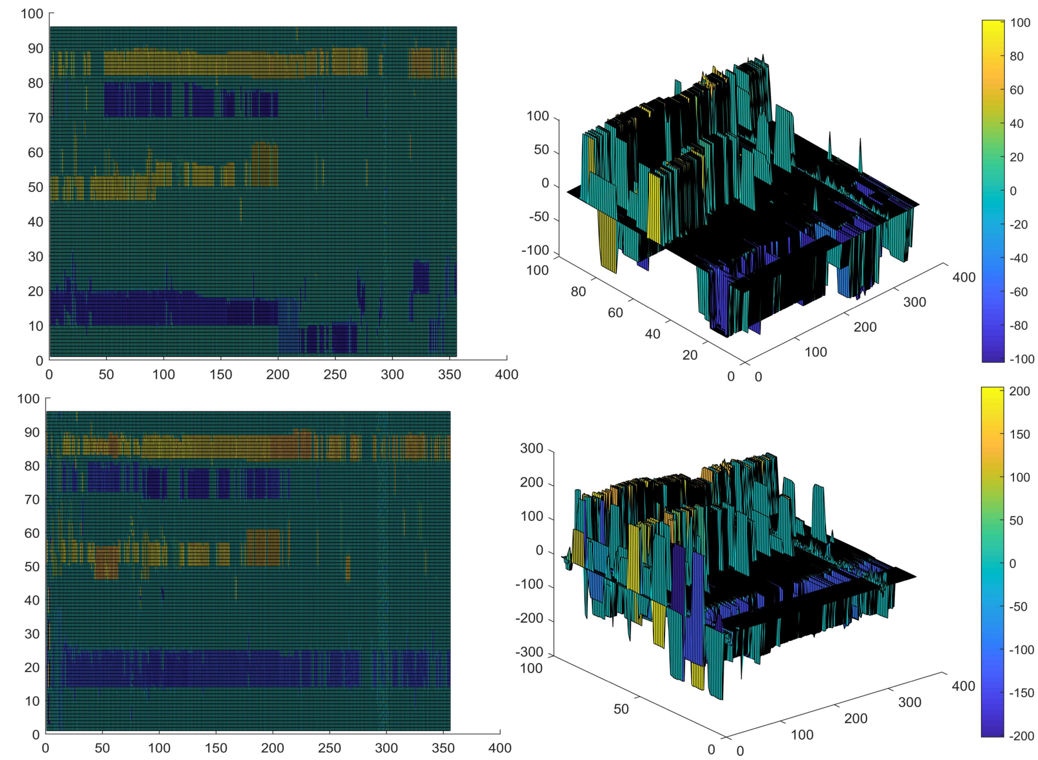


Figure 5. Shuanghuai Energy Storage Power Station (240MW/480MWh).

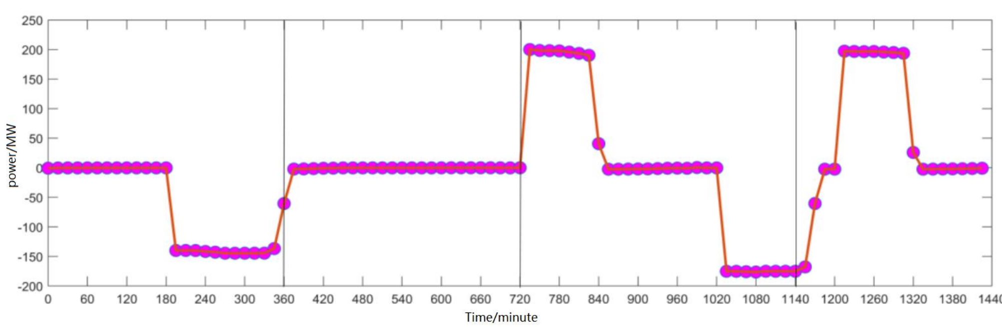


Figure 6. Songgai Energy Storage Power Station (200 MW/400MWh, Day 100).

