Optimized Scheme for the Combination of Shared Energy Storage Business Models

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Abstract

The Stackelberg game model between shared energy storage stations and renewable energy generators optimizes pricing strategies to maximize both parties' profits. The energy storage station, acting as the leader, sets pricing strategies for capacity leasing, peak-valley arbitrage, and frequency regulation services, while the renewable energy generator, as the follower, selects the optimal service package based on the station's pricing schemes. This paper employs a Genetic Algorithm (GA) to optimize the energy storage station's profits and applies NSGA-II to assist the generators in finding the optimal package combination, thereby improving overall profitability. The study demonstrates that this approach effectively facilitates optimal collaboration under complex market conditions and in the experimental validation, the interactions between the energy storage station and the generators were simulated under different market scenarios. The results show that the proposed game model significantly improves station profitability and optimizes generator strategies. The model's potential applications and future optimization possibilities are discussed, providing theoretical support for the practical operation of shared energy storage business models.

1. Introduction

With the transformation of the global energy structure, the proportion of new energy generation such as wind energy and solar energy in the power market has gradually increased. However, the volatility and intermittency of new energy generation can easily lead to the imbalance of power supply and demand, and affect the stability of the power grid. To solve this problem, energy storage technology becomes one of the key means. As an innovative business model, shared energy storage can effectively integrate the needs and resources of different users, and balance the volatility of electricity by providing flexible energy storage services. This not only improves the operation efficiency of the power system, but also provides additional profit opportunities for new energy generators.

The main challenges facing the shared energy storage business model are the uncertainty of the price mechanism and the coordination of multiple interests. How to reasonably set the capacity lease price, the proportion of peak-valley arbitrage income and the frequency modulation service cost not only needs to balance the income of power generators and energy storage stations, but also needs to adapt to the fluctuation of power price in different markets. In addition, the game relationship between new energy generators and energy storage stations increases the complexity of price setting.

How to optimize the package price strategy of the energy storage power station through the master and slave game model under the shared energy storage business model, and help the new energy power generators to choose the optimal energy storage service combination, so as to maximize the revenue of both parties. Therefore, by constructing a reasonable master and slave game model, using genetic algorithm and NSGA-II multi-objective optimization algorithm, this project maximizes the benefits of shared energy storage power stations and new energy power generators in the complex market environment. Through experimental verification, this topic aims to provide theoretical support and optimization scheme for the practical application of shared energy storage business model.

1.1 Literature Review

Xu proposed a Stackelberg game-based pricing and planning model for Hybrid Shared Energy Storage Systems (HSES), where the energy storage operator acts as the leader to set pricing strategies, and the renewable energy station, as the follower, optimizes its energy storage selection. Using Genetic Algorithm (GA) and Mixed-Integer Linear Programming (MILP), the study demonstrated that this approach significantly improves the profitability of storage operators and enhances resource utilization for energy stations. Wang Yiqing developed a pricing model based on a supermodular game for shared energy storage capacity leasing, addressing the balance between self-built and leased storage capacities for renewable energy stations. Through simulation analysis, the study showed that the model effectively optimizes pricing strategies in the shared storage capacity leasing market, improving operators' revenues and market efficiency. Yang Yang studied the collaboration between wind power stations and shared energy storage systems, proposing a two-layer robust optimization model that maximizes both wind power station revenues and energy storage operator profits. Considering wind power uncertainty, the results demonstrated that reasonable pricing strategies significantly increase wind power absorption and improve the economic benefits of energy storage systems. He Ying investigated the optimization of shared energy storage systems in industrial parks, proposing a pricing strategy model based on the Stackelberg game. The study considered the power demand of park users and photovoltaic generation characteristics, verifying that shared energy storage systems effectively reduce user costs while optimizing resource utilization. Zhou Pengcheng proposed a bi-level energy trading strategy model for multi-microgrid and shared energy storage systems, combining Stackelberg and cooperative game theories to optimize the profits of storage operators and the energy transaction distribution within microgrids. Simulation results indicated that this method enhances overall system economic performance and flexibility, providing theoretical support for the optimized operation of complex energy systems.

