Optimal control model and strategy of flexible load participating in distribution network

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Abstract—The double carbon target puts forward higher requirements for end load interaction, user-side electric vehicles, air conditioners and other resources have high elastic characteristics. Their value as schedulable resources has not been fully realized, the interaction ratio is insufficient. Therefore, on the premise of ensuring user satisfaction, the elastic load control technology under load aggregator mode is used to smooth the load fluctuation of distribution network. IEEE33 node distribution system is simulated and user satisfaction model is established. The simulation results show that when the user satisfaction is greater than 80%, the elastic load can better fit the operation control value, and the average error is less than 5%, which can meet the application requirements.

1. INTRODUCTION
In recent years, there has been a large-scale power supply surplus in the domestic power industry [1]. However, due to the access of high-power loads such as air conditioning, electric vehicles and water heaters, there will still be a regional shortage of power supply. The controllable load on the user side, such as air conditioner and electric vehicle, can adjust the power demand in a short time without affecting the user's comfort [2]. A reasonable control means can reduce the peak valley difference of the system and restrain the fluctuation of new energy power generation output, which has good economic benefits. Domestic and foreign researches on orderly electricity use mostly focus on urban distribution network. Starting from the research model, it can be divided into single-layer optimization algorithm and double-layer optimization algorithm. The advantage of double-layer model is that it can describe the problem more clearly, but at the same time, the interaction between two layers will increase the complexity of the algorithm [3-4].

In reference [3], a multi-objective, hierarchical and partitioned orderly charging optimal control model is proposed, which makes the charging facility operators have the highest revenue, the lowest distribution network loss, and the voltage drop has never exceeded the limit, and can discharge in an emergency when the distribution network voltage drop exceeds the limit, so as to minimize the impact of EV load on other loads. In reference [4], discrete particle swarm optimization (DPSO) is used to solve the feasible solution of the charging and discharging plan of a single EV that meets all constraints.

Based on the urban distribution network, this paper establishes a double-layer optimization model, the upper layer is the distribution network, the lower layer is the flexible load control layer, the upper model needs to consider the fluctuation of the root node load of the distribution network, the operation control error and the user satisfaction; the lower model mainly considers the user satisfaction. According to different types of load, the customer satisfaction function is established. The customer satisfaction of electric vehicles participating in orderly electricity use is calculated according to the
upper and lower limits of charging fees and actual fees. The smaller the actual fees, the higher the customer satisfaction. The disordered electricity use satisfaction is to calculate the customer satisfaction by using the size of charging volume after the end of charging. The more the charging volume, the higher the satisfaction. The air conditioning load satisfaction is to establish a direct control load, the membership function of satisfaction degree is calculated. This method can smooth the load curve of distribution network on the premise of ensuring the satisfaction degree of users.

2. TECHNICAL FRAMEWORK OF FLEXIBLE LOAD CONTRON

Load aggregation refers to the integration of a large number of monomer controllable small loads into a simple load polymer with simple control and large adjustable capacity by using certain data methods according to the operation purpose or external environment. With the continuous improvement of the power market, there are load aggregators who are responsible for the management of load polymers. On the one hand, load aggregators can get some peak load regulation benefits by signing agreements with power companies and reducing part of peak load through flexible load control during peak hours of system load; on the other hand, load aggregators and users sign agreements in advance. The calculation formula of user's load reduction, basic load consumption, penalty measures for breach of contract and incentive electricity price, etc., so as to obtain the control right of flexible load [5].

With the emergence of load aggregator, the power operation control department can transfer the flexible load control with complex structure and large amount of operation and maintenance to the load aggregator. In order to facilitate the control of flexible loads, load aggregators can classify according to the types of loads they control. In the load aggregator mode, the implementation scheme of the control strategy is shown in Fig. 1. In Fig. 1, a load aggregator has multiple distributed control devices, and can control them according to the characteristics of flexible load. At the same time, the distribution network control center only needs to communicate with the load aggregator to control a large number of flexible loads.