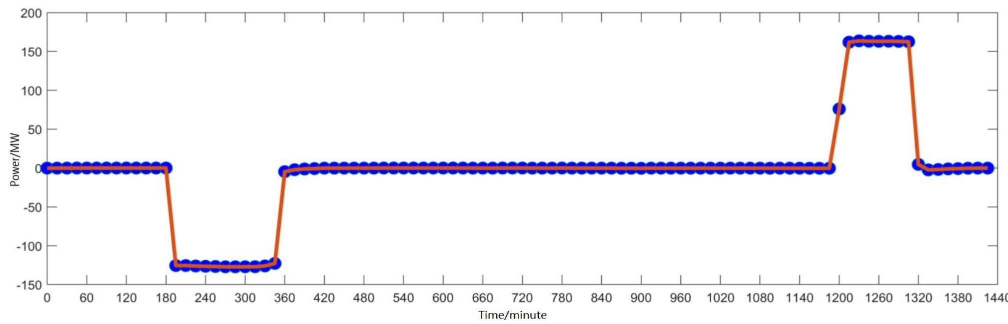


Figure 7. Typical curve of one charge and one discharge

Within 365 days, the stored power of the battery can be discharged within 3 or 2 hours, and the longer the discharge time, the higher the discharge power. The charging period is mainly concentrated between 3am and 6am, which belong to the low valley period, mainly taking 3 hours to charge energy storage station. At the same time, there is a situation where the battery is fully charged during noon peak period from 12:00-14:00, then charged during the normal period from 17:00-20:00, and discharged during the peak period from 20:00-22:00, achieving "two charges and two discharges" throughout the entire 24 hours shown in Figure 8.

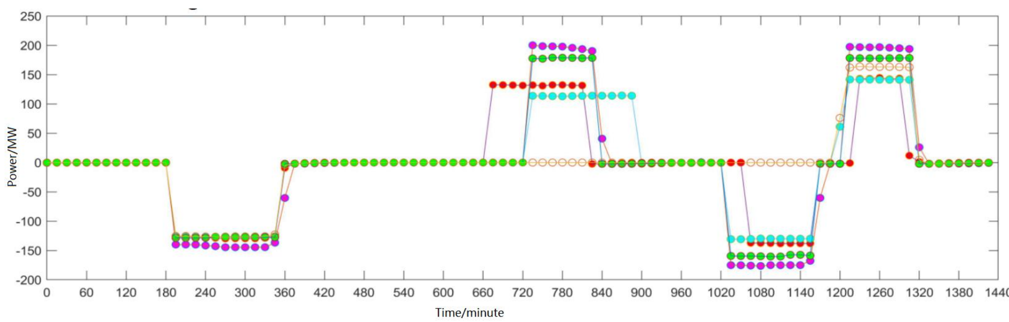


Figure 8. 6 typical charging and discharging types.

Figure 9 shows that within 365 days, the stored power of battery can be discharged within 3 or 2 hours, and longer the discharge time, the higher discharge power. During the peak season of summer (January, July, August, and December), the electricity price increases by 60% on the basis of the average electricity price, decreases by 62% on the basis of the average electricity price during the off peak season, and increases by 20% on the basis of peak electricity price during the peak season. During peak periods in other months, electricity price will increase by 60% on the basis of the average electricity price, while during off peak periods, electricity price decrease by 62% on basis of the average electricity price.

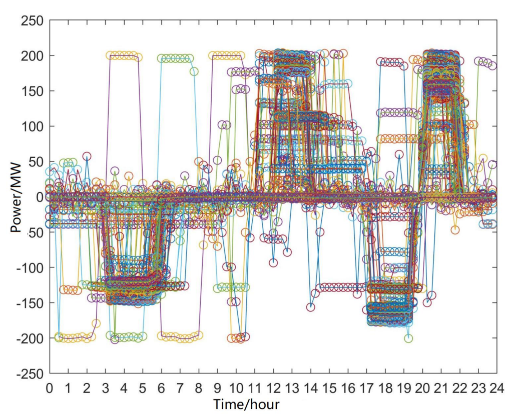


Figure 9. Comparative analysis of 356 types of charge discharge curves.

