Construction of automatic demand response dynamic model for distributed new energy consumption

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Abstract. Based on the current situation of demand side management in China, considering the output characteristics of new energy, this paper analyzes various influencing factors of automatic demand response from the aspects of user response mode, power consumption characteristics, response time, load economy, etc. Taking energy storage air-conditioning users as an example, the paper uses real-time electricity price as demand response incentive measure for demand regulation, and verifies the implementation effect of the optimal response strategy of electricity price incentive.

1. Introduction

With the proposal of "30 • 60 Double Carbon Target", renewable energy in China will realize the transformation from "auxiliary energy" to "main energy" and become an important role in the energy field. However, the large-scale installation of renewable energy represented by wind power and photovoltaic will have a certain impact on the power grid. At the same time, the power consumption on the load side also shows a seasonal peak load rising trend, which aggravates the peak regulation pressure of the power grid. The exploration and research of demand response technology will not only help to clarify the characteristics of energy consumption on the load side in China, tap the potential of demand response of all kinds of loads, but also alleviate the phenomenon of abandoning wind and light, support the large-scale development and utilization of new energy such as wind and light, and accelerate the process of achieving the goal of carbon peak and carbon neutralization.

Since the development of demand response in my country started late compared to developed countries in Europe and the United States, only peak and valley electricity prices are currently implemented in most cities, while peak electricity prices and interruptible loads are still in the trial and exploration stage [1]. Fewer demand response projects, weak technology, and lack of project practical experience hinder the further in-depth and comprehensive development of demand response in my country. In terms of Auto-DR technology, my country has just started, and its development momentum is good, but it lacks an organization dedicated to the research and development of new Auto-DR technology [2]. Domestic power companies have realized that the formulation of DR technical standards will help promote equipment manufacturers, product application companies, service providers and other units to develop related products and services, attract more power users to participate in DR projects, and reduce power consumption and electricity cost, resulting in huge environmental benefits and social benefits.
2. Analysis of factors affecting user's automatic demand response

2.1. Load adaptability and user response
The possibility of users participating in automatic demand response (providing demand-side resources) depends on the user's ability to ensure the comfort of terminal demand and the ability to use electricity at a certain level in the event of a power outage or partial reduction in demand. To this end, it is necessary to measure this ability of users from the following factors: the final service provided by the electric load (such as heat, kinetic energy, electronics, etc.); energy storage capacity; load dispatching equipment; and the cost of changing demand. The first three items are technical requirements for users to adjust electricity usage, and the last item is economic requirements. The difference in technical and economic requirements of user load determines its response to different incentive measures. The user's response behavior to the stimulus signal is not limited to the behavior of load shedding. If the electricity is only cut off, it will have a great impact on industrial production and the comfort of residents' electricity consumption [3]. In order to avoid such serious adverse effects, users can respond according to the electricity price information according to the way they use electricity: interruption of electricity, transfer of electricity, alternative energy, energy storage, etc.

2.2. User response cost
The cost that a user pays to change his own way of using electricity in response to an incentive signal based on demand is defined as user response cost. Although there is not a complete and precise description of the meaning of demand-side resources (DSR), the understanding of it is not far away. Generally, the meaning of demand-side resources is interpreted as: by optimizing the configuration of power demand, the reduced power consumption and power demand on the demand side are regarded as a general term for equivalent supply resources that can meet power demand.

Demand side resource participation in automatic demand response requires cost, user's power interruption cost:

\[ C = C(\theta, Q, t, t_i, t_d, f) \]

Where \( C() \) is the user's power response cost; \( \theta \) is the type of data of the user; \( Q \) is the user's interrupt power; \( t \) is the time type of interruption; \( t_i \) is the duration of the electric interruption; \( t_d \) is load interrupt Inquiry time; \( f \) is the number of load interrupt. When the excitation of the demand response is the price excitation, the last three physical quantities do not work.