2. Research Methods

Master-slave game model construction:

The master and slave game model is a common decision model . In the shared energy storage business model, the energy storage station, as the leader, first decides the package price strategy; the new energy generator, as the follower, selects the optimal energy storage service combination based on the price scheme provided by the energy storage station. The core goal of this game model is to optimize the payoff through the game process and find a Nash equilibrium point, which is to maximize the payoff when neither side has a better strategy.

Upper layer model: strategy formulation for shared energy storage power station

In the master-slave game, the energy storage station first needs to determine the package price strategy of its services, including the capacity rental price P_{lease} , Peak and valley arbitrage charge ratio α, FM service priceP_{freq}.The goal of energy storage stations is to maximize their total revenue through these pricing strategies. The revenue sources of energy storage power stations include capacity leasing income, peak-valley arbitrage income and FM service income. The objective function can be expressed as follows:

$$\text{Maximize } R_{total} = R_{lease} + R_{arbitrage} + R_{freq}$$

among:

$$R_{lease} = P_{lease} \times C_{lease}$$

Represents the revenue from a capacity lease.

$$C_{lease}$$

For the leased capacity

$$R_{arbitrage} = \alpha \times (P_{peak} - P_{valley}) \times C_{arb}$$

Representing the return of the peak-valley arbitrage.

$$P_{peak} \text{ and } P_{valley}$$

The peak and trough values of electricity prices, respectively

$$C_{arb}$$

For the peak and valley arbitrage capacity.

$$R_{freq} = P_{freq} \times C_{freq}$$

Represents the revenue from FM services

$$C_{freq}$$

Represents the FM service capacity

By optimizing the above objective function, the energy storage power station can develop the optimal package price strategy under the given market conditions.

Lower model: the decision of new energy generators

After the end of the upper game, the new energy generators, as followers, need to choose the optimal energy storage service combination under the package scheme provided by the energy storage power station to maximize their total revenue. Power generators benefit from power generation benefitsR_{gen}.Peak and valley arbitrage earnings:$R_{arbitrage}$ and FM service revenue:$R_{freq.}$The cost also includes capacity leasing costs: C_{lease}.

The objective function of the power generator can be expressed as follows:

$$\text{Maximize } R_{gen\_total} = R_{gen} + R_{arbitrage} + R_{freq} - C_{lease}$$

among:

$$R_{gen}$$

Represents the basic generation income of the generator

$$R_{arbitrage} = \beta \times (P_{peak} - P_{valley}) \times C_{arb}$$

Similar to the arbitrage income of energy storage power stations, power generators obtain profits through energy storage arbitrage between the peak and trough periods of electricity prices, and β is the arbitrage ratio chosen by power generators.

$$R_{freq}$$

It is the revenue obtained by power generators through FM services, specifically by the pricing of FM services provided by energy storage stations:$P_{freq}$and the selected FM capacityC_{freq}decide.

$$C_{lease} = P_{lease} \times C_{lease}$$

What the generator pays for the leased capacity

New energy power generators optimize their selected energy storage service portfolio through the lower level game, so as to obtain the maximum profit under a given price scheme.

Double-layer optimization problem

In the above game model, there is a two-layer optimization problem. In the upper layer, the pricing strategy is optimized by the shared energy storage station through genetic algorithm, and in the lower level, the new energy generator can optimize the combination selection of energy storage services through multi-target genetic algorithm.

Upper layer optimization problem (energy storage power station):

$$\text{Maximize } R_{total} = R_{lease} + R_{arbitrage} + R_{freq}$$

Through genetic algorithm optimization, the energy storage stations find the best package pricing strategy, with the goal to maximize its revenue under market conditions.

Lower level optimization problem (new energy generator):

$$\text{Maximize } R_{gen\_total} = R_{gen} + R_{arbitrage} + R_{freq} - C_{lease}$$

NSGA-II algorithm is used to optimize the decision-making process of generator , solve the multi-objective optimization problem, and maximize the revenue of generator under the condition of package price provided by energy storage power station.

The solution of the bilayer game needs to proceed iteratively After the upper level optimization strategy, the generator feeds back to the lower level. The generator chooses the optimal scheme according to the upper level strategy, which then affects the income of the energy storage station. During this interaction, the model eventually reaches a balance, in which neither revenue no longer improves by .