3. MULTI-OBJECTIVE OPTIMIZATION METHOD FOR COORDINATED PLANNING OF FLEXIBLE RESOURCES IN PHOTOVOLTAIC STORAGE AND CHARGING

On the premise that the outer optimization model has determined the node positions and the planned capacities of various user side flexibility resources, inner optimization model aims to minimize the sum of the penalty costs for conventional and the renewable energy generation and the consumption, as well as the operating/maintenance costs of each flexibility resource during the operation phase[10]. The objective function of the outer optimization model is:

$$F_{\mathrm{T}} = \sum_{t=1}^{T}\sum_{i=1}^{N_{\mathrm{T}}}(C_i^{\mathrm{st}}u_{i,t} + C_i^{\mathrm{sd}}v_{i,t} + C_i^{\mathrm{su}}\Delta p_{i,t}^{\mathrm{u}} + C_i^{\mathrm{sl}}\Delta p_{i,t}^{\mathrm{l}} + f_s) \tag{1}$$

$$F_{\mathrm{W}} = \sum_{t\in T}\sum_{j\in N_{\mathrm{W}}}(C_j^{\mathrm{u}}\Delta w_{j,t}^{\mathrm{u}} + C_j^{\mathrm{l}}\Delta w_{j,t}^{\mathrm{l}}) \tag{2}$$

In the formula, N_{W} represents number of renewable energy power plants. C_j^{u}、C_j^{l} are the penalty cost coefficients for the wind/solar power curtailment and the load shedding of renewable energy power plant j, respectively. $\Delta w_{j,t}^{\mathrm{u}}$、$\Delta w_{j,t}^{\mathrm{l}}$ are the amount of abandoned wind/light and load shedding of renewable energy power station j during period t, respectively. In the formula, $F_{\mathrm{g}}^{\mathrm{inv}}$、$F_{\mathrm{g}}^{\mathrm{op}}$、$F_{\mathrm{g}}^{\mathrm{rec}}$、$F_{\mathrm{g}}^{\mathrm{inc}}$、$F_{\mathrm{g}}^{\mathrm{ps}}$ represent the daily investment cost, operating cost, residual value recovery income, deferred transmission line investment income, peak shaving cost of user side energy storage power station, respectively.

$$F_{\mathrm{g}}^{\mathrm{inv}} = \sum_{b\in N_{\mathrm{G}}}\frac{N_b C_b^{\mathrm{G0}}}{365}\frac{r(1+r)^{T_{\mathrm{g}}}}{(1+r)^{T_{\mathrm{g}}}-1}P_b^{\max} \tag{3}$$

$$F_{\mathrm{g}}^{\mathrm{op}} = \sum_{t\in T}\sum_{b\in N_{\mathrm{G}}}\lambda_b^{\mathrm{g}}(\lambda_{2b}(p_{b,t})^2 + \lambda_{1b}p_{b,t} + \lambda_{0b}) \tag{4}$$

$$F_{\mathrm{g}}^{\mathrm{ps}} = \sum_{b\in N_{\mathrm{G}}}(\lambda_{b,t}^{\mathrm{u}}p_{b,t}^{\mathrm{u}} + \lambda_{b,t}^{\mathrm{l}}p_{b,t}^{\mathrm{l}}) \tag{5}$$

When performing the time series decomposition, the trends and periods are typically combined into a single trend period component(sometimes referred to as trend for simplicity). Therefore, it is believed that time series consists of three parts: the trend cycle part, the seasonal part, and the residual part.

$$P_{d,s,t}^{LD} = P_{d,s,t}^{LD'}\frac{T_d^{LD} + S_d^{LD} + I_d^{LD}}{\sum_{Days=1}^{Days_j}\sum_{t=1}^{24}P_{s,t}^{LD'}} \tag{6}$$

After above decomposition work, there has been some exploration of long-term development trend, seasonal components, and the random volatility of the data. Finally, the random component of substation output for the corresponding month is superimposed with its long-term trend and seasonal component to obtain the final prediction result. Among them, $P_{s,t}^{LD}$ and t are the predicted values at time t on days of month d, $P_{s,t}^{LD'}$ and t are the measured values at time t on days of month d. TLD d, SLD d, and ILD d are the long-term trend component, seasonal fluctuation component, and random fluctuation component of month d, respectively. By superimposing above components, final prediction result is obtained, as shown in Figure 10.

