Interruptible load resource pool optimized scheduling technology for multi-scenario requirements

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Abstract. This paper firstly discusses the organization form of interruptible load resource pool, and analyzes the economic benefits of demand response and the timeliness of interruptible load. Secondly, under the premise of ensuring safe and stable operation of power grid, a scheduling strategy with dynamic planning in different scenarios is proposed. At last, the effectiveness of the interruptible load resource pool optimal scheduling technology is verified by the scheduling of temperature-controlled loads, electric vehicles (EV) and energy storage (ES) device.

1. Introduction

With the advancement of China's urbanization process, electric power replacement strategy and frequent emergence of extreme weather, the continuous and rapid growth of elastic loads such as air conditioning loads, electric vehicles (EVs) and energy storage (ES) devices will become a long-term trend. According to statistics, during the peak summer load, the air-conditioning load of first-tier cities, such as Beijing, Shanghai, and Guangzhou, has accounted for 50% of the peak load, while the air-conditioning load of most other cities has accounted for 30% to 40% of the peak load, and the historical record is constantly refreshed. At the same time, with the development of terminal power control technology, distributed generation, ES, EVs and other distributed resources constantly connected to the power grid, the load side begins to have power characteristics, and the difficulty of balancing power supply and demand continues to increase, and more efficient regulation mechanisms are required.

In January 2017, China National Development and Reform Commission issued the "13th Five-Year Plan for Energy Development", recommending the implementation of energy demand response enhancement projects to enhance the flexibility and adaptability of users to participate in energy supply and balance adjustment. Research and practices at home and abroad have also proved that the implementation of rapid response and flexible adjustment of elastic loads is conducive to maintaining the stability of the power system, improving the power grid's absorption capacity to renewable energy, reducing the peak-to-valley difference of the power system, and delaying the construction investment of the power grid.

Reference [9] proposes an economic optimal scheduling model based on risk quantification, aiming at the problem of optimal utilization of emergency reserve capacity in integrated energy system. Reference [10] investigates the demand response behavior of some typical industry users, and
concludes that the user demand response behavior is mainly influenced by the characteristics of enterprise production, related incentives and prices. Reference [11] proposes an economic dispatch model of active distribution network based on information gap decision theory by considering demand response and coordinated charging of EVs. The power loss cost, penalty cost of distributed generation power curtailed, power purchasing cost from upper grid and penalty cost related to the peak-to-valley difference are considered simultaneously in the model. Reference [12] forms a multi-terminal central air conditioning demand response model by combining the characteristics of central air conditioning demand response, and proposes a control strategy based on local terminal temperature regulation, which can realize different control accuracy. Reference [13] analyses the importance of demand-side frequency modulation and established a large number of temperature-controlled load aggregation models, and adjusts the working status of temperature-controlled loads based on load forecasting to provide auxiliary services for power system frequency adjustment. Reference [14] proposes a building peak-shaving potential evaluation model and a building flexible load day-ahead peak-shaving scheduling model. By combining and optimizing the response external characteristic curves of different building flexible loads after the peak-shaving plan is executed, the combined optimization result can meet the system peak shaving target within the total peak shaving capacity of the building. Reference [15] proposes a coordinated wind power accommodation dispatch model based on combined heat and power(CHP) considering thermal storage and EVs, and break the grid coupling relationship between electricity and heat by controlling the thermal storage and energy storage.

In summary, the existing research mainly focuses on single load modelling or load scheduling strategy research in a single application scenario. The coordinated scheduling research for multiple types of flexible loads in multiple scenarios is still in its infancy.

2. Analysis of the economic benefits of interruptible load resource pool

2.1. Cost optimal scheduling strategy decision mechanism of interruptible load resource pool

The cost and benefit of interruptible load resource pool optimal scheduling strategy is an important consideration for power company to carry demand response scheduling. In the non-emergency scenario, if the benefit of the interruptible load resource optimal scheduling is greater than the cost of interruptible load resource optimal scheduling, the interruptible load resource pool optimal scheduling strategy is implemented, and vice versa, the strategy is not implemented.

The cost of the power company is mainly the system cost, including the system operating cost and the construction cost of the input for the interruptible load resource pool optimal scheduling strategy, and the cost of the user is mainly the cost of participation, including the investment in the interruptible load resource pool facility device and the cost of responding the scheduling.

