Demand-side Response User Selection Based on Improved BPSO

Jun Chen1*, Feifei Bu2, Yuanyuan Wang2, Hongkun Bai2, Yuanpeng Hua2, Ding Han2 and Yi Sun3

1 Internet Department of State Grid Henan Electric Power Company
2 Energy Internet Economic Research Centre, Economic and Technical Research Institute of State Grid Henan Electric Power Company
3 Digital Consulting Department of Beijing Forever Technology Co., Ltd.

*Email: lakerboysjun@163.com

Abstract. In order to use the demand-side response activities to stabilize the peak load, ensure the balance of power supply and demand, and promote the quality and efficiency of the power grid, this paper constructs the demand-side response user competition models in different stages. The improved BPSO algorithm is used to optimize the subsidy cost weighted model in the saturated user competition model, and the algorithm is implemented automatically based on the blockchain intelligent contract. Simulation and experimental results show that, compared with other user selection schemes, these models can improve the actual user response and reduce the subsidy cost of the demand response centre. It can be seen that in the case of saturated user competition, the improved BPSO algorithm is feasible in the application of demand-side response to user selection and optimization of demand-side management.

1. Introduction
With the advancement of air pollution prevention and control battles [1], changes in power consumption structure [2] and explosive growth of new energy power generation [3], grid operation is facing new challenges, such as gaps in power supply and demand, and prominent seasonal peak load contradictions, the increasing pressure of peak regulation. Therefore, it is necessary to fully tap the demand-side response potential to effectively alleviate the gap between power supply and demand to ensure the safety and economy of power grid operation. Power market dispatch agencies or power companies and other power grid operators draw up demand response plans to stabilize peak loads, ensure the balance of power supply and demand, and promote the quality and efficiency of power grids. At present, Tianjin, Shandong, Shanghai, Jiangsu, Zhejiang, Henan and other provinces have issued power demand response work plans to effectively cope with the power load gap that may occur during the peak period of summer and winter power consumption in 2021.

The existing demand-side response mode mostly is that the power company issues bidding information, including demand response capacity, maximum price, response time period, etc, then the demand response centre proposes an invitation to the user, and the users declare the response with the information of response capacity, compensation price according to their own situation. The demand response centre selects users to participate in demand response until the response capacity demand is reached according to the principle of "price first, time first". However, in this process, only the price factor is considered, and there is no guarantee that the selected users can complete the declared response volume with quality and quantity. According to the demand-side response results publicized
by various provinces, many participating users have exited halfway in the response process which caused the actual response volume to not meet expectations, and the demand-side response did not not play an expected role in the balance of power supply and demand.

At present, demand-side response is still in the trial and exploration stage. Zhu Liu Zhu et al. [4] put forward two multilateral models of demand-side power rights trading and demand-side participation in peak load adjustment auxiliary service market. On this basis, they built user load interruption and valley-filling loss models, and measured demand-side response subsidy standards. Li Bin et al. [5] proposed an application scheme based on the demand analysis of the existing automatic demand response business in blockchain, and analysed the key issues of blockchain in automatic demand response system from the aspects of workload proof mechanism, interconnection consensus, smart contract, information security, etc. Yu Shaoyuan et al. [6] proposed a decentralized distributed power generation market-oriented transaction mechanism based on blockchain smart contract technology to realize P2P power transactions between production and sales users, and proposed a proxy user transaction decision-making model. This model aims at the optimal user economy and helps users make transaction decisions. Ren Haowen et al. [7] studied the theory of decentralized blockchain mechanism and proposed a method of applying blockchain distributed technology to the management of demand-side response plans of smart grids. This method stored energy consumption information collected from IoT smart metering devices based on the blockchain's tamper-proof distributed accounting technology. Besides, defining each consumer-level self-executing smart contract programmatically ensures transaction flexibility. In order to effectively guide demand-side resources to actively participate in the response, reduce the risk of default, thereby improving the availability of demand-side response participation in scheduling, Wang Beibei et al. [8] proposed a blockchain-based demand-side response resource credit management method. They set up a demand-side response resource transaction mechanism that considers credit values under centralized transactions and bilateral transactions, designed smart contracts at each stage of the transaction and deployed them on the Ethereum test chain, and explored the response effects of users under different credit values. Aimed at the existing problems of demand-side response resources participating in market transactions, Wu Geng et al. [9] proposed a comprehensive demand-side response resource transaction framework based on blockchain technology, and analysed the comprehensive demand based on blockchain technology. Side response to key issues in market transactions. Gong Gangjun et al. [10] designed a real-time power spot dispatching transaction and supervision model in the architecture of the blockchain, and programmed the multi-objective search optimization algorithm to run programmed scripts through smart contracts.