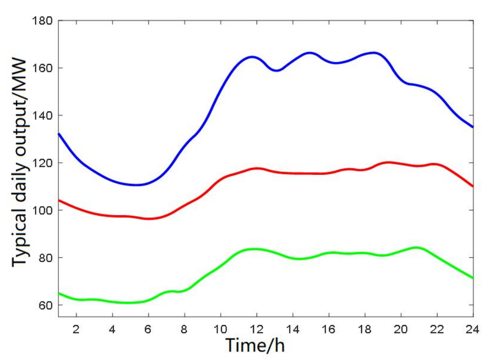


Figure 10. Typical daily output situation.

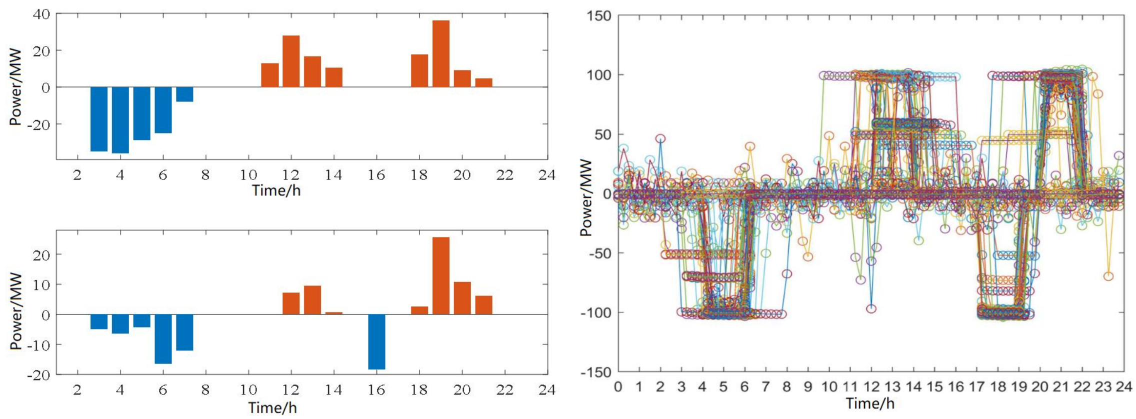


Figure 11. Energy storage charging and discharging power of the same planning model.

Finally, the K-means clustering method is used to obtain the clustering centers of the predicted results and determine the typical days. Based on this, the expected probability of holding inequality constraints with uncertain variables is limited to the lowest allowed confidence level to improve the reliability of the model. Finally, the proposed model is transformed into the linear programming problem through the duality theory and conditional value at risk approximation for solution, ultimately achieving demand response optimization considering the electricity gas coupling distribution network. This can effectively achieve load peak shaving and valley filling, and improve system's ability to absorb new energy. Figure 11 shows the charging and discharging power of energy storage batteries for two optimization model decisions.

From Figure 11, it can be seen that decision results of the robust programming model only have insufficient consumption in the 19th period, resulting in load shedding penalty costs. The decision results of the deterministic programming model show insufficient absorption during the 12th to 15th and 18th to 19th time periods. The adjustment of output amplitude in adjacent time periods is also greater than that of the robust programming model, resulting in the significant reduction in the operating life of the battery. Sensitivity analysis of unit power investment cost and sales revenue coefficient of flexible load equipment is shown in Figure 12.