The benefits of implementing an interruptible load resource pool optimal scheduling strategy mainly include direct benefits on the user side and indirect benefits and other benefits for the entire power engagement user. Direct benefits can be generally measured in monetary terms, and indirect and other benefits are more difficult to measure in monetary terms.

2.2. Analysis of the economic benefits of interruptible capacity library resources

2.2.1. Economic benefits of interruptible load resource pool for incentive-based demand

Firstly, power company contracts with the user, when the dispatch center sends a signal to the user to the interruptible load, the user should consciously respond to the load curtailment\textsuperscript{[10]}. In addition to the load curtailment compensation provided to the user, the power supply revenue of the power company is reduced accordingly, so the incentive demand response cost is the revenue of the power company before the demand response minus the demand response, including the user's response compensation and the reduction of power revenue.

Before the incentive load response, the power company's revenue is shown in Equation (1).
\[ C_{I,n,t}^{\text{pre}} = r_p \cdot q_{IB,n,t} \]  

(1)

Where the subscript I in \( C_{I,n,t}^{\text{pre}} \) refers to the incentive demand response (the symbol below refers to the same), \( r_p \) is a fixed retail electricity price, and \( q_{IB,n,t} \) is the electricity load of the incentive load access point n at t-time before the demand response.

![Figure 1. relationship between marginal benefit and electricity consumption](image)

The compensation cost of the incentive load response is calculated according to the loss of the load curtailment. The marginal cost of reducing electricity use by the user is generally regarded as linear, as shown in Figure 1. The user’s cost of load curtailment response can be derived as a secondary function, so that if the incentive load is reduced by \( q_{IB,n,t} \), compensation to the user by the power company can be represented by Equation (2).

\[ C_{\text{comp}}^{\text{comp}} = K_{1n} \cdot q_{IB,n,t}^2 + K_{2n} \cdot q_{IB,n,t} \]  

(2)

Where, \( K_{1n}, K_{2n} \) are respectively the secondary term coefficient and the first term coefficient of compensation to the incentive load n.

After the incentive loads response, the revenue of power company can be represented by Equation (3).

\[ C_{I,n,t}^{\text{after}} = r_p \cdot (q_{IB,n,t} - q_{I,n,t}) - C_{I,n,t}^{\text{comp}} \]  

(3)

Therefore, the cost of incentive demand response can be represented by Equation (4).

\[ C_{I,n,t} = C_{I,n,t}^{\text{after}} - C_{I,n,t}^{\text{comp}} \]  

(4)

Combining (1-4), the cost of incentive demand response is a secondary function of load curtailment, as shown in Equation (5).

\[ C_{I,n,t} = a_{I,n,t} \cdot q_{I,n,t}^2 + b_{I,n,t} \cdot q_{I,n,t} + r_p \]  

(5)

Where, \( a_{I,n,t}, b_{I,n,t} = K_{1n}, K_{2n} \).

Similar to conventional generators, the incentive demand response should also meet certain constraints in the scheduling process. The constraints of the incentive demand response mainly include the load curtailment upper and lower limit constraints, the minimum duration of load curtailment and the minimum time interval constraint of load curtailment and the total number of curtailment constraints during the scheduling cycle.
the upper and lower limit constraints of the load curtailment can be represented by Equation (6)

$$0 \leq q_{i,n,t} \leq q_{i,n,max} \cdot U_{i,n,t}$$  \hspace{1cm} (6)

Where, $q_{i,n,max}$ represents the maximum load curtailment of the $n$th excitation load, $U_{i,n,t}$ represents the state amount of the $n$th excitation load at $t$-time, $U_{i,n,t}=1$ indicates that the user is called to participate in the demand response at $t$-time, $U_{i,n,t}=0$ indicates that this user is not called at $t$-time to participate in the demand response.

Load curtailment minimum duration and load curtailment minimum interval constraints can be represented by Equation (7)

$$U_{i,n,t} = \begin{cases} 
1 & \text{if } T_{i,n,t}^{on} < T_{i,n}^{on} \\
0 & \text{if } T_{i,n,t}^{off} < T_{i,n}^{off} \\
0 \text{ or } 1 & \text{others} 
\end{cases}$$  \hspace{1cm} (7)

Where, $T_{i,n,t}^{on}$, $T_{i,n,t}^{off}$ are the continuous response time at $t$-time and the cumulative time of the non-participation demand response of the incentive demand $n$, respectively, the minimum response time of the $n$th excitation load and the shortest time interval for the two demand response events, respectively.