This paper separately models the demand-side response user competition behaviours in different development stages, and uses the Binary Particle Swarm Optimization Algorithm (BPSO) to optimize the models to obtain the best user selection plan for demand-side response in order to reduce subsidy expenditures in the case of sufficient demand response.

2. Demand-side Response User Competition Model at Different Stages

In order to give full play to the demand-side response market mechanism and explore the establishment of power demand-side response working mechanism that adapts to the medium and long-term and spot market models, different response user selection strategies for different stages of demand-side response were formulated. When the demand-side response is in a state of unsaturated competition, that is, the response volume of all users is less than the demand volume, all users whose declared prices are lower than the maximum subsidy limit are accepted to participate in the demand-side response, and supplemented by real-time response to complete peak shaving and valley-filling. When the demand-side response is in a state of saturated competition, that is, the response volume declared by all users is greater than the demand volume, in order to regulate user behaviour and improve user participation enthusiasm, this paper introduces a user competition mechanism which is used to select the preferred users to participate in the response. Firstly, we briefly introduce the
relevant regulations on demand-side response, and then introduce the demand-side response unsaturated user competition model and the saturated user competition model respectively.

2.1. Relevant Regulations on Demand-side Response

Normally, demand-side response can be divided into four types: real-time peak-shaving response, real-time valley-filling response, contracted peak-shaving response, and contracted valley-filling response. In order to improve the pertinence of the research, this article only considers peak-shaving response for the time being. The contracted response refers to the completion of the response invitation and confirmation process on the day before the response day, and the response is executed at the contracted time on the response day. Real-time response means that the responding user responds immediately after receiving the response instruction when the grid has insufficient power supply capacity due to emergencies. A user implements the contracted response not more than 2 times within a day, accumulation does not exceed 2 hours, and implements real-time response not more than 2 times a day, and each time does not exceed 30 minutes.

In the demand-side response process, when the actual response volume is less than 80% of the bid response volume, it is an invalid response and the user cannot receive response subsidies. When the actual response volume is within the range of 80% to 120% of the bid response volume, the corresponding subsidy will be calculated based on the quantity. For the part that exceeds 120% of the bid response volume, user will no longer obtain subsidy. The relevant data will be reported to the provincial power company for approval, and the approved effect evaluation data will be publicized by the demand response centre and the users will be notified after demand-side response.

At present, when the declared response volume has not reached the demand response volume within the specified time, the principle of “demand response priority, orderly power consumption guarantee” is often adopted. At the same time, the demand response centre will report to the provincial power company, which determine whether to start an orderly power management process. However, in the implementation process of orderly use of electricity, there are problems, such as lack of supporting incentive policies and measures, difficulty in implementing the plan, lack of continuous financial support for the construction and operation of the load management system and so on. This paper proposes the principle of "contracted response first, real-time response guarantees the bottom". When there is a gap capacity in the contracted response, we supplement it with real-time response. In this way, we can mobilize the enthusiasm of participating users and improve the feasibility of implementing the plan.

When a user declares a real-time demand response, after the review is passed, a resource reserve is formed. The user resource reserve can be divided into two types according to the response speed and control method, as shown in Table 1.

| User resource binning | Way to control | Responding speed               |
|-----------------------|----------------|--------------------------------|
| First gear            | Self-control   | 1 hour notice within the day   |
| Second gear           | Direct-control | Implement according to instruction within the day |

Among them, the self-control users will respond whether to participate in the response within one hour after receiving the invitation; while direct-control users are directly controlled by the response centre. The subsidy fee for direct-control users is twice that of self-control users.

2.2. Demand-side Response to Unsaturated User Competition Model

There are fewer users to participate user competition in the demand side response unsaturated stage. In order to increase the enthusiasm of users’ participation, the penalty for non-performing users will not be considered for the time being. Therefore, the estimated subsidy $F$ can be expressed as:
\[ F = \begin{cases} \sum_{i=1}^{l} c_i \cdot p_i + \sum_{j=1}^{l} m_j \cdot p & \text{if } \sum_{i=1}^{n} c_i + \sum_{j=1}^{m} m_j \geq c \\ \sum_{i=1}^{l} c_i \cdot p_i + \sum_{j=1}^{l} m_j \cdot p + \sum_{k=1}^{k} u_k \cdot 2p & \text{otherwise} \end{cases} \] 

In equation (1), \( c \) is the total demand capacity of the demand-side response for this time, \( c_i \) is the contracted response user \( i \)'s demand from the declared capacity, \( p \) is the response to user \( i \)'s offer, \( i \in \{1,2,\cdots,l\} \), and \( p \) is the subsidy that the self-controlled user can be obtained when they complete 1KW real-time response, \( m_j \) is the \( j \)-th self-control real-time response of user's declared response capacity, and \( u_k \) is the response capacity of the \( k \)-th direct-control user.