![Diagram of flexible load control strategy under load aggregator mode](image)

Fig. 1 Implementation scheme of control strategy under load aggregator mode

3. TWO LEVEL OPTIMAL CONTROL MODEL

3.1 Optimal control model of distribution network layer

3.1.1 Distribution layer objective function
The objective function of the distribution network includes the standard deviation of load fluctuation at the root node of the feeder. The total load of the system includes three items: the first item is the normal
load, the second item is the flexible load, and the third item is the line loss in the grid, as shown in formula (1)

\[ F = \min F = \frac{1}{J} \sum_{j=1}^{J} (P_{\text{flex, load, } j} + P_{\text{loss, } j} + P_{\text{con, load, } j} - P_{\text{ave}})^2 \]  

Where, \( j \) is the total number of study periods; \( P_{\text{con, load, } j} \) is the regular load of \( j \) period; \( P_{\text{flex, load, } j} \) is the true value of flexible load of \( j \) period; \( P_{\text{ave, } j} \) is the average value of root node load of distribution network in all periods; \( P_{\text{loss, } j} \) is the network loss of the whole distribution network in \( j \) period. \( P_{\text{flex, load, } j} \) can be expressed as

\[ P_{\text{flex, load, } j} = \sum_{i=1}^{N_{\text{air}}} (P_{\text{cha, } i, j} - P_{\text{dis, } i, j} V_{i, j}) + \sum_{i=1}^{N_{\text{air}}} P_{\text{air, } i, j} \]  

In the formula, \( P_{\text{cha}} \) is the charging power of EV. Constant power charging is adopted for EV, i.e. the charging power is independent of the time period; \( u_{i,j} \) are the charging state of electric vehicles, 0 and 1 respectively represent the non charging and charging state; \( P_{\text{dis, } i, j} \) is the discharging power of EV, constant power discharging is adopted for EV, i.e. the discharging power is independent of the charging time period; \( v_{i,j} \) is the EV discharge state, 0 and 1 are the non discharge and discharge states respectively; \( N_{\text{air}} \) is the total number of air conditioners; \( P_{\text{air, } i, j} \) is the power consumed by air conditioners \( i \) in the period \( j \).

\( P_{\text{ave, } j} \) can be expressed as

\[ P_{\text{ave, } j} = \frac{1}{J} \sum_{j=1}^{J} (P_{\text{con, load, } j} + P_{\text{loss, } j} + P_{\text{flex, load, } j}) \]  

\[ P_{\text{loss, } j} \] can be expressed as

\[ P_{\text{loss, } j} = \sum_{(m,n)\in S} (P_{\text{in, } m,n,j} V_{m,j} V_{n,j}) \]  

Where, \( S \) is the set of all branches; \( P_{\text{loss, } (m,n)\in S} \) is \( m, n \) branch network loss. \( P_{\text{loss, } (m,n)\in S} \) can be expressed as

\[ P_{\text{loss, } (m,n)\in S}(V_{m,j}, V_{n,j}, \delta_{m,n,j}) = G_{m,n}(V_{m,j}^2 + V_{n,j}^2 - 2V_{m,j} V_{n,j} \cos \delta_{m,n,j}) \]  

Where, \( V_{m,j}, V_{n,j} \) are the voltage amplitudes at the first and last ends of node \( m \) and \( N \) branch periods respectively; \( \delta_{m,n,j}, \delta_{n,m,j} \) are the voltage phase angles at the first and last ends of node \( m \) and \( N \) branch periods respectively; \( \delta_{m,n,j} = \delta_{m,n,j} - \delta_{n,m,j} \) is the difference between the voltage phase angles at the first and last ends of branch at \( J \) moment; \( G_{m,n} \) is the real part of mutual mobility between node \( m \) and \( n \).

3.1.2 Constraints of distribution network layer

Equality constraints:

1) In the process of optimization, it is necessary to meet the balance of active and reactive power in distribution network.

\[ \begin{align*}
V_{m,j} \sum_{a=1}^{n} V_{a,j} (G_{a,m} \cos \delta_{a,m,j} + B_{a,m} \sin \delta_{a,m,j}) + P_{\text{m, } j} + P_{\text{in, } m,n,j} = P_{\text{con, } m,j} \\
V_{m,j} \sum_{a=1}^{n} V_{a,j} (G_{a,m} \cos \delta_{a,m,j} + B_{a,m} \sin \delta_{a,m,j}) + Q_{\text{m, } j} + Q_{\text{in, } m,n,j} = Q_{\text{con, } m,j}
\end{align*} \]  

Where, \( P_{\text{con, } m,j}, Q_{\text{con, } m,j} \) are the active and reactive power input by \( m \) nodes at \( j \) time; \( P_{\text{m, } j}, Q_{\text{m, } j} \) are the active and reactive load of \( m \) nodes at \( j \) time; \( P_{\text{flex, load, } m,j}, Q_{\text{flex, load, } m,j} \) are the active and reactive power of flexible load at \( j \) time; \( B_{m,n} \) are the virtual part of mutual mobility between \( m \) nodes and \( n \) nodes.