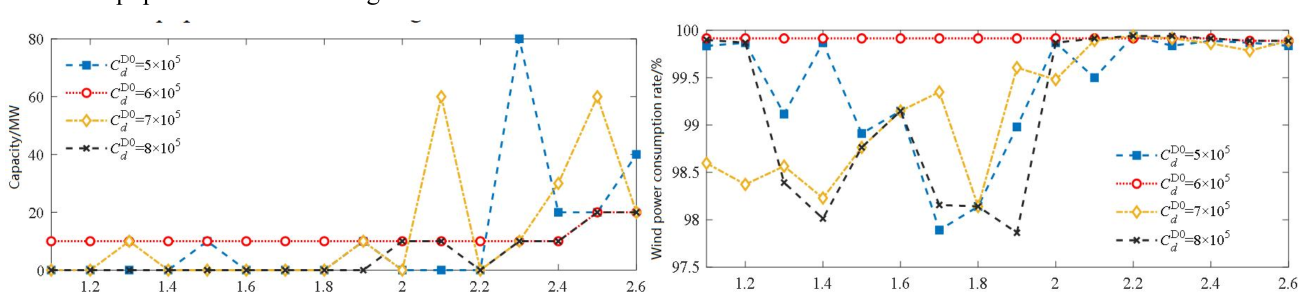
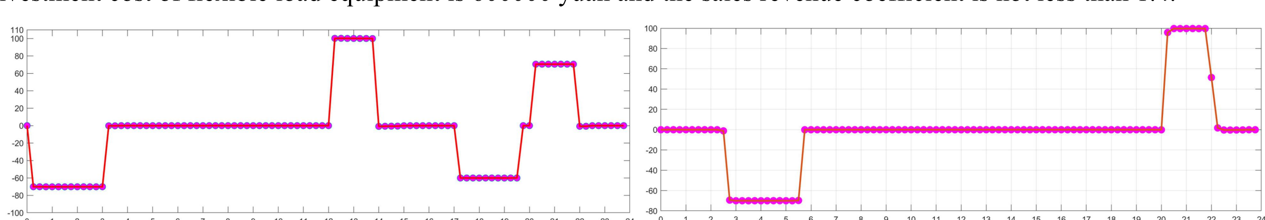


Figure 12. Analysis of Total Cost and Flexible Load Daily Investment Cost

From Figures 12, it can be seen that under the same unit power investment cost of flexible load equipment, the planned capacity of flexible loads tends to increase with the increase of electricity sales revenue coefficient. Under the same sales revenue coefficient, the lower the unit power investment cost of flexible load equipment, the greater the planned capacity, which is related to the selection of the sales revenue coefficient. When the sales revenue coefficient is higher than 2.2, lower investment costs per unit power of flexible load equipment can achieve larger planned capacity and higher wind power consumption rate. The comparison results of the comprehensive wind power consumption rate, flexible load daily investment cost, and total cost show that the optimal comprehensive performance can be obtained when the unit power investment cost of flexible load equipment is 600000 yuan and the sales revenue coefficient is not less than 1.4.



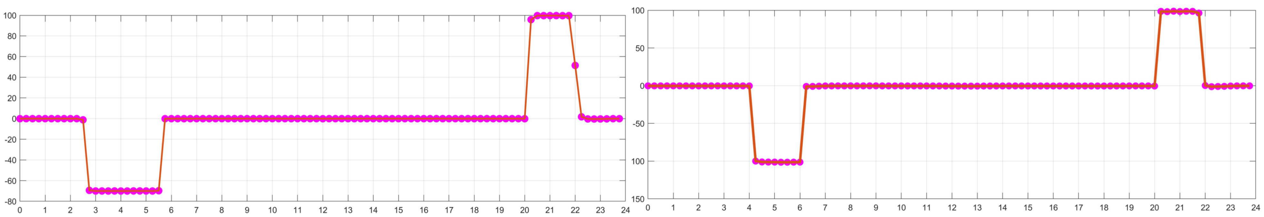


Figure 13. Analysis of Charging and Discharging Conditions of Huaiyuan Energy Storage Power Station (100MW/200MWh).

Figure 13 shows that energy storage station of Huaiyuan Energy Storage Power Station exhibits a typical "two charging and two discharging" characteristic. During the low valley period: from 0:00 to 8:00, it is fully charged within the three hours, and during the peak period from 12:00 to 14:00, it is discharged. Then, it continues to charge from 5 pm to 8 pm, and finally discharges during the peak period from 20:00 to 22:00 pm. The Huai-yuan Energy Storage Station exhibits a typical "one charge, one discharge" characteristic, still charging for 3 hours during the low valley period to fully charge the energy storage station, and then discharging during the peak period from 20:00 to 22:00 in the evening.

Table 1. Comparison of Flexible Resource Planning Results for Source Grid Load Storage under Wind Power Integration Ratios.