2.3. Demand-side Response Saturated User Competition Model

When the demand-side response has developed to a certain stage and the participating users have reached a certain scale, in order to give full play to the demand-side response market mechanism and explore the establishment of a power demand-side response working mechanism that adapts to the medium and long-term and spot market models, it is necessary to establish an adjustable capacity covering the demand-side The power market demand response model of bidding and electricity energy bidding will give play to the decisive role of the market in resource allocation, further enhance user load management capabilities, increase user-side peak shaving enthusiasm, and strive to build a clean, low-carbon, safe and efficient new power system. From the perspective of the demand response centre, this section constructs a weighted model of user performance priority. Users with higher priority are more likely to be selected to participate in the response.

2.3.1. Demand-side Response Saturation User Competition Model

In order to standardize user behaviour and encourage participating users to implement contracted responses in sufficient time and in sufficient quantities, this section introduces a priority mechanism. Users with higher priority have an advantage in the process of competing and participating in demand response. The priority is mainly determined by users. The performance of the contract is determined. The user performance probability can be used to quantify the user response execution effect, and it can be expressed as:

\[ \lambda = \begin{cases} 0.1 & T_i^{\text{valid}} = 0 \& T_i^{\text{total}} \neq 0 \\ \frac{T_i^{\text{valid}}}{T_i^{\text{total}}} & T_i^{\text{valid}} \geq 1 \\ 0.3 & T_i^{\text{valid}} = 0 \& T_i^{\text{total}} = 0 \end{cases} \] 

In equation (2), \( T_i^{\text{total}} \) is the number of user \( i \)'s historical participation in demand response, and \( T_i^{\text{valid}} \) is the number of times that user \( i \) participates in the demand response confirmation, that is, the number of times that the actual response volume is greater than or equal to 80% of the declared response volume. In order to ensure the competitiveness of users participating in demand response for the first time, the initial probability of performance is set to 0.3. At the same time, users who participated in the response before but whose effective response times are zero are set to 0.1.

2.3.2. Subsidy Cost Weighted Model

Generally, the existing demand-side response user selection scheme sorts the declared prices of users from low to high, and preferentially selects users with low prices. However, the demand-side response user selection scheme determined in this way cannot guarantee sufficient response volume. In this section, priority is introduced into the subsidy fee calculation model, and the declared price and priority jointly affect the probability of users being selected.
The contracted response in the case of user saturation, when the $i$-th user participates in the demand-side response, the weighted subsidy $r_i$ can be expressed as:

$$r_i = \frac{p_i}{\lambda_i}$$

(3)

Therefore, the weighted subsidy cost $R_i$ can be expressed as:

$$R_i = \sum_{i=1}^{I} x_i \cdot c_i \cdot r_i = \sum_{i=1}^{I} x_i \cdot c_i \cdot \frac{1}{\lambda_i}$$

(4)

s.t.

$$\sum_{i=1}^{I} x_i \cdot c_i \geq c$$

(5)

$$x_i \in \{0,1\}$$

(6)

$$\text{Num}_i \in \{0,1,2\}$$

(7)

$$0 \leq \sum_{j=1}^{\text{Num}_i} L_{ij} \leq 2$$

(8)

In equation (4), $x_i$ is the selection factor which is used to characterize whether the user $i$ is selected to perform demand-side response. When $x_i = 0$, it means that the demand response centre does not select user $i$ to perform demand-side response, and when $x_i = 1$, it means that the demand response centre selects user $i$ to perform demand-side response. $c_i$ is the response capacity declared by user $i$, $c$ is the total demand response volume, Num$_i$ is the number of contracted responses per day by the $i$-th user, $L_{ij}$ is the total single-day duration of the $i$-th user.

Therefore, the demand response capacity $C$ that can be completed by the demand-side response is:

$$C = \sum_{i=1}^{I} x_i \cdot b_i$$

(9)

In equation (9), $b_i$ is the actual response capacity of responding to user $i$.

3. Optimization of Subsidy Cost Weighting Model Based on Improved BPSO Algorithm

The BPSO algorithm can be used to optimize the objective function, while when the demand response capacity is close to the response capacity, it will take a very long time to run. In order to improve the convergence time, this paper proposes an improved BPSO algorithm. In the power market demand-side response environment, this paper takes the response capacity, the number of responses, and response time as constraints, and considers the impact of user declared prices and performance probability on user choices. Under the premise of meeting the demand response volume, the improved BPSO algorithm is used to obtain the best user selection strategy that minimizes the weight of the subsidy cost, that is, under the constraints of equations (5) to (8), find the user response scheme that minimizes the equation (4).