Inequality constraints:

1) Node voltage constraint

When the EV is connected to the radial distribution network, its larger charging and discharging power will seriously affect the node voltage. In order to ensure the safe and stable operation of the system, the node voltage must not exceed the limit. According to the national standard, the deviation range of power supply voltage of 20 kV and below distribution network is ± 7%.

\[ V_{m,j}^\text{min} \leq V_{m,j} \leq V_{m,j}^\text{max}, \quad m \in S_B \]  

Where, \( V_{\text{min}} \) and \( V_{\text{max}} \), are the upper and lower limits of node voltage respectively.

2) Line capacity constraints

\[
|P_{mn,j}| \leq P_{\text{max}}^{mn,j}
\]

Where, \( P_{mn,j} \) is the active power flow passing through branch m, n in period j; \( P_{\text{max}}^{mn,j} \) is maximum active power flow passing through branch m, n in period j.

3) Scheduling error constraint

\[
\eta = \frac{1}{J} \sum_{j=1}^{J} \left| P_{\text{flex-load},j} - P_{\text{flex-plan},j} \right| \leq 3\%
\]

Where, \( P_{\text{flex-load},j} \) is the adjusted load value of flexible load in period j.

4) User satisfaction constraint

\[
C_{\text{flex}} = \min(C_{\text{air}}, C_{\text{ev}}) \geq 0.8
\]

Where, \( C_{\text{air}} \) is the air conditioning load satisfaction; \( C_{\text{ev}} \) is the EV load satisfaction.

3.2 Optimal control model of flexible load layer

The flexible load control layer mainly uses the flexible load with large capacity to reduce the impact of peak load on the power grid by means of peak load shifting or low power consumption. At the same time, according to the difference of each load characteristic, the corresponding control model is established to realize the optimal interaction with the distribution network layer. The user is an important participant in promoting the construction of the power market, and the implementation of the control of the user's flexible load will also affect the comfort of the user's power consumption to a certain extent. Therefore, in order to attract more users to actively participate in the optimization and regulation of the flexible load, it is necessary to ensure that the user can obtain certain economic benefits, and improve the satisfaction of the user's power consumption as much as possible.

3.2.1 Objective function of flexible load control layer

The objective function of power consumption satisfaction in flexible load control layer includes two parts: first EV user satisfaction, second, air conditioning user satisfaction. Two calculation methods of flexible load satisfaction are given below.

1) Satisfaction model of electric vehicle

The EV users who participate in the orderly use of electricity are most concerned about the economy of charging and discharging. They have low requirements for the timeliness of charging. At the same time, due to the long time of access to the power grid, the final battery capacity can generally be guaranteed. Therefore, for the orderly use of electricity users, a satisfaction model is established based on the economy of user charging. The operation cost of orderly EV mainly includes two parts: first, charging cost; second, battery loss cost caused by participating in grid regulation. According to the electricity cost of each user, the membership function of electricity satisfaction can be established as

\[
C_{\text{ev}} = \begin{cases} 
1 & F_{i,j} = F_{i,j}^{\text{max}} \\
\frac{F_{i,j}^{\text{max}} - F_{i,j}}{F_{i,j}^{\text{max}} - F_{i,j}^{\text{min}}} & F_{i,j}^{\text{min}} < F_{i,j} < F_{i,j}^{\text{max}} \\
0 & F_{i,j} < F_{i,j}^{\text{min}} 
\end{cases}
\]

In the formula, \( F_{i,j}^{\text{max}} \) it is the maximum charging cost of the i electric vehicle; \( F_{i,j}^{\text{min}} \) it is the minimum charging cost of the I electric vehicle; \( F_{i,j} \) it is the satisfaction of the I electric vehicle’s orderly use of electricity; \( F_{i,j} \) it is the charge and discharge cost of the i electric vehicle, because there will be certain differences in the daily access of the EV to the network, therefore, the daily cost of the same EV will fluctuate accordingly.
It can be seen from equation (11) that the user cost of orderly use of electricity consists of two parts: charging cost and discharge revenue. To minimize the charge and discharge cost of orderly use of electricity, the following two points should be met simultaneously:

First, the cost of charging is the smallest: all charging periods are low rate periods; second, the benefit of discharging is the largest. Literature [6] gives a comparison table of battery loss of a certain type of EV under different discharging depths. When charging in the valley price period and discharging in the peak price period, one charging and discharging can obtain a benefit of 0.28 yuan. When the depth of discharge is less than 19.8%, the battery loss in each discharge cycle is less than 0.28 yuan, that is to say, when the depth of discharge is less than 19.8%, the positive return can be obtained, that is to say, when the depth of discharge is 19.8%, the maximum return can be obtained. Therefore, the minimum charge and discharge cost is that all charging periods are low rate periods, and the number of discharges reaches the critical value of positive benefits.