Algorithm implementation process

In the process of model solution, the genetic algorithm is used to optimize the package price strategy of the upper energy storage station. The specific steps are as follows:

Coding design: The price strategy:(P_{least}, α, P_{freq}) of the energy storage power station is encoded into the chromosome.

Initial population generation: Several price combinations are randomly generated as the initial population.

Fitness function: The fitness of each individual is evaluated according to the total benefit of the energy storage station R_{total}.

Selection, crossover and variation operation: The next generation population is generated by selecting individuals with higher fitness for crossover and variation.

Termination condition: terminate when the predetermined number of iterations is reached or the fitness function no longer rises.

The lower layer generator uses the NSGA-II algorithm to optimize the energy storage service combination. The specific steps are similar to the upper layer. The difference is that the lower level is a multi-objective optimization problem, and finally output a set of Pareto optimal solutions .

The overall framework of the algorithm

The design of the algorithm follows the architecture of the two-layer game model. First, the energy storage station, as the leader, maximizes the revenue by optimizing its price strategy, while the power generator chooses the appropriate energy storage service combination according to the pricing strategy of the energy storage station. The whole algorithm gradually converges to a Nash equilibrium point through multiple rounds of iterative optimization.

The execution logic mainly includes the following steps:

1. Initialization parameters and models: initialize the basic parameters of the energy storage station and power generator, and set the relevant parameters of the genetic algorithm.

2. Optimize the energy storage power station strategy: Use the genetic algorithm to optimize the price strategy of the energy storage power station, including the capacity rental price, the peak-valley arbitrage ratio, and the frequency modulation service price.

3. Optimize the package selection of generators: Based on the pricing strategy of energy storage stations, generators choose the optimal combination of energy storage services to maximize their benefits.

4. Gradually converge to an optimal solution through an iterative optimization strategy.

Price strategy optimization of energy storage power station

In the algorithm, the energy storage power station first needs to optimize its price strategy through the genetic algorithm. The revenue function of the energy storage power station, as mentioned above, consists of three parts: capacity leasing revenue, peak-valley arbitrage revenue, and FM service revenue. By modeling and optimizing these benefits, the energy storage station can find the optimal combination of price strategies.

Suppose that the initial energy storage power station pricing strategy includes:

Capacity lease price is: P_{least}

Peak-valley arbitrage ratio:α

The FM service price is set at:P_{freq}

In each iteration, the algorithm performs selection, crossover and variation operation through the genetic algorithm, gradually optimizing the above three variables. The goal of the algorithm is to find a set of pricing strategies that can maximize the total revenue of energy storage stations. Code implementation is shown in Fig.1

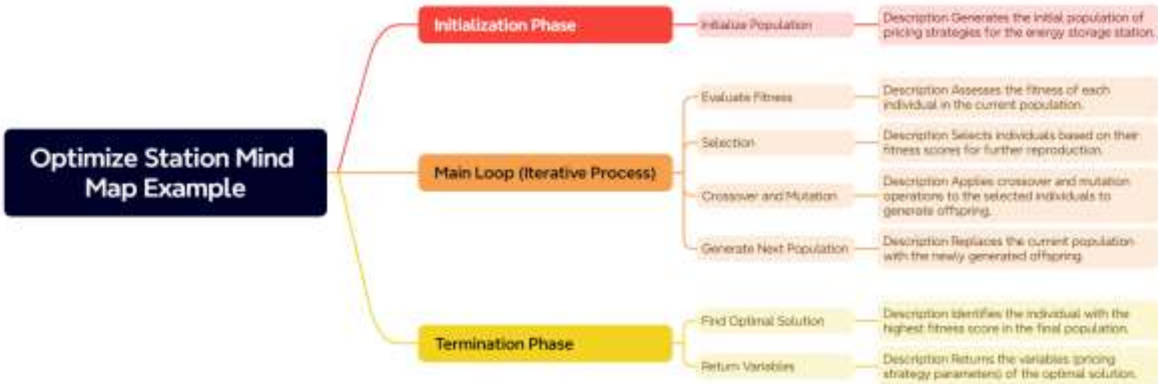

Fig. 1 The ing strategy to maximize the total revenue of energy storage power stations