3.1. Improved BPSO Algorithm

In order to improve the problem of premature convergence of the BPSO algorithm, this paper introduces the roulette selection operator to improve the BPSO algorithm. In the view of the fact that our purpose is to find the minimum weighted subsidy cost, the roulette selection operator is appropriately improved. The smaller the fitness value, the greater the probability of being selected.

The algorithm flow chart is shown in figure 1. In summary, it can be divided into 5 parts, namely:

1) Initialization: Initialize the particle swarm (the particle swarm has M particles in total, and each particle has N dimensions): Give each particle a random initial position and velocity. Here the position of the particle corresponds to the decision factor $x_i$ in the weighted subsidy cost model, that is, when $x_i = 0$, it means that the demand response centre does not select user $i$ to perform demand-side
response, and when \( x_i = 1 \), it means that the demand response centre selects user \( i \) to perform demand-side response.

**Figure 1.** Improved BPSO algorithm flow chart.

In order to ensure the universality of the algorithm, a set of \( M \times N \) matrices composed of 0 and 1 elements are randomly generated in this paper as the initial position of the particles, where \( M \) is the population number, that is, the number of particles, and each particle corresponds to a set of solutions, and \( N \) is the dimension, that is, the number of decision variables for each particle.
The position of the particle is changed by the particle speed to complete the optimization operation. The initial velocity of each particle can be randomly generated using equation (10).

\[ v_i = -v_{\text{max}} + 2 \cdot v_{\text{max}} \cdot \text{rand}() \]  

BPSO algorithm realizes the update of particle velocity through equation (11).

\[ v_i = \omega \cdot v_i + c^1 \cdot r_1 \cdot (pBest_i - x_i) + c^2 \cdot r_2 \cdot (gBest_i - x_i) \]  

In equation (11), \( v_i \) is the velocity of the particle in the \( i \)-th iteration, \( c^1 \) and \( c^2 \) are constants, \( r_1 \) and \( r_2 \) are random numbers in the interval \([0, 1]\), \( pBest_i \) is the individual optimal particle position, \( gBest_i \) is the global optimal particle position, and \( x_i \) represents the position of the particle in the \( i \)-th iteration.

\( \omega \) is the dynamic inertia weight, which can adjust the local and global search capabilities. When the inertia weight value is large, the global optimization ability is strong, and the local optimization ability is weak. And when the inertia weight value is small, the global optimization ability is weak, and the local search ability is strong. According to the linearly decreasing weight strategy, the inertia weight \( \omega_i \) of the \( i \)-th iteration can be expressed as:

\[ \omega_i = \omega_{\text{max}} - ((\omega_{\text{max}} - \omega_{\text{min}}) \cdot G_i) \cdot g_i \]  

In equation (12), \( \omega_{\text{max}} \) is the maximum inertia weight, that is, the set initial inertia weight value, \( \omega_{\text{min}} \) is the minimum inertia weight, that is, the final set inertia weight value, \( G \) is the maximum number of iterations, and \( g_i \) is the current iteration number.

In this paper, the Sigmoid function is used to update the position of the particle according to the velocity of the particle. \( s(v_i) \) is the number in the interval \([0, 1]\) generated by the Sigmoid function which is shown in equation (13).

\[ s(v_i) = \frac{1}{1 + \exp(-v_i)} \]  

Then \( s(v_i) \) is compared with the random number generated in the interval \([0, 1]\). When \( s(v_i) \) is greater than or equal to the random number, the current position changes, that is, if the current position is 0, it changes to 1, and if it is 1, it changes to 0. And when \( s(v_i) \) is less than a random number, the current position does not change, that is, if the current position is 1, then it is 1, and if the current position is 0, it is 0, which can be expressed as:

\[ x_i = \begin{cases} 
1 & \text{if } \text{rand()} \geq s(v_i) \& x_i = 0 \\
1 & \text{if } \text{rand()} < s(v_i) \& x_i = 1 \\
0 & \text{if } \text{rand()} \geq s(v_i) \& x_i = 1 \\
0 & \text{if } \text{rand()} < s(v_i) \& x_i = 0 
\end{cases} \]  

2) Calculate the fitness value: In this stage we calculate the weight of the subsidy cost of each particle according to equation (4), and calculate the total fitness value \( \sum_{i=1}^{M} R_i \) of all individuals, then the probability of the individual being selected can be expressed as equation (15)

\[ P_i = \frac{\sum_{i=1}^{M} R_i - R_i}{(M-1) \cdot \sum_{i=1}^{M} R_i} \]  

3) Find the best fitness value of the individual and the group: For each particle, we compare the weighted subsidy cost of its current position with the corresponding subsidy cost of the best position in history (pbest) and the global best position(gbest). If the subsidy cost of the current position is smaller
than pbest, pbest will be updated by the current position. And if the subsidy cost of the current position is smaller than gbest, gbest will be updated by the current position.