2) Air conditioning load satisfaction model

In the constant frequency air conditioning control, it needs to meet the user’s temperature requirements, that is, the indoor temperature meets the range agreed in advance. The constant frequency air conditioning maintains the indoor temperature within the set range by controlling the start and stop of the compressor. The lower the indoor temperature setting is, the higher the proportion of the compressor start-up time to the whole operation time is, the more power is consumed during operation. For the k-th group of air conditioning load, the calculation formula of continuous on and off time of air conditioning in J period is as follows

$$
\tau_{on,k}(j) = \left\lfloor \tau_{on,k}(j-1) + [1 - s_k(j-1)] \mu_j \right\rfloor [1 - s_k(j)] \\
\tau_{off,k}(j) = \left\lceil \tau_{off,k}(j-1) + s_k(j) \mu_j \right\rceil s_k(j)
$$

In the formula, $\tau_{on,k}(j)$ is the continuous opening time of J time; $\tau_{off,k}(j)$ is the continuous closing time of J time; $S_k(j)$ is the controlled state of J time. When the value of $S_k(j)$ is 1, it means that the air conditioning of group k is controlled, that is, the air conditioning is off. When the value of $S_k(j)$ is 0, it means that the air conditioning of group k is not controlled, that is, the air conditioning is on.

In direct load control, $\tau_{off}$ and $\tau_{on}$ correspond to two constraints respectively. $\tau_{off}$ is the process of load interruption in each group. In order to ensure the user comfort, it is required that the controlled time of each load shall not be too long, and each group of load shall report its maximum continuous interruptible time. $\tau_{on}$ is to limit the frequent start and stop in the process of load control, otherwise it will seriously affect the service life of the load. Therefore, the minimum continuous operation time of each load should also be reported. In the process of implementing direct control, the following constraints should be met

$$
\begin{align*}
\tau_{on} & \geq \tau_{on,\text{min}} \\
\tau_{off} & \leq \tau_{off,\text{max}}
\end{align*}
$$

Where $\tau_{on,\text{min}}$, $\tau_{off,\text{max}}$ are the maximum continuous interruptible time and the minimum continuous operation time respectively. According to the theory of fuzzy set, the fuzzy membership function is established by using continuous running time and continuous controlled time, and then the user satisfaction is expressed by using the fuzzy membership function. Then the satisfaction models of the k-th group load to the continuous controlled and continuous power supply operation in j period are as follows

$$
C_{off,k}(j) = \begin{cases} 
1 & 0 < \tau_{off,k}(j) < \tau_{off,\text{best}} \\
\frac{\tau_{off,k}(j) - \tau_{off,\text{best}}}{\tau_{off,\text{max}} - \tau_{off,\text{best}}} & \tau_{off,\text{best}} \leq \tau_{off,k}(j) < \tau_{off,\text{max}} \\
0 & \tau_{off,k}(j) \geq \tau_{off,\text{max}}
\end{cases}
$$
In the formula, \( \tau_{\text{off},k,\text{best}} \) and \( \tau_{\text{off},k,\text{max}} \) are respectively the best continuous controlled time length and the maximum continuous controlled. \( \tau_{\text{off},k,j}(j) \) is time length of the load in group \( k \); \( \tau_{\text{on},k,\text{best}} \) and \( \tau_{\text{on},k,\text{min}} \) are respectively the best continuous power supply operation time length and the minimum continuous power supply operation time length of the load in group \( k \) in period \( j \); \( \tau_{\text{on},k,j}(j) \) is the length of continuous power supply operation for the load of group \( k \) in period \( j \). Then the comprehensive satisfaction function of users is

\[
C_{\text{air},k}(j) = s_j(j)C_{\text{off},k}(j) + (1 - s_j(j))C_{\text{on},k}(j)
\]