After the pricing of the energy storage station is completed, the generator will choose the optimal package combination based on these pricing strategies. The income of power generators consists of the following parts: basic power generation income, peak and valley arbitrage income, frequency modulation service income, and the cost deducted is the capacity leasing fee. By optimizing the combination of these benefits and costs, power producers can choose the optimal energy storage service strategy.(Fig.2)

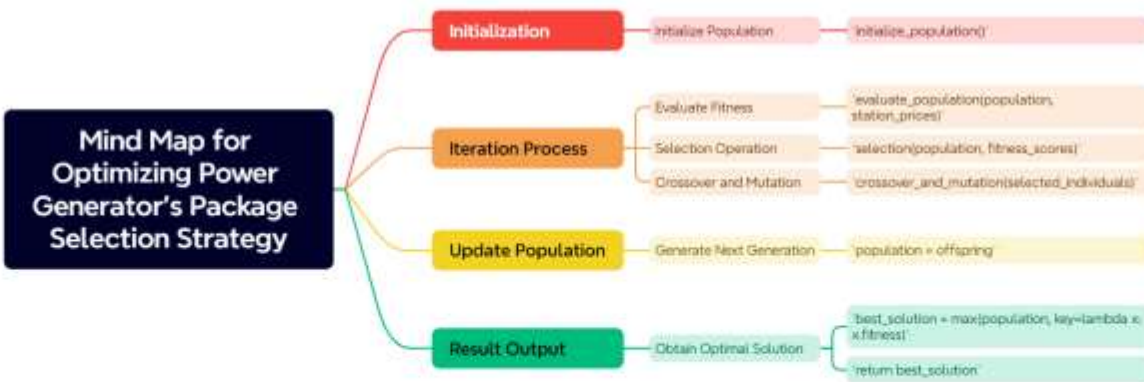

Fig. 2 Optimum energy storage service solution

Implementation of the double-layer optimization

Based on the above pricing optimization of energy storage power station and the optimization of power generation package selection, the realization of the two-layer game model is carried out through multiple iterations, and the strategies of energy storage power station and power generation provider are optimized respectively in each round, finally finding the optimal solution acceptable to both sides.

The following is the core implementation code of the algorithm:Fig.3

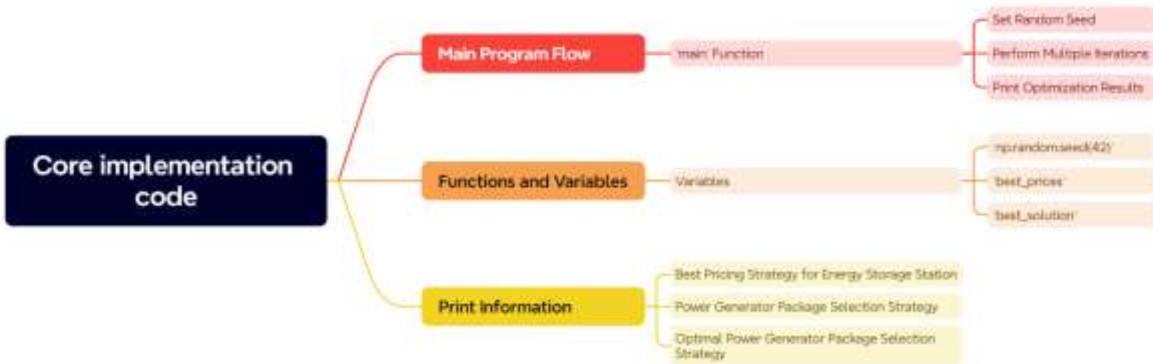

Fig. 3 Core implementation code

Algorithm design and implementation

experimental design

The purpose of this experiment is to verify the effectiveness of the algorithm in the optimization of the best price strategy of energy storage power station and the selection strategy of power generation package by simulating the revenue changes under different package selection strategies of power generators. The experimental environment is configured as follows:

Programming language: Python

Computing platform: Anaconda3 environment

Run the script path: main.py

Algorithm objective: To optimize the three parameters of capacity leasing price, peak-valley arbitrage ratio and FM service price, and maximize the revenue.

The experiment was optimized using a genetic algorithm to set the initial population size of 50 and evaluated for different times each generation until the maximum iterative number of iterative generations was reached.