4) Update particle position and speed: Then we will update the speed and position of each particle according to equation (11) and equation (14), here the roulette selection operator is introduced into the BPSO algorithm, and a roulette is constructed according to step 2): \( \sum_{j=1}^{i} p_{j}, j \in \{1,2,\ldots,M\} \). By simulating roulette to select the next round of particles, the system will generate a random number \( \kappa \), \( \kappa \in [0,1] \), if \( \sum_{j=1}^{i} p_{j} \leq \kappa \leq \sum_{j=1}^{i} p_{j} \), select individual \( i \) to enter the offspring.

5) Determine whether the end condition is met: if the end condition is not met, return to step 2, and if the end condition is met, the algorithm ends, and the global best position (gbest) is the global optimal solution.

### 3.2. Algorithm Execution Based on Blockchain Smart Contract

Blockchain, as a distributed database and decentralized P2P network, has the characteristics of smart contracts, distributed decision-making, collaborative autonomy, high security, openness and transparency of anti-tampering, etc. [11-13] Blockchain smart contracts go through five stages: negotiation, development, deployment, operation, and destruction [14]. Generally, rules are programmed through smart contracts and the contract is published on the chain. The smart contract system regularly monitors whether related events have occurred to meet the trigger conditions for contract execution [15]. In this paper, through smart contracts, the multi-objective search optimization algorithm based on the improved BPSO algorithm is run in a programmatic script to realize the equation of the demand-side response to the user's selection strategy.

When the demand response centre releases the response invitation to the contracted users through the platform, the demand response capacity, the peak price and their identifier information will be stored on the chain, so that when the scope of the invitation is expanded later, the information will not be sent repeatedly. When a contracted user participates in the response, the user ID, the declared response capacity, the declared response price, the response time period and other information are stored on the chain through the private key signature. When the amount of response exceeds the demand, the smart contract system of the blockchain is triggered. The winning user is determined by the user's declared price and contract performance probability based on the improved BPSO algorithm written into the smart contract in advance to obtain the minimization weighted subsidy fee. Then the winning bidder is notified through the platform in a timely manner, and relevant data such as the user ID, declared capacity, and declared price of the winning user are recorded on the chain. The bid-winning user carries out demand-side response during the contracted time period on the response day, and the user side automatically measures the amount of electricity during the response period. After the response, the private key will sign and store its response start time, response end time, power at the beginning of the response, and power at the end of the response on the chain. The response data is recorded on the chain, and the demand response centre monitors the load in real time according to the electric mining system. The demand response centre summarizes the user demand response data tables participating in the demand-side response, hashes the actual response capacity, subsidy fees and other data, then records them on the blockchain, and distributes them to power users for confirmation. The demand response centre conducts the Merkel tree processing on the demand response data table after the final verification, and the root hash is stored on the chain. The power company uses the public key of the subsidy bank to encrypt the financial data table and sends it to the bank. The bank uses the private key to decrypt it, and automatically transfers the subsidy fee to the account bound to the responding user on the demand-side. The bank encrypts the transfer information table with the public key of the power company, sends it to the power company, and calculates the Merkel tree of the transfer information table, and the root hash deposits the certificate on the chain. The specific flow of this process is shown in figure 2.
Blockchain has the characteristics of non-tamperable and traceable data. The whole process of demand-side response is stored in the trusted alliance chain, which not only ensures that the data on the chain cannot be tampered, but also can be traced to the source of doubtful data when necessary.

Figure 2. Blockchain-based demand-side response transaction flow chart.

4. Numerical Example Simulation

4.1. Experimental Data and Parameter Settings
Assume that 50 users respond to the request and declare their response capacity and price in a demand response. The declared capacity, declared price, historical participation response times, historical effective response times, and historical average completion percentage of these 50 users are shown in
table 2. This data is based on the relevant data of Henan electric power company’s response to unsaturated competition.

