An Optimization Strategy for Intra-day Demand Response Based on Security Constraints

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Abstract. Demand response (DR) has become an effective means to deal with renewable energy integration and load fluctuations in the power system. This article first analyzes the classification and characteristics of controllable resources used in DR. Secondly, taking into consideration the transferable load, interruptible load and the energy storage system in DR, an intra-day scheduling model is then established based on safety constraints. Finally, a case is studied to analyze the role of DR in improving system safety and reducing operating costs. Results show the effectiveness of this model.

1. Introduction
In a modern power system, DR is one of the effective measures to optimize the operation of the power system. According to different beneficial mechanisms, DR can be divided into price-based and incentive-based, regardless of the above classification, the core of DR is to improve the system's utilization. Currently, much progress has been made on DR. A data-based Stackelberg market strategy for DR participants is proposed in [1] to coordinate dispatch among different demand-side resources. Incentive-based DR is incorporated in optimal dispatch problems to enhance the flexibility of the demand side in [2]. Reference [3] studies the energy trading mechanism among various DR aggregators. The multi-energy-based DR scheme and the corresponding optimization model are established in [4] to minimize dispatching expenses. In [5], the agent-based modelling and simulation method is used to explore the impact of DR on the electricity market. Reference [6] proposes a layered stochastic optimization approach for residential DR under real-time pricing and an incentive-based mechanism. To alleviate real-time congestion within distribution networks, a two-tier DR scheme is proposed in [7] with flexible demand swap and transactive control for real-time congestion management in distribution networks. However, as traditional generators are gradually replaced by renewable energy sources, the randomness in modern power systems increases, resulting in the increment of peak-to-valley load difference and posing challenging to intra-day power system operation. Therefore, it is necessary to study the optimization strategy for intra-day demand response.

2. Demand-side Resource Classification and Characteristics
This article combines user types and response characteristics, taking industrial loads as transferable loads, and non-industrial loads like temperature control load as reducible loads.
2.1. Industrial Load
The main characteristics of industrial load are large load capacity, high-reliability requirements, no seasonal influence, and small fluctuations in load curves. Previous studies usually took the entire industrial load as a rigid load to participate in the collaborative analysis of the energy Internet, while paying little attention to various industries. Due to the differences in the production lines of different factories, industrial loads may have certain complementary characteristics.

2.2. Temperature Control Load
Temperature control load is the most potential non-industrial load, among which the air conditioning load is the major one that dominates the residential municipal and commercial electricity consumption, with energy conversion and storage characteristics. The air conditioning load can be reasonably controlled within the user's optimal comfort temperature demand range, thereby increasing system flexibility and reducing the peak-to-valley difference.

2.3. Energy Storage System (ESS)
According to the characteristics of charging and discharging, the DR service provided by ESS can be divided into up-regulation response and down-regulation response. When the system power is higher than the power at the balance point, indicating that ESS is charging, namely down-regulation response. On the other hand, ESS is discharging, namely up-regulation response.

3. Intra-day Scheduling Model Based on Security Constraints
The power system dispatch is mainly based on power forecasting. Due to the randomness of renewable energy resources and the volatility of load, there is bound to be a certain power deviation. With the shortening of the time scale, the forecast errors for renewable energy and load are also reduced. In terms of it, this paper proposes an intra-day scheduling model based on security constraints, which optimizes the active power of the system within one hour.

3.1. Objection
In this paper, the minimum cost is set as the objective function, and the penalty cost to indicate the wind curtailment in the power system. The equation is as below

$$\min \sum_{t=1}^{T} C_{\text{gen}}(t) + C_{\text{bat--pu}}(t) + C_{\text{load--trans}}(t) + C_{\text{load--cut}}(t) + C_{\text{punish}}(t)$$

Among them,

$$C_{\text{gen}}(t) = \sum_{t=1}^{T} \sum_{i=1}^{NG} \left( a_i P_{Gi,t}^2 + b_i P_{Gi,t} + c_i \right) + S_{Gi} u_{Gi,t} \left( 1 - u_{Gi,t-1} \right) + \left( \gamma_{Gi}^+ R_{Gi,t}^+ + \gamma_{Gi}^- R_{Gi,t}^- \right)$$

Where $C_{\text{gen}}(t)$ represents the total cost of conventional units in period $t$, $P_{Gi,t}$ represents the output of the $i$th conventional unit in period $t$. $a_i$, $b_i$, $c_i$ represent the fuel cost coefficient of an $i$th conventional unit, $NG$ is the number of conventional units, $S_{Gi}$ is the start-up cost, $u_{Gi,t}$ is the start-stop state of the $i$th conventional unit at moment $t$, $\gamma_{Gi}^+$ and $\gamma_{Gi}^-$ represent the positive/negative spinning reserve capacity cost coefficients of an $i$th conventional unit, $R_{Gi,t}^+$ and $R_{Gi,t}^-$ represent the positive/negative spinning reserve capacity provided by the $i$th conventional unit.

