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Research on Optimal Control of Home Energy Management System Based on Real-time Tariffs

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Abstract: *With the widespread use of smart appliances, the optimization of electricity consumption behavior has become an important research content for residential smart electricity consumption. Considering the economy and comfort of electricity consumption, we propose an optimization model of users' electricity consumption behavior under the intelligent electricity consumption environment. Firstly, we model the operation characteristics of household load equipment, establish different comfort evaluation indexes for different household loads, and add the influence of the number of interruptions on users' comfort to the comfort evaluation indexes of interruptible loads; then, based on the time-sharing tariff, we propose an optimized operation model of residential smart electricity equipment with the goals of economy and residents' comfort; finally, through Matlab simulation experimental cases. It is verified that arranging a reasonable number of interruptible load interruptions achieves the purpose of reducing residential electricity consumption costs while safeguarding customer comfort.*

Keywords: *Smart Power, Real-time Tariffs, Facility Operation*

1. Introduction

With the rapid development of China's economy and the increasing improvement of people's living standards, the proportion of residential electricity consumption in the total social electricity consumption is gradually increasing, and the use of high-power household smart appliances is growing, thus bringing the problem of seasonal electricity load peaks. In the context of prioritizing energy saving, it is necessary and urgent to realize intelligent electricity consumption by residential users, enhance residents' awareness of electricity saving, and guide them to use electricity economically and reasonably. Therefore, it is important to reasonably arrange and optimize residents' intelligent electricity consumption behavior while considering the economy and comfort of residents' electricity consumption

More scholars at home and abroad have studied the optimal operation of household equipment, but less research has been done on the impact of interruptible equipment on users. Although the switching of interruptible loads can optimize the economy of customers, the frequent switching of their operating conditions not only reduces the service life of the equipment, but also affects the comfort of customers' daily life. Therefore, based on the existing research, it is necessary to study the impact of interruptible load interruptions on customers' electricity consumption.

2. Home Energy Management System Model

2.1 Photovoltaic power generation and energy storage model

For the photovoltaic system, the maximum power tracking mode of operation is used and the output PPV (t) is obtained by the prediction method and brought into the home energy management model as a constant parameter. The household energy storage device uses a battery as the storage device whose physical model is not described here. In addition, the PV and energy storage systems do not involve the comfort of the customer's electricity consumption, and thus no comfort model is available.

2.2 Uncontrollable load model

The uncontrollable load of household power equipment usually includes TV sets, general lighting, etc. Since the demand of the above equipment is immediate and needs to keep stable operation during the demand time, otherwise the quality of service will be affected. Therefore, this type of equipment has the characteristics of non-adjustable, non-transferable and non-interruptible power. The uncontrollable load is not regulated by HEMS, and its power can be predicted by historical data, which is a known quantity; its power comfort can be considered as a constant.

2.3 Transferable load model

Transferable load is a household load that must continue to work until the task is completed once the household smart device is running, and cannot be interrupted but can advance or delay the working period.The working characteristics of this type of electricity-using equipment can be expressed as follows.

$$\begin{cases} \alpha_{a,start} \le t_{a,start} \le t \le t_{a,end} \le \beta_{a,end} \\ t_{a,end} - t_{a,start} = T_a \\ P_a = P_a^N \cdot x_a(t) \\ x_a(t) = 1, t \in [t_{a,start}, t_{a,end}] \\ x_a(t) = 0, t \notin [t_{a,start}, t_{a,end}] \end{cases} \tag{1}$$

Where, $\alpha_{a,start}$, $\beta_{a,end}$ is the starting and ending time period of the allowed operation of the power equipment; , $t_{a,start}$, $t_{a,end}$ is the actual starting and ending time period of the equipment operation; indicates the number of operating time periods of the transferable equipment; $x_a(t)$ is the 0-1 variable, indicating whether the equipment a is started in time period t.

For transferable loads, the longer their delayed operation time, the greater the impact on the comfort of users. Therefore, the comfort of the transferable load is modeled using the delay time ratio of the load as follows.

$$U_{comf1} = \frac{|\Delta t|}{\beta_{a,end} - \alpha_{a,start} + 1} \tag{2}$$

Where, Δt is the time interval between moment t and the moment of maximum comfort.