**Table 2. Report Response User Information.**

| User | Declared capacity (kW) | Declared price (yuan/kW) | Historical participation response times | Historical effective response times | Historical average completion percentage |
|------|------------------------|--------------------------|----------------------------------------|-----------------------------------|----------------------------------------|
| 1    | 10139                  | 2.29                     | 0                                      | 0                                 | 0.00                                   |
| 2    | 12814                  | 1.2                      | 9                                      | 5                                 | 0.76                                   |
| 3    | 2617                   | 1.83                     | 0                                      | 0                                 | 0.00                                   |
| 4    | 18617                  | 1.11                     | 6                                      | 3                                 | 0.81                                   |
| 5    | 13103                  | 1.91                     | 7                                      | 3                                 | 0.58                                   |
| 6    | 14492                  | 1.6                      | 4                                      | 2                                 | 0.75                                   |
| 7    | 6132                   | 1.81                     | 4                                      | 1                                 | 0.62                                   |
| 8    | 10982                  | 1.38                     | 5                                      | 2                                 | 0.68                                   |
| 9    | 8817                   | 2.43                     | 8                                      | 5                                 | 0.91                                   |
| 10   | 3098                   | 1.37                     | 4                                      | 2                                 | 0.62                                   |
| 11   | 13895                  | 1.35                     | 5                                      | 1                                 | 0.44                                   |
| 12   | 8170                   | 1.08                     | 10                                     | 4                                 | 0.67                                   |
| 13   | 17741                  | 1.1                      | 6                                      | 0                                 | 0.58                                   |
| 14   | 18635                  | 1.92                     | 2                                      | 1                                 | 0.17                                   |
| 15   | 14194                  | 1.05                     | 6                                      | 4                                 | 0.89                                   |
| 16   | 2811                   | 2.27                     | 8                                      | 3                                 | 0.64                                   |
| 17   | 2723                   | 2.19                     | 7                                      | 5                                 | 0.88                                   |
| 18   | 4405                   | 1.93                     | 6                                      | 5                                 | 0.92                                   |
| 19   | 4792                   | 1.67                     | 5                                      | 1                                 | 0.48                                   |
| 20   | 16496                  | 2.27                     | 3                                      | 2                                 | 0.86                                   |
| 21   | 9664                   | 2.31                     | 10                                     | 3                                 | 0.50                                   |
| 22   | 2454                   | 1.62                     | 6                                      | 1                                 | 0.27                                   |
| 23   | 5532                   | 1.17                     | 9                                      | 7                                 | 0.99                                   |
| 24   | 5667                   | 1.48                     | 2                                      | 2                                 | 0.89                                   |
| 25   | 15939                  | 1.78                     | 4                                      | 1                                 | 0.59                                   |
| 26   | 7120                   | 1.89                     | 4                                      | 3                                 | 0.93                                   |
| 27   | 10546                  | 2.17                     | 5                                      | 5                                 | 1.05                                   |
| 28   | 14443                  | 1.79                     | 5                                      | 1                                 | 0.56                                   |
| 29   | 7267                   | 1.88                     | 1                                      | 0                                 | 0.43                                   |
| 30   | 4234                   | 1.29                     | 2                                      | 1                                 | 0.45                                   |
| 31   | 6257                   | 1.22                     | 8                                      | 4                                 | 0.66                                   |
| 32   | 6548                   | 1.21                     | 7                                      | 3                                 | 0.66                                   |
| 33   | 18288                  | 1.8                      | 9                                      | 8                                 | 0.95                                   |
| 34   | 7047                   | 2.23                     | 7                                      | 6                                 | 0.99                                   |
| 35   | 3663                   | 2.03                     | 6                                      | 4                                 | 0.84                                   |
| 36   | 10060                  | 1.95                     | 1                                      | 1                                 | 0.80                                   |
| 37   | 7196                   | 2.28                     | 5                                      | 5                                 | 0.97                                   |
| 38   | 19519                  | 1.58                     | 4                                      | 3                                 | 0.95                                   |
| 39   | 8131                   | 1.84                     | 0                                      | 0                                 | 0.00                                   |
| 40   | 14683                  | 2.13                     | 4                                      | 4                                 | 1.01                                   |
| 41   | 6682                   | 2.28                     | 10                                     | 7                                 | 0.88                                   |
| 42   | 19634                  | 1.72                     | 3                                      | 2                                 | 0.76                                   |
| 43   | 13095                  | 1.34                     | 0                                      | 0                                 | 0.00                                   |
### 4.2. Analysis of Experimental Results

When the total number of responses declared by the contracted responding users is lower than the response volume, all responding users will participate in the demand-side response, and the insufficient part will initiate a real-time response. When the total amount of contracted response users' declaration is much higher than the demand response volume, the demand response center comprehensively considers the user's declared price, performance probability and other factors, and selects the user response plan that minimizes the weighted subsidy. If the user's offer and performance probability are the same, the user who confirms the response first will be selected.