For interrupt contracts under the same physical conditions, the user is facing the same advance notification time, interrupt duration, interrupt time, and considering the case of interrupting once, it is determined that the main factor of user terminal cost is the type of user and the electricity consumption of the interrupt is \( C = C(\theta, Q) \).

2.3. User type and electrical properties
There are all kinds of electricity users in the power system, which can be classified from different perspectives. From the perspective of the user body, it can be divided into industrial users, urban residents, commercial users, agricultural users, and other users. Resident users are mainly the household appliances load of urban residents [4]. Commercial and industrial users are loads that serve commerce and industry. Agricultural users are the collective term for all loads in rural areas, including rural civil electricity, electricity for production, drainage and irrigation, and rural commercial electricity. Other users include municipal electricity, public utility electricity, government office electricity, and railway electricity.

The user's ability to respond to demand depends on its electrical characteristics. How can users automatically adjust their own electricity consumption methods to achieve optimal electricity consumption, with the lowest electricity purchase costs and the greatest compensation [4]. To study the optimal response of users to electricity prices, the basic method is to establish an optimal response model according to various load types, and the actual user load is a combination of these basic loads. Taking
electricity price incentive measures as an example, through the analysis of three types of typical power user load optimization response models, the relationship between user power characteristics and automatic demand response capabilities is revealed.

(1) Users with storage capacity
Some air conditioners, electric heating devices and electric water heating systems in large hotels, shopping malls and factories have certain heat storage capacity. Companies that have their own power plants also fall into this category. For users with storage capacity, the load optimization response model is:

\[
\begin{align*}
C_{op} &= \min \left[ \sum_{k=1}^{N} \rho_k \times E_k \right] \\
\text{s.t. } X_{k+1} &= X_k + E_k - W_k \\
X_N &= X_0 \\
0 \leq X_k &\leq X_{\text{max}} \\
P_k &\geq 0
\end{align*}
\]

In the formula: \( C_{op} \) is the optimized total cost, in yuan; \( k \) is the sequence of electricity price changes, and the total number of electricity price changes is \( N \); \( \rho_k \) is the electricity price in the period, yuan/kWh; \( X_0 \) is the initial energy storage; \( X_k \) is the energy in the \( k \) period Storage capacity, kWh; \( X_{\text{max}} \) represents the maximum energy storage capacity, kWh; \( E_k \) represents the maximum energy consumption, kWh; \( W_k \) represents the electric energy consumed during production in the \( k \) period, kWh. Equation (3) indicates that when the system is in the low period, that is, when the \( k \) period is in the evening, \( W_k \) is small, then \( E_k \) is mainly used for energy storage; and when the system is peak, the electric energy \( E_k \) obtained from the system is small, and the production consumption \( W_k \) is taken from the energy storage \( X_k \). According to this formula, it is not difficult for users to determine the optimal use of electric energy for each electricity price period. Due to the existence of energy storage \( X_k \), users have reduced more electricity and demand during peak periods to achieve the goal of demand response. This type of load is the most suitable type for automatic demand response. It can participate in both TOU price and IL incentives.

(2) Subsequent load
Some industrial load production processes have strict process restrictions. A production process must be after another production process and cannot be transferred. If this type of demand is to respond to electricity prices, the overall demand level must be reduced, which will have a greater impact on enterprises. The optimization process is as follows:

Assuming that \( Q_1, \ldots, Q_m \) is the power consumption of each period of \( m \) production processes, \( I_j^k \) represents a day divided into \( k \) periods, \( k = 1, \ldots, n \) (represents a day divided into \( n \) time periods, \( n \) electricity prices), \( j \) represents the decision variable of the production process, \( j = 1, \ldots, m \) (represents a day’s production process divided into \( m \) processes), \( n \geq m \), \( I_j^k \) or 0 indicate whether the load is working in a certain process.