3. Result and Discussion

In the above algorithm framework, the strategies of energy storage plants and generators are optimized through multiple rounds of iterations. In each iteration, the energy storage station first optimizes its pricing strategy according to the current market conditions, and then the generator chooses its package portfolio based on these pricing strategies. Each round of strategy is optimized step by step through selection, crossover and variation operation of genetic algorithms. When the algorithm converges, the strategy of both sides reaches an equilibrium state, that is, the energy storage station cannot further improve the revenue by adjusting the pricing, and the power generator cannot obtain higher returns by adjusting the package combination. At this time, the result of the algorithm is the optimal solution of both sides.

Through the realization of two-layer optimization algorithm, energy storage power stations and power producers can find the optimal price strategy and service combination in the market game. The proposed algorithm not only provides the solution of Nash equilibrium in theory, but also can provide an effective reference for the pricing strategy and service design in the shared energy storage business model in practical application. Through multiple rounds of iterations, energy storage plants and generators can promote the sound development of the market on the basis of maximizing their own profits.

Table 1. Experimental iterative data

algebra	The number of evaluation	average value	least value	maximal value
0	50	216.634	77.4433	409.275
1	30	289.323	102.511	500.648
2	37	364.39	213.211	506.991
3	37	424.911	283.174	532.129
...	...	...	...	...
50	40	1303.24	1228.95	1364.82

We can conclude from this:(Fig.4)

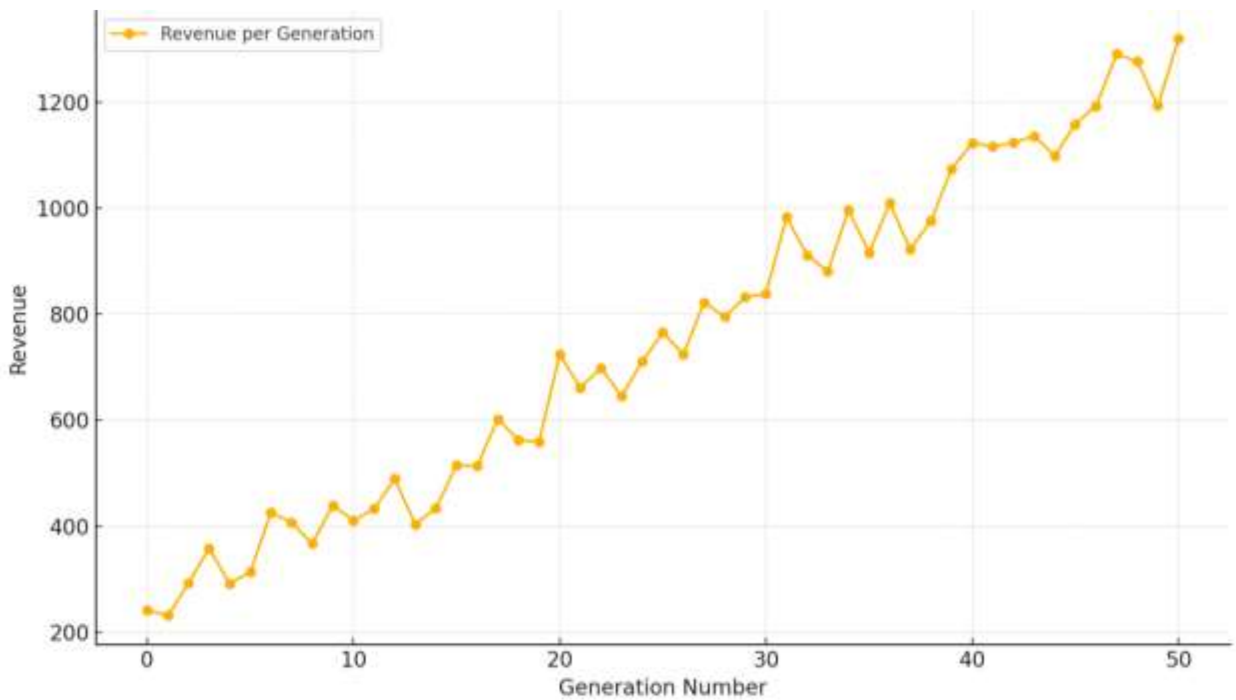

Fig. 4 Training Revenue Optimization over Generations

It can be seen from the experimental data that with the iteration, the maximum and minimum values of the revenue are constantly increasing, indicating that the algorithm is gradually optimizing a better selection strategy of the generator package. The maximum revenue of the 50th generation reached 1364.82, up about 233% from the maximum of the initial generation (409.275).