In the experiment, the improved BPSO algorithm is used to optimize the weighted model of the subsidy cost of the demand response. The related parameter settings of the improved BPSO algorithm are shown in Table 3.

| User | Declared capacity (kW) | Declared price (yuan/kW) | Historical participation times | Historical effective response times | Historical average completion percentage |
|------|------------------------|--------------------------|-------------------------------|-----------------------------------|----------------------------------------|
| 44   | 9568                   | 1.58                     | 6                             | 2                                 | 0.54                                   |
| 45   | 7818                   | 1.26                     | 1                             | 0                                 | 0.32                                   |
| 46   | 8500                   | 1.5                      | 6                             | 3                                 | 0.68                                   |
| 47   | 7516                   | 1.42                     | 0                             | 0                                 | 0.00                                   |
| 48   | 9247                   | 1.43                     | 2                             | 0                                 | 0.34                                   |
| 49   | 8962                   | 1.18                     | 8                             | 2                                 | 0.44                                   |
| 50   | 15010                  | 2.11                     | 4                             | 3                                 | 0.96                                   |

### Table 3. improved BPSO Algorithm Parameters.

| Parameter name         | Parameter value | Parameter name         | Parameter value | Parameter name      |
|------------------------|-----------------|------------------------|-----------------|---------------------|
| total group number     | 100             | Number of iterations   | 1000            |                     |
| Particle dimension     | 50              | Maximum inertia weight | 2               |                     |
| Upper bound            | 3               | Minimum inertia weight | 1               |                     |
| Lower bound            | -3              | Social learning factor | 2               |                     |
| Maximum particle       | 1.2             | Individual learning    | 2               |                     |
| velocity               |                 | factor                 |                 |                     |

#### 4.2.1. Unsaturated Demand-side Response

When the demand-side response capacity is higher than the response capacity of the user response, real-time response is required to fill the gap in the contracted response capacity. Taking the demand-side response volume of $6 \times 10^3$ kV as an example, the total declared contracted response capacity is 494963 kW, which is lower than the demand-side response volume. In this case, all contracted demand response users participate in the contracted response, and the subsidy fee is 837306.26 yuan, and the remaining 105037 kW needs to be supplemented by real-time response. The method of user resource reserve classification has been elaborated in section 1.1 of this article. It is assumed that self-control real-time response user has declared a total response capacity of $5 \times 10^4$ kW, and the remaining 55037 kW will be completed by the direct-centre user. Assuming $p = 2.5$, the subsidy cost can be calculated by equation (1), and the cost is $F = 837306.26 + 5 \times 10^4 \times 2.5 + 55037 \times 2 \times 2.5 = 1237491.26$.

#### 4.2.2. Saturated Demand-side Response

When the demand-side response capacity is lower than the user's response capacity, this paper proposes a weighted subsidy cost model that comprehensively considers the declared price and the performance of the contract. The user participation response with low weighting is preferentially selected, and the improved BPSO algorithm is used to optimize the...
operation strategy. The plan is determined according to the weighted order of subsidies, and the BPSO algorithm is used to select users to participate in the response, referred to as Plan One. The strategy of choosing from small to large according to the smallest order of subsidy costs, hereinafter referred to as Plan Two. The strategy of choosing users with small weighting to participate in response and optimizing operation by improved BPSO algorithm is referred to as Plan Three. In order to prove the effectiveness of the proposed optimization model and algorithm, the decision response capacity, subsidy cost and probabilistic completion response capacity of the three schemes were compared.

The following analyses the decision-making response capacity, subsidy cost, and actual completion response capacity according to the probability of Plan One, Plan Two, and Plan Three under different demand response capacities.

**Figure 3.** Change curve of decision response capacity vs. response capacity.

Figure 3 shows the decision response capacity obtained by running three scenarios. It can be seen from figure 3 that the decision response volume obtained by the three schemes is higher than the demand response capacity. That is because in the sequencing process, it is difficult to obtain the capacity that exactly meets the demand. Therefore, the decision response capacity is greater than the demand response capacity. Plan One and Plan Three are more flexible in responding to user choices, while Plan Two uses the smallest order of subsidies and chooses from small to large with poor flexibility. Therefore, in most cases, the decision response capacity obtained by the Plan One and Plan Three are lower than the decision response capacity obtained by the Plan Two.
Figure 4. Change curve of expected subsidy cost with response capacity.

Figure 4 shows the change curve of the subsidy cost with the response capacity under the three operation schemes. Generally speaking, the subsidy cost increases with the increase of the response capacity. Plan Two select users from the smallest to the largest declaration cost, while Plan One and Plan Three comprehensively take declaration cost and performance probability into consideration. Therefore, not all the users with the minimum declaration cost selected by Plan One and Plan Three, so the subsidy cost of Plan One and Plan Three is generally higher than that of Plan Two.

Figure 5. Change curve of forecast actual response capacity vs. response capacity.

In figure 5, we can see the curve of the actual response capacity of users is estimated based on the user performance probability determined by equation (2). The actual response capacity increases with the increase in demand response capacity. For Plan Two, the change is basically linear, but for Plan One and Plan Three, as the demand response capacity increases, its change trend gradually slows down. That is because users with a high-performance probability have a higher probability to be
selected when the demand response capacity is low. When the demand response capacity is high, more low-performance probability users are selected, so the actual response capacity growth trend slows down.