The load optimization model of this type of user is expressed as:

\[
\begin{align*}
C_{opt} &= \min_{I_j^k, \forall j \neq k} \left( \sum_{k=1}^{n} \rho_k \times \sum_{j} I_j^k Q_j \right) \\
\text{s.t. } & I_j^k \leq \sum_{i=1}^{k-1} I_j^i \leq \sum_{i=1}^{k-2} I_j^i \ldots \leq \sum_{i=1}^{k-1} I_j^i \\
& \sum_{k=1}^{n} I_j^k = 1
\end{align*}
\]
Equation (8) establishes the load sequence, and equation (9) represents that a certain procedure is executed once in any production process. The definition of $\rho_k$ is the same as before.

(3) Simple transfer load

The staff can shift the electricity load by shifting. This is the most common industrial load condition. Suppose the amount of load transferred from stage $k$ to stage $j$ is $Q_{kj}^T$, the unit cost transfer fee for re-arrangement of production and personnel arrangement is $C_{kj}$, the original electric energy of each stage is $Q_k$, the electric energy adjusted by the transfer is $Q_k^T$, and the production stage is divided into $n$ section, $k = 1, \ldots, n$.

The load optimization model of this type of user is expressed as:

$$C_{opt} = \min \left\{ \sum_k \left( \rho_k Q_k^T - \sum_j \rho_j Q_{kj}^T \right) \right\}$$

s.t. $Q_k^T = Q_k \sum_j (Q_{ji}^T - Q_{ij}^T)$

1. $Q_{k\min} \leq Q_k^T \leq Q_{k\max}$
2. $\sum_j Q_{kj}^T \leq Q_{j\max}^T$
3. $\sum_j Q_{kj}^T \leq Q_{j\max}^T$
4. $P_{kj}^T \geq 0$

In the formula, $Q_{k\min}$ represents the minimum power consumption of $k$ at a certain stage, kWh, which is related to equipment capacity; $Q_{k\max}$ represents the maximum power consumption of $k$ at a certain stage, kWh, which is related to equipment capacity; $\rho_j$ represents the electricity price of stage $j$, yuan/kWh. Equations (13) and (14) represent the maximum transferable electrical energy at a certain stage, which is related to the production process.

2.4. User response time

When power users with different load characteristics participate in Auto-DR’s response measures, the Auto-DR implementing agency will participate with the power users at the time agreed in the contract. Related to the response time in the contract are the advance notice time and the duration of the interruption.

(1) Advance notice time

The advance notice time refers to the timeliness of the response, and it is a key factor in solving the Auto-DR problem. In some cases, a very advanced notice can mitigate the expected losses in the future. The advance notice time has a great impact on the power outage loss of users, and the advance notice time is often specified as an important parameter in interruptible load operation. In general, the shorter the notice in advance, the higher the compensation for interrupted load.

(2) Power outage duration

The duration of a power outage is also an important parameter for users to lose from a power outage. Interruptible load operation often requires clear regulations on the duration of a power outage. Industrial users are the main body implementing interruptible load management. For electricity users participating in the time-of-use electricity price response measures, it is through the use of low electricity prices to achieve the purpose of reducing production costs by transferring part of the load during peak hours to low times. For power users participating in interruptible load response measures, the duration of the power outage is selected and determined according to the signed interruptible contract. Generally, the longer the power outage time, the greater the total loss of users, but the smaller the unit loss, frequent short-term power outages will cause great losses to users.
2.5. User load urgency

When the load is tight during the peak hours of power consumption, measures such as peak shifting and peak avoidance are used to ensure the normal power consumption of the entire region, and implement power restriction measures according to the nature and reliability of the user's work. When there is a power gap, firstly, ensure that the party and government organs, residents' lives, schools, troops, hospitals and other important units and urban infrastructure use electricity, and secondly, ensure flood prevention and drought resistance, and summer crops. At the same time, industrial electricity must be taken into account, especially for The 30 key enterprises that account for 70% of the total industrial economy in the local area are guaranteed to use as much electricity as possible, and high-energy-consuming enterprises that do not comply with the national industrial policy are strictly restricted, and the production and use of electricity by enterprises that do not install load monitoring devices are strictly controlled. Therefore, it is necessary to rank users according to load importance.