Calculation results	Wind power access ratio		
	1.25	1.50	1.75
Wind power consumption rate/%	100	100	100
Flexible load fluctuation absorption rate/%	100	100	100
Planned capacity of gas turbine unit/MW	100	150	150
New transmission lines and capacity/MW	5-7/100	5-7、6-7/200	5-7、6-7/200
Flexible load planning capacity/MW	10	20	40
Planning location and capacity of energy storage power stations/MW	26/60	2/60	23/120
Battery operating life/year	9.0420	9.0420	8.5520

4. USER SIDE ENERGY STORAGE MULTI SCENARIO AND MULTI TIME SCALE CASE TESTING

To verify the feasibility of the proposed model algorithm, the coordinated optimization test case of the substation energy supply micro ecosystem and a virtual power plant was built through programming.

Figure 14. Modified user side energy storage node distribution system topology diagram.

The aggregated virtual power plant still uses the modified IEEE-33 node distribution system example from the previous section. The substation energy supply micro ecosystem adopts the modified 10 node distribution system example in the MATPOWER, and its topology diagram is shown in Figure 14. After setting the relevant parameters, call the GUROBI solver in the YALMIP toolbox to solve convex optimization problem of relevant process, and obtain the coordinated optimization operation strategy of the substation energy supply micro ecosystem virtual power plant. Figure 15 shows the exchange of active power between the substation energy supply micro ecosystem and the virtual power plant. It can be seen that during peak load periods, the virtual power plant supplies power to the higher-level substation, while during low load periods, it acts as a load to help higher-level substation absorb new energy.

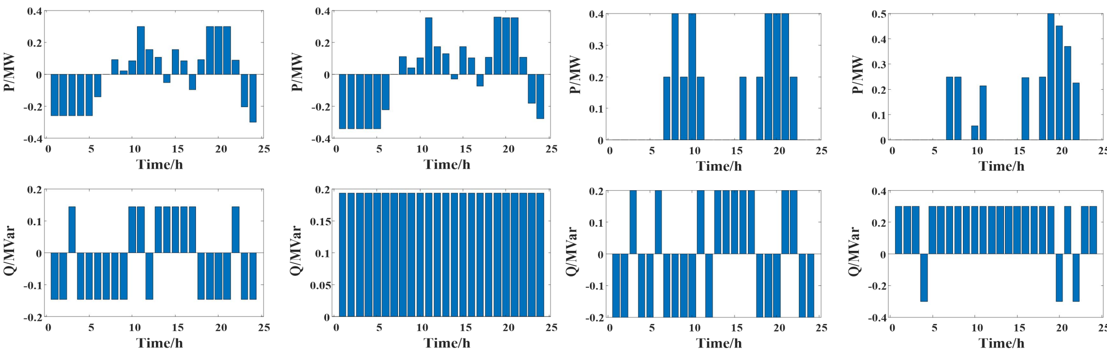


Figure 15. Distributed energy storage output situation.

From the output situation of the micro gas turbines, it can be seen that due to their flexible start stop compared to large thermal power units, the output of micro gas turbines mainly plays a supporting and regulating role in virtual power plants. Distributed energy storage charges during low load periods and discharges during high load periods, which can play the role in peak shaving and valley filling, while also utilizing the electricity price differences to obtain the certain profits. Interruptible loads can be interrupted normally during peak load periods.

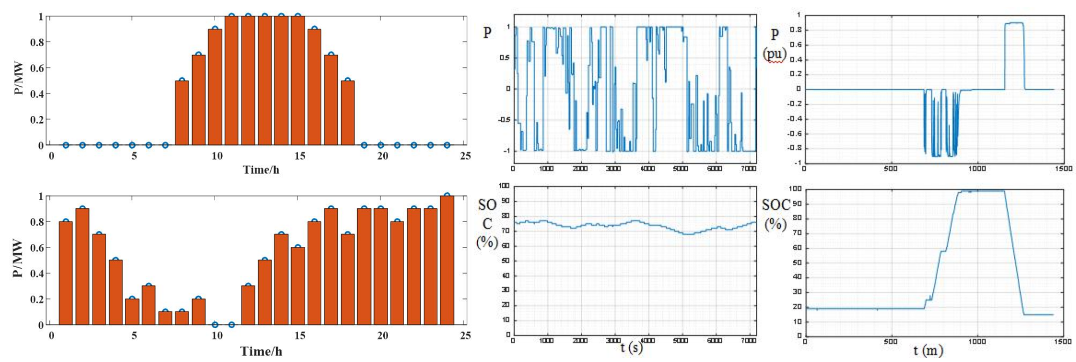


Figure 16. Analysis of operating condition data of energy storage system.

