Home energy management method for realizing demand response based on virtual power plant platform

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Abstract Demand-side management is an important measure to reduce peak load. This paper proposes a home energy management strategy based on a virtual power plant platform to achieve demand response. Ordinary household users respond to the electricity prices or incentives provided by the interactive platform of the virtual power plant, and adjust the time-transferable loads such as air conditioners, water heaters, and electric cars in the home to achieve the effect of reducing electricity expenditure while meeting the demand for electricity. The validity of the proposed method is verified by a numerical example.

1. Introduction
In recent years, the cumulative duration that the peak load more than 95% in China's annual continuous load curve is only about ten hours. It is uneconomical to rely solely on increasing the capacity of the peak-shaping generator set to meet this peak load. By managing the electricity consumption of residential users, it can reduce the peak load of the power grid and provide auxiliary services for the distribution network [1].

There are already some achievements in the optimization of family costs. Some researchers aimed to reduce the peak-to-valley ratio of household electricity consumption curves, optimized the electricity consumption of controllable devices within the household, and proposed a family load optimization strategy based on machine learning [2-3]. Some researchers considered the impact of load transfer on users, and reduced the peak and valley rate of household electricity based on the reduction of household electricity costs [4]. Some researchers proposed the influencing factors for home users with distributed power sources to participate in the virtual power plant, and gave a two-level planning scheme [5]. Some researchers are based on the three-tier market structure of "grid company-sale company-user", which analyzes the operation control and demand response potential of households, and proposes a day-to-day electricity price for electricity sale companies based on a multi-agent service structure Risk decision making methods [6-7]. In addition, corresponding household load management strategies have been proposed for households containing distributed power sources [8-9] and energy storage equipment [10]. Although the peak power consumption on the household side can be solved by increasing the capacity of existing distribution facilities, this solution requires high investment costs and subsequent maintenance costs, which will lead to problems such as excessive asset scale and low equipment utilization [11-12].

This paper proposes a home energy management strategy based on a virtual power plant platform to achieve demand response. Ordinary household users respond to the electricity prices or incentives provided by the interactive platform of the virtual power plant, and adjust the time-transferable loads
such as air conditioners, water heaters, and electric cars in the home to achieve the effect of reducing electricity expenditure while meeting the demand for electricity. Grid companies also achieved the goal of peak cutting and valley filling through this demand response.

2. Implementation Framework for Power Users to Participate in Virtual Power Plants

The mode of user participation in grid operation is shown in Figure 1. Grid companies negotiate and sign demand response control agreements with potential customers. When the power grid company collects the current peak or trough of user power at the moment, the power grid company issues specific dispatch tasks on the power supply and demand interactive platform based on real-time unit output and grid operation, and sends relevant regulatory information to the user according to the agreement. The smart energy gateway collects the user load operation status, uses adjustable potential analysis technology to perform real-time analysis of user data, and combines scheduling tasks released in real time by the power grid to obtain a scientific adjustable potential size. Use resource scheduling optimization strategies to formulate specific scheduling solutions. Then the smart energy gateway sends control instructions to the load equipment according to the specific scheduling scheme. After receiving the instruction, the user-side control terminal makes corresponding switching actions and returns a signal of successful regulation to the smart energy gateway. The gateway then uniformly monitors and verifies the overall regulation and control. Finally, report the results of regulation to the supply and demand interactive platform.

![Figure 1. Family participation demand response scenario model.](image)

In the above information interaction model, the interaction information at the time of initialization includes user equipment classification information, modeling information, basic user information, electricity meter parameters, and contract information. In the reduction process, the main contents of the interactive information are shown in the following table, including demand response protocols, scheduling tasks, load parameter collection, real-time regulation, and feedback regulation results.

| Number | Name                      | Specific contents                                                                 |
|--------|---------------------------|-----------------------------------------------------------------------------------|
| 1, 2   | Demand response protocol  | Types of equipment, specifications and subsidy measures                             |
| 3, 4   | Scheduling tasks          | Demand response schedule                                                           |
| 5, 6   | Load parameter collection | Device real-time power, user charging level, acceptable charging time and power     |
| 7      | Real-time regulation      | Power regulation of load                                                            |
| 8, 9   | Feedback scheduling results | Real-time power after scheduling, total scheduling volume and load scheduling      |
3. Home Energy Management Method for Realizing Demand Response