$$C_{\text{bat--pu}}(t) = \sum_{t=1}^{T} \sum_{k=1}^{npu} S_{puGk} u_{puGk,t} \left( 1 - u_{puGk,t-1} \right) + S_{puPr} u_{puPr,t} \left( 1 - u_{puPr,t-1} \right)$$
Where, \( C_{bat-pu}(t) \) represent the total cost of the pumped storage system in period \( t \), \( S_{puGk}, S_{puPk} \) are the start-up cost of pumped storage power generation state and pumped state, \( u_{puP,t}, u_{puG,t} \) are the binary variables of the pumping state and power generation state of the pumped storage power station at moment \( t \).

\[
C_{\text{load-trans}}(t) = \sum_{t=1}^{T} \sum_{s=1}^{N_L} \left( c_{\text{TL}}^+ P_{\text{TL},s,t}^- + c_{\text{TL}}^- P_{\text{TL},s,t}^+ \right) \Delta t
\]

Where, \( C_{\text{load-trans}}(t) \) represent the total cost of controllable loads moment \( t \), \( P_{\text{TL},s,t}^- \) and \( P_{\text{TL},s,t}^+ \) indicate the transferable load’s in and out the amount, \( c_{\text{TL}}^+ \) and \( c_{\text{TL}}^- \) indicate the transferable load’s in and out cost coefficient.

\[
C_{\text{load-cut}}(t) = \sum_{t=1}^{T} \sum_{s=1}^{N_L} \left( 1 + P_{\text{cut},t}^f P_{\text{cut},t}^r \Delta t \right) \cdot \lambda_{\text{cut},t} \cdot P_{\text{cut},t}^f \Delta t
\]

Where, \( C_{\text{load-cut}}(t) \) represents the total cost of interruptible load in period \( t \), \( P_{\text{cut},t}^f \) represents the system load amount in period \( t \), \( \lambda_{\text{cut},t} \) represents the load price in period \( t \), \( P_{\text{cut},t}^r \) is the interrupted load in period \( t \).

\[
C_{\text{punish}}(t) = \sum_{t=1}^{T} \lambda_{\text{punish},t} \cdot P_{\text{wind},t}^\text{Wcur,t}
\]

Where, \( C_{\text{punish}}(t) \) indicates the total cost of paying fines for wind curtailment in period \( t \), \( P_{\text{wind},t}^\text{Wcur,t} \) represents the amount of wind curtailment in period \( t \), \( \lambda_{\text{punish},t} \) is the penalty corresponding to the wind curtailment.

3.2. Constraints

3.2.1. Power balance

\[
\sum_{i=1}^{NG} P_{\text{Gi},t} + \sum_{k=1}^{N_P} P_{\text{puGk},t} + P_{\text{wind},t} + P_{\text{punish},t} + \sum_{s=1}^{N_L} P_{\text{TL},s,t}^- = P_{\text{L},t}^f + \Delta P_{\text{ess},t} - P_{\text{cut},t}^r + \sum_{k=1}^{N_p} P_{\text{puK},t}^r
\]

Where, \( P_{\text{wind},t} \) represent the intra-day forecast of wind power, \( P_{\text{L},t}^f \) represent the intra-day forecast of load, \( P_{\text{puK},t}^r \) represent intra-day pumping power in period \( t \), \( P_{\text{puGk},t} \) represent intra-day power generation in period \( t \).

3.2.2. Conventional Units and Pumped Storage Power Stations

Due to the limitation of the length of the article, the specific constraint formulas for conventional units and pumped storage power plants can be found in reference [8] and reference [9].

3.2.3. Transferable load

The transferable load generally needs to meet the transferable period, the upper and lower limits of the transferred load, the balance of the transferred load, and the upper limit of the total transfer amount.

\[
\begin{align*}
& z_{\text{TL},s,t}^- P_{\text{TL},s,t}^+ \leq P_{\text{TL},s,t}^r \leq z_{\text{TL},s,t}^+ P_{\text{TL},s,t}^- \\
& z_{\text{TL},s,t}^- P_{\text{TL},s,t}^+ \leq P_{\text{TL},s,t}^r \leq z_{\text{TL},s,t}^+ P_{\text{TL},s,t}^-
\end{align*}
\]

(8)
Where, \( z_{\text{TL},x,t}^+ \) and \( z_{\text{TL},x,t}^- \) represent the transfer-in and transfer-out status of the transferable load respectively, and it is 0 when it is not transferred, \( P_{\text{TL},x,t,\text{max}} \) and \( P_{\text{TL},x,t,\text{min}} \) indicate the upper/lower limit of load transferring in, \( P_{\text{TL},x,t,\text{max}}^r \) and \( P_{\text{TL},x,t,\text{min}}^r \) indicate the upper/lower limit of load transferring out.