Since the state of load \( K \) is unique (controlled or uncontrolled) at a certain time, equation (18) determines that the user's satisfaction at a certain time is determined by either the controlled time or the uncontrolled time. In the whole control process, the average satisfaction degree of group \( k \) air conditioning load users in the whole research period is

\[
C_{\text{air},k} = \frac{\sum_{j=1}^{J} C_{\text{air},k}(j)}{J}
\]

Parameter determination method in customer satisfaction model of constant frequency air conditioning

![State transition diagram of constant frequency air conditioner](image)

Fig. 2 state transition diagram of constant frequency air conditioner

The operation state of the air conditioner can be obtained by using the thermal power model as shown in Fig. 2 [7]. It can be seen from Fig. 2 that the continuous control time of the air conditioner cannot exceed \( \tau_{\text{off}} \), otherwise the user's room temperature will exceed the limit. Therefore, \( \tau_{\text{off},\text{max}} \) is set as \( \tau_{\text{off}} \) in the figure, that is, the time required for the user's indoor temperature to rise from the lowest temperature to the highest temperature. When only considering the temperature to the user, the shorter the controlled time is, the better, that is, \( \tau_{\text{off},\text{min}} \) is zero. The optimal value of \( \tau_{\text{on},\text{best}} \) of the continuous operation time is set to \( \tau_{\text{on}} \), that is, the time when the room temperature drops from the highest temperature to the lowest temperature. Frequent start and stop will cause great damage to the service life of the air conditioner. Therefore, the value of \( \tau_{\text{on},\text{min}} \) is set to be \( 1/3 \) of \( \tau_{\text{on},\text{best}} \).

3) Temperature range restriction of load of group air conditioner for constant frequency air conditioner users
\[
\sum_{j=1}^{J} \frac{\tau_{i,j}^{on}}{\tau_{i,j}} \geq \frac{\tau_{i,j}^{on}}{\tau_{i,j}} \sum_{j=1}^{J} \tau_{i,j}^{off} (j) \neq 0
\]  

Where, \( \tau_{i,j}^{on} \) is the number of open states corresponding to the set temperature; \( \tau_{i,j}^{off} \) is the number of closed states corresponding to the set temperature.

4) User satisfaction constraint

\[
\begin{cases}
C_{air} > C_{air}^{min} \\
C_{ev} > C_{ev}^{min}
\end{cases}
\]

Where, \( C_{air}^{min} \) is the lower limit of air conditioning load user satisfaction; \( C_{ev}^{min} \) is the lower limit of EV load satisfaction.

4. Solution flow

In this paper, the interaction between the flexible load control layer and the distribution network layer is solved by two-level optimization. First, the distribution network sends operation control instructions to the flexible load control layer according to the daily load curve, and the particle swarm optimization algorithm is used to issue the operation control instructions. Second, the flexible load control layer receives the operation control instructions and charges the EV according to the operation control instructions. Discharge: the flexible load control layer charges and discharges the orderly electric vehicles according to the way of "economic priority and capacity leading", and participates in peak load cutting and valley filling while ensuring the interests of users to the greatest extent; for the disordered users, the principle of minimizing the charging time is adopted. Because the control of air conditioning load adopts the direct control method, the difference between the control cycle of 1 min and the operation control cycle of EV is quite large.

5. Simulation analysis of a numerical example

In reference [8], the orderly charging strategy is established, but the orderly charging users are not considered to participate in grid regulation through V2G, and the influence of disordered users is not considered.

5.1 parameter setting

Taking a large residential area as an example, its power supply mode is radial feeder network, which is connected with EV load and conventional load. The IEEE33 node feeder network shown in Fig. 3 is used for simulation. See table C1 in Appendix C for its network parameters and conventional load data, and table C2 in Appendix C for its conventional load data. The flexible load is connected to the grid from node 5. The number of electric vehicles is 100, and the charging power is 3 kW. As a controllable load, the air conditioning load is separated from the conventional load. The air conditioning parameters are: the number of constant frequency air conditioners is 40, which are divided into four groups for wheel control. The rated power of a single air conditioner is 2.5 kW, and the set temperature is 25 °C, then \( \tau_{off, max} = 9, \tau_{off, min} = 2, \tau_{on, best} = 4 \); There are 40 sets of variable frequency air conditioners, which are controlled by four groups. The power adjustment coefficients are \( \pm 0.15 \) and \( \pm 0.25 \) respectively when the temperature range is \( T_{best} = 25 \) °C, \( T_{max} = 27 \) °C, \( T_{min} = 23 \) °C, and the temperature adjustment range is \( \pm 0.2 \) and \( \pm 0.4 \) °C. The regulation period of air conditioning load is 20:00-24:00 during the peak period of power consumption, from which the regulation period is 1 hour and the regulation period is 1 min.
5.2 Simulation analysis results

1) Influence of different scenes on load curve

There are many factors influencing the load curve of the power grid. In this paper, the factors such as no / orderly charging ratio of electric vehicles, air conditioning load, customer satisfaction and other factors are mainly considered, and four different power use scenarios are set, as shown in Table 1.