The total number of reduction constraints can be represented by Equation (8).

$$U_{i,n,t} + \sum_{t=1}^{T} U_{i,n,t} \cdot (1-U_{i,n,t-1}) \leq P_{i,n}$$  \hspace{1cm} (8)

Where, $P_{i,n}$ represents the maximum responses of the $n$th excitation load in scheduling period $T$.

### 2.2.2. Economic benefits of interruptible load resource pool for price-based demand

The user's demand for electricity is strongly related to the electricity price, with the increase of electricity price, the user's demand for electricity decreases, the demand and electricity price has a counter-proportional relationship\(^{[17]}\). By linearizing the user demand curve, the power elasticity coefficient can be represented by Equation (9).

$$\lambda = \frac{\Delta q_{i}}{q_{0}} / \frac{\Delta r_{p}}{r_{p}}$$  \hspace{1cm} (9)

Where, $\Delta q_{i}$ represents the implementation of the load curtailment after the time-sharing tariff, $\Delta r_{p}$ represents the amount of price change, $q_{0}$ is the load capacity, $r_{p}$ is the base price, $\lambda$ is the price elasticity coefficient.

There are two modes of time-sharing tariff response for users, single-time response and multi-time response. Single-time response is the user's demand for electricity is only related to the price of electricity in a single time period. Multi-time response is the user's demand for electricity for a certain period of time is not only related to the price of electricity in a single period, but also related to the price of electricity for the rest of the day, because the user's electricity reduction will be transferred to another time. To simplify the demand response cost model, single-time response modelling is used, with the known elasticity factor of demand, the relationship between the user's electricity curtailment and the price of electricity changes can be represented by Equation (10).
Where, the subscript 0, 1 indicates the electricity price pre- and post-adjustment, T indicates the moment.

Before the price load response, the revenue of the power company can be represented by Equation (11).

\[
C_{P,k,t}^{\text{pre}} = r_p \cdot q_{PB,k,t}
\]

(11)

Where, the subscript p in \(C_{P,k,t}^{\text{pre}}\) refers to the price-type demand response (which appears later refers to the same), \(r_p\) is the fixed electricity price of retail side, \(q_{PB,k,t}\) refers to the baseline load for the price load.

After the price-based load response, the electric power company's revenue can be represented by Equation (12).

\[
C_{P,k,t}^{\text{after}} = R \cdot (r_p + \Delta r_{P,t}) \cdot (q_{PB,k,t} - q_{P,k,t})
\]

(12)

Where, \(R\) indicates the discount on electricity prices by encouraging users to participate in demand response. \(\Delta r_{P,t}\) denotes the change of the electricity price at t-time. \(q_{PB,k,t}\) denotes load curtailment amount of the kth price-based load at t-time. When the price of electricity increases, the user's demand for electricity decreases, and the user's demand for electricity increases when the price of electricity decreases, therefore, \(\Delta r_{P,t}, q_{PB,k,t}\) can be positive or negative.

The elasticity coefficients are available according to the demand price, as shown in Equation (13).

\[
\Delta r_{P,t} = \frac{q_{P,k,t} \cdot r_p}{q_{PB,k,t} \cdot \lambda}
\]

(13)

The cost for the price-based demand response can be represented by Equation (14).

\[
C_{P,k,t} = C_{P,k,t}^{\text{pre}} - C_{P,k,t}^{\text{after}}
\]

(14)

Combine equations (12)-(14), the price-type load response cost of the power company is a secondary function of the load curtailment amount, as shown in Equation (15).

\[
C_{P,k,t} = a_{P,k,t}q_{P,k,t} + b_{P,k,t}q_{P,k,t} + c_{P,k,t}
\]

(15)

Where, \(a_{P,k,t} = \frac{R \cdot r_p}{\lambda \cdot q_{PB,k,t}}\); \(b_{P,k,t} = R \cdot r_p (1 - \frac{1}{\lambda})\); \(c_{P,k,t} = (1 - R) \cdot r_p \cdot q_{PB,k,t}\).

The price-based demand response only needs to meet the tariff adjustment constraints in response to the tariff, as shown in Equation (16).
\[
\Delta r_{\text{min}} \leq \Delta r_{p,t} \leq \Delta r_{\text{max}}
\]  

(16)

Where, \( \Delta r_{\text{min}}, \Delta r_{\text{max}} \) represents minimum and maximum tariff adjustments, respectively.