3.1. Consider the use of energy-optimized home users to participate in the grid operation model

This article aims to meet the needs of household electricity consumption with minimum energy expenditure. The power loads involved in the optimization are transferable loads, optimized appliances mainly include washing machines, clothes dryers, vacuum cleaners, water heaters, etc. The optimization based on real-time electricity prices during the allowed operating hours of the appliances allows the household appliances to operate within the low electricity prices. With the goal of minimizing household electricity costs, the objective function is as follows.

\[
MinE(i,t) = \sum_{t=1}^{T} \left[ \rho(t) \times \sum_{j=1}^{N} \left( C_i f_c \left( \theta \left[ k + j \right] \right) + C_m f_m \left( E_{TRS} \left[ k + j \right] \right) \right) \right]
\]

(1)

\[
f_c(\theta) = \begin{cases} 
\left( \theta_i - \theta_n \right) \big/ \theta_{up} - \theta_n, & \theta_n \leq \theta_i \leq \theta_{up} \\
\left( \theta_i - \theta_n \right) \big/ \theta_{up} - \theta_n, & \theta_{low} \leq \theta_i \leq \theta_n \\
100, & \text{else}
\end{cases}
\]

(2)

\[
\Delta \theta_{\text{max}} = \theta_{\text{upper}} - \theta_n
\]

(3)

\[
\Delta \theta_{\text{min}} = \theta_n - \theta_{\text{lower}}
\]

(4)

\[
f_m(E_{TRS}) = S_e \times \Delta E_{AC}
\]

(5)

Restrictions:

1) Power Constraint: The maximum total power allowed within a family unit hour.

\[
\sum_{i=1}^{N} y(i,t) \ast Q(i) \leq Q_{\text{max}}(t)
\]

(6)

2) Constraint of total hours of operation time: The total number of hours of operation of household appliances within T hours will not change, and the power consumption will not change.

\[
T_{\text{sum}}(i) = \sum_{t=1}^{T} y(i,t)
\]

(7)

3) Constraint of operating time range: The household appliances should run within the specified time range.

\[
T_{\text{run}}(i) = \sum_{t=\text{start}}^{t=\text{end}} y(i,t)
\]

(8)

4) Constraint of indoor temperature and air conditioning energy consumption.

\[
\theta_{\text{start}} = \varepsilon \theta_t + (1 - \varepsilon) \left( \theta_{\text{out}} - \eta \Delta E_{AC} / A \right)
\]

(9)

5) Indoor temperature constraints.

\[
\theta_i < \theta_{\text{upper}} = \min \left( 28^\circ C, \theta_n + \omega \times a \right)
\]

(10)

\[
\theta_i > \theta_{\text{lower}} = \max \left( 21^\circ C, \theta_n - \omega \times (1-a) \right)
\]

(11)

6) Power Constraint per Hour.

\[
0 \leq \Delta E_{AC} \leq \Delta E_{AC_{\text{max}}}
\]

(12)

In equation (1), \(y(i,t)\) is the operating status of electrical i at the time t, 0 means not operating, 1 means operating; T is the total period of optimization; N is the total number of optimized appliances; \(\rho(t)\) is the electricity price at the time t; \(Q(i)\) is the power consumption of appliance i; \(Q_{\text{max}}(t)\) is the maximum power value for home operation; \(T_{\text{sum}}(i)\) is the total operating hours of appliance i during the T period; \(T_{\text{run}}(i)\) is the total operating hours of appliance i during the operation constraint period; \(\Delta E_{AC}\) is the air conditioning energy; \(\theta_i\) is the indoor temperature; \(\theta_n\) is the outdoor temperature.
temperature; $\theta_0$ is the most comfortable temperature of the human body; $\theta_{\text{out}}$ is the outdoor temperature; $\theta_{\text{upper}}$ is the highest acceptable indoor temperature; $\theta_{\text{lower}}$ is the minimum acceptable indoor temperature; Under 10% dissatisfaction, $\omega$ and $\alpha$ are and 0.7 respectively; The constants $C_c$ and $C_m$ are weights; $\epsilon$ is the heat dissipation value, which is generally 0.96; $\eta$ is the air conditioning efficiency; $A$ is the thermal conductivity.