### 3.2.4. Interruptible load

In addition to price constraints, interruptible loads also have dispatch time constraints, the purpose of which is to prevent interruptible loads from continuously utilizing.

\[
0 \leq P_{\text{curt},t} \leq \eta_{\text{max}} P_{\text{d},t}, 0 \leq \frac{P_{\text{curt},t}}{P_{\text{d,t}}} + \frac{P_{\text{curt},t+1}}{P_{\text{d,t+1}}} \leq \eta_{\text{cut}}^{\text{max}}
\]

(9)

Where, \( \eta_{\text{max}} \) represents the maximum dispatch rate of controllable load in a single period, \( \eta_{\text{cut}}^{\text{max}} \) is the maximum continuous dispatch rate.

### 4. Case study

#### 4.1. Background

Take an actual park in a province of China as an example. Among them, there are 5 thermal power units, see Table 1 and reference [8] for specific parameters; 2 pumped storage units, see reference [9] for specific parameters; The day-ahead and intra-day forecasts of power and load are shown in Figure 2 and Figure 3; suppose that the transferable industrial load transfer cost in the park is 100 yuan/MW, the maximum transfer volume is 100MW, and the minimum transfer volume is 50 MW; interruptible temperature-controlled residential load interruption cost is 80 yuan/MW, and the maximum interruption is 100MW; wind curtailment cost is 500 yuan/MW.

#### Table 1. Basic information about thermal units

|       | Maximum output /MW | Minimum output /MW | Ramping rate MW/min |
|-------|-------------------|--------------------|---------------------|
| Gen1  | 110               | 50                 | 5.0                 |
| Gen 2 | 100               | 50                 | 6.0                 |
| Gen 3 | 300               | 90                 | 5.9                 |
| Gen 4 | 220               | 75                 | 5.9                 |
| Gen 5 | 200               | 50                 | 5.8                 |

Figure 1. day-ahead and intra-day load forecast

Figure 2. day-ahead and intra-day wind forecast
4.2. Intra-day DR analyzation

Using the Gurobi solver based on Matlab2019a to deal with the model, results can be shown in Figure 3 and Figure 4. Figure 3 shows the output of 5 conventional thermal power units, and Figure 4 shows the specific adjustments of the controllable resources involved in DR during the day. In this case, the load curve is a typical bimodal curve. Obviously, there are load fluctuations around 8:00-12:00 and 19:00-21:00, so the positive DR is mainly concentrated in these periods. The load curve is at a trough in the early morning, but at this time the wind power capacity still maintains a certain level of output. Meanwhile, since the start-stop costs of the second and fifth units are relatively high, it is necessary to avoid the switch of the unit as much as possible. Therefore, there are some negative DR and a small amount of wind curtailment in the low period of load demand.

In Figure 4, it is obvious that the transferable load shifts from the two peak load moments during the early morning. Since this kind of industrial load is best to start and stop automatically, some industrial loads can be put into operation in the early morning to reduce the peak demand of the system during the daytime. At peak hours, some interruptible loads participate in DR, to maintain the comfort and satisfaction of users, their capacity is not that large and cannot be operated so frequently. Furthermore, both pumped storage power stations are pumped during low-load periods and generate electricity during peak hours. However, the second one has adjusted much amount of power involved in DR due to its lower cost. Besides, the wind curtailment curve shows that there is an obvious wind curtailment moment
at around 23:30, the reason can be summarized below: 1. there is a considerable difference in the forecast error between intra-day and day-ahead time scale 2. the temperature control load almost stops working within this period 3. the pumped storage power station cannot adjust the charge/discharge state fast enough. Nevertheless, the impact of them is not that serious, reducing the wind curtailment by about 5%.

5. Conclusion
This paper analyzes the controllable resources that can participate in the DR, and studies the optimization problem on the intra-day time scale of the power system. The results of calculation examples verify the effectiveness of the model. The following conclusions are obtained from the results of the calculation example:

(1) According to the characteristics of different industrial production, some industrial loads with obvious changes in the curve can be selected as transferable loads to participate in the DR of the system.

(2) Under the condition of ensuring user comfort, the temperature load participates in the DR of the system as an interruptible load, which can effectively increase the safety of the system and reduce operating costs.

(3) By studying the intra-day DR, it is determined that the fluctuation of the system load curve caused by the inaccurate forecast can be reduced, and the system's ability to absorb renewable energy can be improved.

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