(1) First class load

The first type of load is important users related to the national economy and people’s livelihood. These users have high requirements for the reliability of power supply. Generally, power outages or power restrictions are not allowed. If the power supply is interrupted, it will cause personal injury and death, equipment damage, social disorder and major economic problems. Loss etc. Such users are willing to pay high prices to ensure the reliability of their power supply, and build their own security power supply to solve reliability problems when necessary.

(2) Second class load

The second type of load is also a relatively important user. This type of user has higher requirements for the reliability of power supply. If the power supply is interrupted, it will cause production shutdown, product scrap, traffic jams, and greater economic losses.

(3) Third class load

The three types of load refers to all other loads other than the second class load. Such load users have low requirements on the reliability of power supply. If the power supply is interrupted, the loss caused is not large. Power outages and poor power quality only affect product output, not product quality and damage to production equipment.

3. Example analysis

Taking the energy storage air conditioner user as an example, the real-time electricity price is used for demand response incentives to regulate the demand control, verify the response effect of the optimized response strategy for the electric price incentive.

The objective function of optimal control is to minimize the user's electricity charge, that is:

\[ C = \min \sum P Q \]  
\[ \text{s.t. } 0 \leq Q_i \leq Q_{\text{max}} \]  
\[ T_{\text{min}} \leq T_i \leq T_{\text{max}} \]  
\[ T_{\text{ihi}} = \varepsilon T_i + (1 - \varepsilon)(T_{\text{out}} - \eta Q_i / A) \]  

In the formula, \( C \) represents the electricity cost of the air-conditioning load; \( T_i \) represents the indoor temperature in the i-th hour; \( T_{\text{min}} = T_{\text{ideal}} - d \), \( T_{\text{max}} = T_{\text{ideal}} + d \), \( d \) is the acceptable temperature deviation; \( Q_i \) represents the electricity consumed by the air-conditioning in the i-th hour, kWh; \( P_i \) represents the electricity price in the i-th hour, yuan/kWh; \( T_{\text{out}} \) represents outdoor temperature.

The calculation process uses slack variables, which can be solved by linear programming:

\[ T_{\text{max}} \geq \varepsilon T_i + (1 - \varepsilon)(T_{\text{out}} - \eta Q_i / A) \]  
\[ Q_i \geq A / \eta[(\varepsilon T_i - T_{\text{max}})/(1-\varepsilon) + T_{\text{out}}] \]  
\[ Q_i = A / \eta[(\varepsilon T_i - T_{\text{max}})/(1-\varepsilon) + T_{\text{out}}] + S^2 \]  
\[ T_{\text{min}} \leq \varepsilon T_i + (1 - \varepsilon)(T_{\text{out}} - \eta Q_i / A) \]
\[
Q_i = A/\eta[(\varepsilon T_i - T_{\text{num}})/(1-\varepsilon) + T_{\text{out}}] \\
Q_i = A/\eta[(\varepsilon T_i - T_{\text{num}})/(1-\varepsilon) + T_{\text{out}}] - S^2
\]

(24)

(25)

Table 1. Variable value and description

| Variable | Numerical value | Description | Variable | Numerical value | Description |
|----------|-----------------|-------------|----------|-----------------|-------------|
| T0/℃     | 22              | Indoor initial temperature | A/(kW °C⁻¹) | 0.18            | Thermal Conductivity |
| η         | 2.5             | Air conditioning efficiency | T_{\text{out}}/℃ | 31              | Outdoor temperature |
| Qᵢ/kWh   |                 | Air conditioning power consumption in the i-th hour | T_d/℃ | 21              | Ideal indoor temperature |
| Q_{max}/kWh | 3.5             | Air conditioning maximum output electricity hourly | T_{\text{min}}/℃ | 20              | Minimum acceptable indoor temperature |
| ε         | 0.96            | Cooling function | T_{\text{max}}/℃ | 24              | Upon acceptable indoor temperature |
| T_c/h     | 25              | Time constant | T_i/℃ | 22              | Current indoor temperature (i=0) |
| τ/h       | 1               | Control interval |