The predicted actual response capacity in figure 5 is the estimated response capacity based on the historical completion of the selected user. If the goal is to complete the demand response, the amount of demand response that is not completed by the contracted response will be completed by the real-time response. Here, demand response capacity of $2.5 \times 10^4 \text{ kW}$ is taken as an example. The actual response capacity of Plan One is $213833.33 \text{ kW}$, which requires a real-time response of $36166.67 \text{ kW}$, and the actual response capacity of Plan Two is $155276.93 \text{ kW}$, which requires a real-time response capacity of $94723.07 \text{ kW}$. The actual response capacity of Plan Three is $217519.48 \text{ kW}$, which requires a real-time response volume of $32480.52 \text{ kW}$. Refer to section 3.2.1, we assume that the self-control real-time response users declare a total response capacity of $5 \times 10^4 \text{ kW}$, and the remaining response volume is completed by the direct-control real-time response users. The real-time response subsidy fee for Plan One is $36166.67 \times 2.5 = 90416.68 \text{ yuan}$, and the real-time response subsidy fee of Plan Two can be expressed as $50000 \times 2.5 + (94723.07 - 50000) \times 2 = 328615.35 \text{ yuan}$, and the real-time response subsidy fee of Plan Three is $32480.52 \times 2.5 = 81210.13 \text{ yuan}$. Integrating the contracted response and real-time response subsidy costs, the total cost of Plan One is $521499.65 \text{ yuan}$, the total cost of Plan Two is $670666.74 \text{ yuan}$, and the total cost of Plan Three is $505788.28 \text{ yuan}$. The total cost of Plan One and Plan Three are much lower than Plan Two.

In summary, there is no obvious difference between Plan One and Plan Three in terms of decision-making response capacity, subsidy costs, and actual completion of response capacity based on performance probability. However, in terms of convergence time, especially when the demand capacity is close to the response capacity, Plan Three is significantly better than Plan One. The details are shown in figure 6.

![Figure 6](image.png)

**Figure 6.** Convergence time vs. response capacity curve.

5. Conclusion
This article outlines the operating principles of smart contracts, combs the demand-side response transaction framework based on blockchain technology, and constructs a demand-side response user optimization algorithm. The following conclusions are obtained.

1) Demand-side response management measures and management mechanisms are still under development, and the evaluation indicators and means of demand-side response effects need to be
further enriched. Therefore, the construction of demand-side response optimization model is of vital importance to promote demand-side response effects. Different factors need to be considered in the unsaturated state and the saturated state of demand side response in the construction of optimization model, so as to obtain the response effect under different states.

2) In the demand-side response saturation competition, the risk of paying high subsidies for real-time response user response capacity can be hedged, taking account of user performance.

3) The improved BPSO algorithm is effective for the optimal user set selection under the saturation state of demand side response to obtain the subsidy cost optimization of demand-side response.

References

[1] Ni W Q and Shen J 2021 Low Carbon World 7 43-44
[2] Zheng X D, Zhang H Z, Chen H M and Li H H 2020 Contemporary Economics 7 103-109
[3] Jiang X, Qiao J, Zhang X J and Shi S Q 2018 GAS & HEAT 38 6-11
[4] Zhu L Z, Shi X B, Wang B, Ye B, Cheng Q J and Shao X Y 2020 Journal of Anhui Vocational and Technical College of Electrical Engineering 25 51-55
[5] Li B, Lu C, Cao W Z, Qi B, Li D Z, Chen S S and Cui G Y 2017 Proceedings of the CSEE 37 3691-3702
[6] Yu S Y, Yang S C, Li Y P, Geng J and Shi F 2018 Smart Power 46 43-48
[7] Ren H W and Yang Y Q 2019 Telecommunication Science 35 155-160
[8] Wang B B, Wang Q X, Li Y C, Zhao S N and Wu M 2021 Automation of Electric Power System 45 30-38
[9] Wu G, Zeng B, Li R and Zeng M 2017 Proceedings of the CSEE 37 3717-3728
[10] Gong G J, Wang H J, Zhang T, Chen Z M, Wei P F, Su C, Wen Y F and Liu X J 2018 Proceedings of the CSEE 38 6955-6966+7129
[11] Guo S T, Wang R J and Zhang F L 2021 Computer Science 48 271-281
[12] Zeng M, Cheng J, Wang Y Q, Li Y F, Yang Y Q and Dou J Y 2017 Proceedings of the CSEE 37 3672-3681
[13] Yli-Huumo J, D Ko and Choi S 2016 PLoS ONE 11
[14] Dong Z H, Lv X Q, Ren W P, Jiang Y and Li G L 2021 Data Analysis and Knowledge Discovery 5 14-24
[15] Zhu K 2021 Network Security Technology & Application 4 1-2