Figure 16 shows within 24-hour time scale every day, the maximum output power of photovoltaics exhibits a significant output trend at noon, showing overall inverted "U" - shaped distribution trend. On the other hand, the output of wind power generation shows smaller output during day and larger output at night, and the storage types of user side energy storage stations are diverse, including continuous charging and discharging between standard values of -1 and 1. On the other hand, energy storage power stations exhibit a "1 charge 1 discharge" pattern, and there are significant differences in depth of battery charge and discharge in two situations: for the frequency modulation function, due to short re-discharge time, the SOC charging depth of the battery is between 70% and 80%, while for the "1 charge 1 discharge" situation, the SOC charging depth of battery varies between 20% and 100%, indicating that there are significant differences in depth of battery charge and discharge of energy storage power stations operating in different states, which can be quantitatively calculated through on-site operational data.

5. CONCLUSION

(1) The decision results of the deterministic programming model show insufficient absorption during 12th to 15th and 18th to 19th time periods. The adjustment of the output amplitude in adjacent time periods is also greater than that of the robust programming model, resulting in the significant reduction in the operating life of the battery.

(2) K-means clustering method is used to obtain the clustering centers of the predicted results and determine the typical days. Based on this, the expected probability of holding inequality constraints with uncertain variables is limited to the lowest allowed confidence level to improve the reliability of the model. Finally, the proposed model is transformed into the linear programming problem through the duality theory and the conditional value at risk approximation for solution, ultimately achieving demand response optimization considering the electricity gas coupling distribution network.

ACKNOWLEDGMENT

This article is sponsored by the technology project "Research and Application of Key Technologies for Optimizing Configuration and Market Mechanism of User side Energy Storage Service Grid Operation" (Project No: 4000-202327094A-1-1-ZN).

REFERENCES

[1] Lei, S., Liu, Z., Wang, Q., et al., Research on green development framework of the virtual power plants[J].IOP Conference Series:Earth and Environmental Science, 687, 1-7 (2021).

[2] Liang, K., Liu, Y., He, H.., et al., Demand-side response Resource Value Evaluation Method based on Entropy-weighted Close Value Method[J] Journal of Physics:Conference Series, 1827, 1-6 (2021).

[3] Lv, X., Li, D., Chen, Y., et al., Research on Technical and Economic Feasibility Evaluation Model of Energy Storage Power Station[J].IOP Conference Series Earth and Environmental Science, 252, 1-7 (2019).

[4] Choi, D., Min, D., Ryu, J. H., Economic Value Assessment and Optimal Sizing of an Energy Storage System in a Grid-Conected Wind Farm[J] Energies, 11(3), 591 (2018).

[5] Dong, J., Sun, X., Dou, X., Evaluation of Electricity Demand Response from the Perspective of Marketization[J].Journal of Electrical & Electronic Engineering, 5(4), 141-148 (2017).

[6] Wang, H., Riaz, S., Mancarella, P., Integrated techno-economic modeling, flexibility analysis, and business case assessment of an urban virtual power plant with multi-market cooptimization[J] Applied Energy, 259(02), 11-17 (2020).

[7] Tian, Y., Fan, L., Tang, Y., et al., A Coordinated Multi-Time Scale Robust Scheduling Framework for Isolated Power System With ESU Under High RES Penetration[J] IEEE Access, 6, 9774-9784 (2018).

[8] Sun, H., Zhang, B., A systematic analytical method for quasi-steady-state sensitivity[J] Electr.Power Syst.Res, 63(2), 141-147 (2002).

[9] Carrin, M., Arroyo, J. M., A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem. IEEE Trans.Power Syst. 21(3), 1371-1378 (2006).

[10] Ding, T.., Li, C., Yang, Y., et al., A Two-Stage Robust Optimization for Centralized-Optimal Dispatch of Photovoltaic Inverters in Active Distribution Networks.IEEE Trans.Sustain.Energy, 8(2), 744-754 (2017).