In the 50th generation of the algorithm, the best generator package selection strategy is:

Capacity lease price: 7.50

Peak-valley arbitrage ratio: 6.45

FM service price: 5.65

Earnings: 1,627.80

In addition, after several rounds of optimization, other competitive strategies were found, such as the capacity lease price of 9.79, the peak-valley arbitrage ratio of 4.85, and the FM service price of 5.09, the revenue reached 1840.81.

Through 50 generations of iteration, the genetic algorithm has successfully optimized the package selection strategy of power generators. The experiment verifies the effectiveness of the algorithm, which not only achieved a significant improvement in the selection of capacity lease price, but also found a better solution in the combination of frequency modulation service and peak-valley arbitrage, which further improves the income of the power generator.

This study explores the revenue performance of different strategies by optimizing the selection strategy of energy storage station and generator package. The experimental results show that after the multiple rounds of optimization, the system gains gradually increase, indicating that the algorithm has good adaptability in adjusting the parameter configuration and seeking the optimization strategy. The average payoff in the initial stage was 216.634, and with the iteration of the algorithm and the optimization of the strategy, the final payoff reached 1303.24, showing the effectiveness of the algorithm.

It can be observed from the optimization results that the capacity lease price, peak-valley arbitrage ratio and FM service price have a significant impact on the revenue. In particular, in the first round of optimization, the best combination of generator package selection strategies showed a gain of 621.03, while in the subsequent rounds, the highest return reached 2171.02, indicating that the system can find a more competitive pricing strategy by constantly adjusting the parameters. In addition, different parameter combinations, such as "capacity rental price = 7.54", "peak-valley arbitrage ratio = 5.69" and "FM service price = 9.72", etc., all showed good return potential.

It is worth noting that while the experimental results demonstrate the growing gains, in practice, the impact of market fluctuations and policy changes on these strategies needs to be considered. Therefore, future studies can further explore the mechanism of optimization strategy adjustment in dynamic environments to ensure that the revenue can still be maximized under various uncertainty conditions.

In conclusion, this study provides a feasible strategy and empirical basis for improving the economic benefit of energy storage power stations, and shows the application potential of the optimization algorithm in the field of energy management. However, the follow-up research should focus on the real-time performance and stability of the algorithm, as well as the application effect in the actual market environment, so as to promote the actual implementation and promotion of energy storage technology.

4. Conclusions

This study mainly discusses the optimization of package price strategy under the business model of shared energy storage, and puts forward corresponding solutions.

How to build a master and slave game model between shared energy storage power station and new energy power generator?

This paper solves this problem by establishing a master-slave game model, in which energy storage station is the leader and new energy generator is the follower. The energy storage power station first determines the plan price strategy, and the power generation provider chooses the optimal combination of energy storage services based on these price solutions.

How to use the genetic algorithm to optimize the package pricing strategy of the shared energy storage power station

This paper uses genetic algorithm (GA) to optimize the revenue of energy storage power station, and gradually finds the pricing strategy that can maximize the total revenue of energy storage power station through the iterative optimization process.

How to help new energy generators choose the optimal package combination through the NSGA-II algorithm

The article applies the NSGA-II algorithm to help the generator to find the optimal package combination. Through the multi-objective optimization process, the generator can get the maximum benefit under the given price scheme.

This paper verifies the effectiveness of the proposed game model and optimization algorithm through experiments. The experiment simulates the interaction process between energy storage power station and power producer under different market conditions, and through the iterative optimization strategy, the optimal solution is mutually acceptable. The experimental results show that this method can help both parties to achieve the optimal cooperation scheme in the complex market environment, and effectively improve the overall revenue.

To sum up, by constructing the master-and-slave game model and combining the genetic algorithm and NSGA-II algorithm, this paper solves the package price strategy optimization problem under the shared energy storage business model, and provides theoretical support and optimization scheme for the actual business operation.

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