Convert the adjustment amount of electricity price into the load response amount constraint, the price-based demand elasticity Equation can be obtained, as shown in Equation (17).

\[
\frac{\Delta r_{\text{min}} \cdot q_{P,k,t}}{r_p} \leq \frac{\Delta r_{\text{max}} \cdot q_{P,k,t}}{r_p}
\]  

(17)

2.3. Timeliness analysis of interruptible load resource pool

The time-sensitive resources of the interruptible load resource pool are mainly influenced by the control mode between the power company and the user, and the control mode of power company to the user's load mainly includes direct load control and interruptible load control.

Under the direct load control mode, the operation of interruptible load resource is directly controlled by the power company. When the emergency scenario occurs, the power grid company can turn on/cut off the load directly. The interruptible load resource has the fastest response speed, within the control second and millisecond levels.

Under the interruptible load control mode, the operation of interruptible load resource is controlled by the user. The power company has a contract with the user, which can be divided into minute-level spinning reserve and minute-level non-spinning reserve according to the user's response speed.

2.4. Interruptible load resource pool scheduling technology adapted to multi-scenario requirements

2.4.1. Interruptible load resource pool reservation technology

The interruptible load resource pool can be regarded as a call library consisting of various types of interruptible load groups, which are directly connected to the load aggregator and maintain the continuous adjustable state of the load under the support and monitoring of communication technology. Depending on the scenario, the load aggregator selects the right resource to respond quickly. It is necessary to select a certain amount of load-side resources reserved to ensure the safe operation of the power grid.

In practice, each interruptible load can be regarded as a prepared resource, all resources can be consolidated into the interruptible load resource pool. For each interruptible load, its dispatchable state is not fixed, and may be transferred between dispatchable and unscheduled states for a variety of reasons, as shown in Figure 2.

![Resource reservation status and migration](image)

Figure 2. Resource reservation status and migration
2.4.2. Response process of interruptible load resource pool with scenarios
First, the dispatch center determines whether the current grid state is stable by analysing and diagnosing the situational awareness results. If it is determined or predicted that the power grid has an emergency failure, a control plan is issued to restore safety indicators such as frequency, voltage, and reactive power. It should be pointed out that when the interruptible load participates in the emergency control of the power grid, it is necessary to set a higher starting threshold than the traditional automatic devices such as low frequency and low voltage load shedding. When implementing specific adjustments to interruptible loads, since the time scale required for emergency scenarios is relatively strict, the interruptible loads with good communication are preferred for adjustment.

If it is not an emergency control scenario, it is determined whether the power grid is currently in an increase or decrease scenario. First of all, it is necessary to determine the optimal target curve of the control amount according to the interruptible load adjustable potential within the jurisdiction of the dispatch center or aggregator. Then, according to the actual economy, volatility minimization and other goals, the global optimization goal of regulation is formulated. The load groups participating in the regulation are determined based on the load usage characteristics and power consumption behavior prediction results in the full-time domain. Finally, adjust and control in sequence according to the order of interruptible load.

In the response, the scenarios are not completely isolated, but have alternating relationships based on a situational awareness. Under the scenario situational awareness, the system automatically determines whether it is urgent or not. In case of emergency, control directly according to the emergency scenario plan. Otherwise, the dispatcher will judge the specific demand scenario and make a choice. Emergency scenarios may switch to peak-shaving and valley-filling scenarios or clean energy consumption scenarios with the elimination of key fault points. Peak-shaving and valley-filling scenarios and clean energy consumption require real-time monitoring of the situation with scenarios switching based on the needs of different time periods.

The resources in the interruptible load resource pool and the demand situation of the grid are dynamically changing over different periods of time, so it is significant to plan the resources for each time period according to the different needs of the grid, taking into account the safety and reliability of the grid[18,19].