3.2. Model solving

The variables of the model are the working state of the load during 24 periods, with 0 indicating that the load is not working and 1 indicating that the load is working. Binary coding is used to encode individuals, and individuals are selected using traditional roulette. The commonly used penalty function is adopted for the safety power consumption constraint, load working time constraint and temperature control load constraint in the model, that is, the penalty term is added to the individual who does not meet the constraint condition to obtain the fitness value to reduce the individual fitness value of the individual is eliminated by the genetic method of survival of the fittest in the genetic algorithm.

![Figure 2. Family participation demand response scenario model.](image)

The solution algorithm flow using the improved genetic algorithm is shown in Figure 2. First, the individual codes in the generated initial population are improved to obtain continuous codes of continuous working load. Secondly, calculate the fitness value of all individuals, and copy the code of the individual with the best fitness value. Save it to the selection filter; then select, mutate, and cross the population to determine whether the population has reached the genetic number. If the genetic algebra is not reached, the steps on the shake are re-circulated from the improvement of the individual code until the genetic algebra is reached. When the genetic algebra is reached, the fitness of each
generation of the optimal individuals stored in the selection filter is calculated for the fitness, and the optimized individual is decoded and output to obtain the final optimal solution.

4. Example Analysis

The calculation example will simulate power consumption optimization of typical domestic appliances in economic mode, the simulation time is one day. According to the establishment of a mathematical model, the model takes the minimum household electricity bill as the optimization goal, considers the power constraints, the total hours of operation constraints, and the constraints of the operating time range. The required data information is shown in Tables 2 and Table 3.

| Parameter               | Value                      |
|-------------------------|-----------------------------|
| Point of division       | (0, 8, 21)                 |
| Electricity price matrix| [0.3583, 0.5583, 0.3583]    |
| Maximum power constraint| (8, 5, 8)                  |

Table 3. Household electrical equipment data.

| Device name | Hours/h | Operating period | Power/kW | Transferable | Interrupted |
|-------------|---------|-----------------|----------|--------------|-------------|
| electric car| 6       | 17:00-06:00     | 2        | yes          | yes         |
| washing machine | 1       | 18:00-22:00     | 0.8      | yes          | no          |
| vacuum cleaner | 1       | 07:00-10:00     | 0.5      | yes          | yes         |
| Clothes dryer | 1       | 19:00-24:00     | 0.65     | yes          | no          |
| dishwasher   | 1       | 20:00-22:00     | 1        | yes          | no          |

Among the household electrical equipment considered above, electric vehicles are transferable and interruptible devices, and washing machines, vacuum cleaners, clothes dryers, dishwashers, and water heaters are transferable and non-interruptible devices. These electrical appliances shift their operating hours to the time when the electricity price is appropriate. Combining the objective function and constraint conditions of the economic model, and after programming on the CPLEX, the optimization results of households are provided. From the state diagram of the household electrical equipment before and after optimization, the state of basically every electrical equipment has shifted, and try to avoid running at peak electricity prices. Other loads such as electric cars, vacuum cleaners, clothes dryers and dishwashers also can run properly at low power prices.

Figure 3. Power curves of household energy management in different ways.

Figure 3 shows the power curves of household energy management in different ways. The operating hours of loads such as water heaters before and after optimization have changed greatly. Most of the household electrical appliances before optimization run in high electricity price periods,
resulting in an increase in household operating costs; the optimized household electrical equipment transfers operate in low electricity price periods, and partial load transfer during the trough period, electricity costs are reduced. At the same time, the power grid also played a role in cutting peaks and filling valleys.

5. Conclusion
This paper studies the response methods of ordinary household users based on the virtual power plant interactive platform, and proposes a strategy for implementing household energy management based on demand response. Through the analysis of the calculation examples, it can be known that with appropriate management and control methods, the adjustment of time-transferable load can be realized, and the reduction of electric energy expenditure can be achieved while meeting the demand for electricity.

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