In the formula, the quantities are shown in Table 1. From 8:00 to 21:00, the comparison of the optimized air conditioning power consumption costs is shown in Table 2. The total power consumption is equal to the constant temperature regulation mode, and the daily savings of the total electricity consumption are 10%. During the 8h period when the electricity price was the highest, the air conditioning load of users was reduced by 19.4% without exceeding the room temperature adjustment range.

Table 2. Calculation results

| Time | Time-round price | Outdoor temperature/ ºC | Constant temperature regulation | Controllable regulation |
|------|------------------|--------------------------|---------------------------------|-------------------------|
|      | yuan/kWh         |                          | Indoor temperature/ ºC | Power consumpt | Electric i-ty charge | Indoor temperature/ ºC | Power consumpt | Electric i-ty charge |
|      |                  |                          | i-on (kWh)               | i-on (kWh)     | /yuan                 | /kWh               | /yuan               |
| 08:00| 0.2              | 31                       | 22                       | 0.648         | 0.1296                | 20.00              | 2.0096              | 0.4019               |
| 09:00| 0.2              | 31                       | 22                       | 0.648         | 0.1296                | 20.33              | 0                  | 0                    |
| 10:00| 0.4              | 33                       | 22                       | 0.792         | 0.3168                | 20.57              | 0.338               | 0.1352               |
| 11:00| 0.4              | 33                       | 22                       | 0.792         | 0.3168                | 20.80              | 0.4911              | 0.1964               |
| 12:00| 0.75             | 35                       | 22                       | 0.936         | 0.702                 | 20.99              | 0.6247              | 0.4685               |
| 13:00| 0.75             | 35                       | 22                       | 0.936         | 0.702                 | 21.18              | 0.6744              | 0.5058               |
| 14:00| 0.75             | 35                       | 22                       | 0.936         | 0.702                 | 21.36              | 0.6772              | 0.5079               |
| 15:00| 0.75             | 35                       | 22                       | 0.936         | 0.702                 | 21.49              | 0.6675              | 0.5006               |
| 16:00| 0.75             | 35                       | 22                       | 0.936         | 0.702                 | 21.61              | 0.6693              | 0.5020               |
| 17:00| 0.75             | 34                       | 22                       | 0.864         | 0.648                 | 21.58              | 0.693               | 0.5198               |
| 18:00| 0.75             | 31                       | 22                       | 0.648         | 0.486                 | 21.52              | 0.7253              | 0.5440               |
| 19:00| 0.75             | 31                       | 22                       | 0.648         | 0.486                 | 21.31              | 0.7838              | 0.5879               |
| 20:00| 0.4              | 30                       | 22                       | 0.576         | 0.2304                | 20.93              | 1.002               | 0.4008               |
| 21:00| 0.4              | 30                       | 22                       | 0.576         | 0.2304                | 21.24              | 1.2977              | 0.5191               |
| Total |                  |                          |                          | 10.872        | 6.4836                | 10.6536            | 5.7898              |
It can be seen from Table 2 that the user's demand response can be used to reduce the user's load curve. In the real-time market, the price of electricity can be reduced, and under the incentive of TOU, the purpose of peak cutting can be achieved.

**Conclusion**

In short, the basic condition of a real-time demand response project is user response. Only when users have response characteristics can incentives work. This article starts with the basic characteristics of user response, analyzes user response methods and response costs, and proves the feasibility of users participating in demand response projects from a physical and economic point of view; analyzes the response optimization models of different types of users, and uses calculations. An example proves that after adopting an optimized response strategy, it can not only obtain economic benefits, but also alleviate the social pressure.

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