3. Simulation examples and analysis

3.1. Simulation examples
This section uses interruptible load resource pool optimal scheduling technology based on dynamic planning technology to plan the scheduling resources to meet the needs of different scenarios for response speed, response cost, response capacity, and response time. The simulation is initialized with 15min as a cycle, and the resources are scheduled at 1min for a period of time. The simulation parameters are shown as Table1.

| Table 1. The parameters used in the simulation   |
|-----------------------------------------------|
| Number | Optimal range | Charge-discharge power (W) | Response cost | Control type | Response speed |
|------|--------------|-----------------|--------------|-------------|---------------|
| 400  | 22°~30°      | 1000~5000       | Medium       | Interruptible load control | Medium       |
| 300  | Fully charged| 4000            | Low          | Interruptible load control | Medium       |
| 300  | 0.2<Soc[20]  | 3000            | High         | Direct control            | Fast         |
3.2. Simulation result analysis

3.2.1. Analysis of load coordinated schedule under multi-scenario demand
The load coordinated scheduling effect under the multi-scenario response demand is shown in Figure 3. The green curve represents the target consumption, and the red curve represents the combined consumption amount. The two curves are basically fitted, indicating that the multi-type load coordinated schedule can fully meet the needs of the specific scenario. The remaining three curves represent electric water heater(EWH), electric vehicle(EV) and energy storage(ES) device in the process of scheduling. Because of their difference sesame in the time domain characteristics and function characteristics, in non-emergency scenarios, EVs and EWHs have a higher priority than ES device, but EVs and EWHs are only capable of dissipation, ES device at the same time with the capacity to eliminate the capacity and reduction capacity. And due to the time limit, EVs will focus on a certain period of time.

![Figure 3. Resource reservation status and migration](image)

3.2.2. State change analysis during typical load dispatch
The study selects 400 EWHs, 300 EVs, 300 ES devices, in the process of scheduling, the state of various types of load changes as shown in Figure 4 to 6. As can be seen from Figure 4 to 6, the temperature of the EWH in the scheduling process is always maintained in the comfortable temperature range of 22 to 30 degree and EVs can reach the desired state when they leave. Because some electric vehicles have a long charging time, a centralized charging phenomenon appears in 6:00 to 10:00. During this time period, the load charging demand is greater than the consumption demand, so the ES devices discharge. After 12:00, except ES devices, the charging demand of other loads decrease, and the ES devices charge, and the ES devices are charged to meet the demand for cancellation in different scenarios.

![Figure 4. Temperature of electric water heater](image)
3.2.3. Analysis of interruptible resources during the demand response

Figure 7 shows the comparison between the scheduled resource capacity reserved for each time period throughout the day by dynamic planning technology and the actual scheduling capacity. In order to meet the scenario scheduling needs to the maximum extent possible, more resources are allocated for the time period when the capacity demand is greater. Figure 8 shows the reserved quantity and actual scheduling number of EWHs, EVs and ES device in each time period throughout the day. The coordinated scheduling combination for each time period is obtained according to the needs of the scenario and the various types of load reservation under the scenario.

Figure 7. The capacity of resources allocation and the amount of resources requirement
3.2.4. Multi-scenario load response demand analysis

Figure 8. The quantity of resources allocation and the amount of resources requirement

Figure 9. Response speed and response cost of scheduling resources in multiple scenarios

Figure 9 shows the response cost and response speed of the load scheduling at various time periods throughout the day. The higher the response cost degree, the smaller the response cost, the higher the response speed degree, and the faster the response speed. In the simulation case, the feature membership under the emergency scenario is defined as the response speed, and the load group response speed in the emergency scenario that can be seen in the Figure is obviously higher than that of other scenarios, which can meet the needs of the emergency scenario. The difference between the new energy consumption scenario and the peak averting and valley filling scenario is different from the energy supplied, and the target aims to match the consumption/reduction capacity to the maximum extent on the premise that the response cost is minimal. The required response capacity is entered in the simulation, and the corresponding cost of the scheduling load group in both scenarios is lower than that of the emergency load control scenario.

4. Conclusion

This paper studies the optimal scheduling technology for the interruptible load resource pool for multi- scenarios. The research results show that the coordinated scheduling of multiple types of loads can fully meet the needs of the scenario. The dynamic planning technology can reserve and allocate more resources for time periods with high capacity requirements, which can meet the scenario scheduling
requirements as much as possible. In the emergency scenario, the response speed is the feature membership, and the response speed of the load group is significantly higher than other scenarios. Both the new energy consumption scenario and the peak averting and valley filling scenario are aimed at matching the absorption/reduction capacity to the greatest extent under the premise of ensuring the minimum response cost, the difference between them is that they are different from the energy supplied.

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