Table 1: Contents considered in different scenarios

| Scenario   | Disordered power consumption | Orderly use of electricity | Air conditioning load | Two-layer optimization | Air conditioning satisfaction | EV satisfaction |
|------------|------------------------------|---------------------------|----------------------|------------------------|-------------------------------|-----------------|
| Scenario 1 | 70% disorder                 | 30% order                 | /                    | /                      | /                             | /               |
| Scenario 2 | 100% disorder                | /                         | /                    | /                      | /                             | /               |
| Scenario 3 | 70% disorder                 | 30% order                 | /                    | /                      | consider                      | 80%             |
| Scenario 4 | 70% disorder                 | 30% order                 | /                    | /                      | consider                      | larger than 80% |

Scenario 1: consider the ratio of with / without charging and the constraints of the distribution network layer;
Scenario 2: all electric vehicles are the constraints of disordered power consumption and distribution network layer;
Scenario 3: using the two-level operation control model established in this paper, but not considering the air conditioning load;
Scenario 4: using the two-layer operation control model established in this paper, taking into account the air conditioning and EV load.

It can be seen from Table 2 that the power consumption mode of scenario 2 increases the peak valley difference, which makes the utilization ratio of power resources decrease. Compared with scenario 2, the other three power consumption modes can reduce the peak load and improve the level of system valley load. Among them, scenario 4 power consumption mode improves the peak valley characteristic of load curve most obviously.

Table 2: Comparison of system load level indicators in different scenarios

| Original load | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---------------|------------|------------|------------|------------|
| Peak load/kW  | 2459       | 2597       | 2640       | 2525       | 2533       |
| Valley load/kW| 1660       | 1687       | 1660       | 1687       | 1699       |
| Peak-to-valley difference/kW | 799 | 910 | 980 | 838 | 835 |

Comparing scenario 1 and scenario 3, scenario 1 does not consider the double-layer optimization, just to meet the operation parameters of the distribution network without exceeding the limit, and does not consider the optimal operation of the entire distribution network. When 30% of the electric vehicles participate in the orderly use of electricity, the distribution network has enough capacity to meet the...
charging of all the electric vehicles with different charging methods. At this time, the satisfaction of the EV charging can be as high as 100%, greater than 80% of its requirements. Scenario 3 needs to restrain the fluctuation of distribution network load in the process of two-layer optimization, which will limit the charging behavior of some electric vehicles during the peak load period. Therefore, it will cause charging failure of some electric vehicles, especially the impact on the charging satisfaction of disordered electric vehicles. At this time, the satisfaction of electricity consumption is 80%, which is lower than that of scenario 1.

Comparing scenario 3 and scenario 4, because the air conditioning load participates in the mediation, the peak-valley difference in scenario 4 is reduced, and the satisfaction of the four sets of fixed frequency and inverter air conditioning loads are: 0.8181, 0.8046, 0.7917, 0.7847; 0.835, 0.815, 0.835 and 0.855, the air conditioning load satisfaction degree is 0.8174.

2) Comparison between operation control value and real value of flexible load

Fig. 4 is the comparison of the distribution network's issued operation control value of the flexible load with its real load value. From Fig. 4 it can be seen that EV can better prepare the operation control value issued by the distribution network, The average error is less than 5%, which can meet the application requirements.

6. CONCLUSION

A two-layer optimal operation control model is established. The upper layer is the distribution network, and the lower layer is the flexible load control layer. The upper layer model needs to consider the distribution network load fluctuations, user satisfaction and flexible load operation control errors; the lower layer model mainly considers users satisfaction. Studies have shown that the two-layer model optimization can better fit the operation control value under the premise of ensuring the user's power consumption satisfaction, and achieve the purpose of smoothing the load fluctuation of the distribution network. The average error is less than 5%, which can meet the application requirements.

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