2.4 Temperature-controlled load model

The temperature-controlled loads in households have their special operating characteristics, and air conditioners and storage water heaters are common temperature-controlled loads. According to the literature [8], the thermodynamic first-order equivalent model of temperature-controlled loads is established as follows.

$$\begin{cases} T_{in}(t) = T_{out}(t) + Q_a(t)R - (T_{out}(t) + Q_a(t)R - T_{in}(t-1))e^{-\frac{\Delta t}{RC}} \\ Q_a(t) = \eta_a P_a(t) + Q_{a.loss}(t) \\ T_{in,\min} x_a(t) \le T_{in}(t) x_a(t) \le T_{in,\max} x_a(t) \end{cases} \tag{3}$$

where, $T_{in}(t)$, $T_{out}(t)$denotes the indoor and outdoor temperature, respectively, °C; R denotes the room thermal resistance, °C/kw; C denotes the room thermal capacity, kWh/°C; $Q_a(t)$ denotes the equivalent thermal power, kW; η_a is the thermal efficiency of the equipment;$T_{in,min}$, $T_{in,max}$ is the upper and lower temperature limits, °C.

For air conditioning equipment, ignoring the heat loss of air flow inside and outside the room, there is $Q_{a,loss}(t)$=0. For water heaters, while the user uses the water heater hot water, cold water entering the water heater will cause heat loss, according to the principle of conservation of energy, $Q_{a,loss}(t)$ calculated as follows.

$$Q_{a.loss}(t)=\frac{m_a(t)C_w(T_{in}(t)-T_w)}{\Delta t} \tag{4}$$

Where, $m_a(t)$ is the user water consumption in t time, kg; C_w is the specific heat capacity of water, J/kg-°C; T_w is the cold water inlet temperature, °C.

For temperature-controlled loads, the comfort level of temperature-controlled loads is directly related to the temperature. The greater the deviation of the temperature from the set temperature, the greater the impact on the user's comfort level; therefore, its comfort model is as follows

$$U_{comf\,2}=\frac{\sum_{t=1}^{T}[\left|t_{a,in}(t)-t_{a,in,best}\right|x_a(t)]}{\sum_{t=1}^{T}[\left|t_{a,in,\max}-t_{a,in,best}\right|x_a(t)]} \tag{5}$$

2.5 Interruptible load model

Interruptible load refers to the load that can be used intermittently by customers according to their habits under the premise of ensuring the completion of electricity consumption tasks.The working characteristics of this type of power equipment can be expressed as follows.

$$\begin{cases} \alpha_{a,start}\le t_{a,start}^{i}\le t^{i}\le t_{a,end}^{i}\le \beta_{a,end} \\ \sum_{i=1}^{T_d+1}t_{a,end}^{i}-\sum_{i=1}^{T_d+1}t_{a,start}^{i}+T_d+1=T_a \\ P_a=P_a^{N}\cdot x_a(t) \\ x_a(t)=1,t^{i}\in[t_{a,start}^{i},t_{a,end}^{i}] \\ x_a(t)=0,t^{i}\notin[t_{a,start}^{i},t_{a,end}^{i}] \end{cases} \tag{6}$$

Where, $t_{a,start}^{i}$, $t_{a,end}^{i}$ denotes the interruptible equipment a each work start time period; T_d denotes the number of interruptible load interruptions.

For interruptible loads, in addition to the comfort concept of transferable loads, the frequent start/stop and switching of the working behavior significantly affects the service life of the equipment. Therefore, the comfort model for interruptible loads is linked to the delay time ratio and the number of interruptions of the load.

$$U_{comf\,3}=\lambda_1\cdot(\frac{\left|\Delta t\right|}{\beta_{a,end}-\alpha_{a,start}+1})+\lambda_2\frac{T_d}{T_D} \tag{7}$$

$$\lambda_1+\lambda_2=1 \tag{8}$$

Where，λ_1 and λ_2 denote the weighting coefficients of the load delay time ratio and the number of interruptions on the comfort impact, respectively; denotes the maximum number of interruptible interruptions allowed for interruptible loads.

2.6 Objective function and constraints

After considering the economy and comfort of intelligent electricity consumption of residential customers, the objective function of residential customers' electricity consumption optimization strategy is as follows.

$$\min C_{total}=F_{total}+\omega_{all}U_{comf} \tag{9}$$

Where, C_{total} is the total cost function of residents; F_{total} is the cost of electricity for residents; U_{comf} denotes the overall comfort level of residential customers, and ω_{all} is the overall comfort weight of customers.

The total cost of residential electricity consumption F_{total} includes the cost of electricity purchase F_{buy}, the revenue from electricity sales F_{sell}, and the maintenance cost of energy storage system F_{ess}, where the revenue from electricity sales is negative. F_{total} can be expressed as

$$F_{total} = F_{buy} + F_{sell} + F_{ess} \tag{10}$$

$$F_{buy} = \sum_{t=1}^{T} p_{t,grid}^{+}(t)\Delta t p^{+}(t) \tag{11}$$

$$F_{sell} = \sum_{t=1}^{T} p_{t,grid}^{-}(t)\Delta t p^{-}(t) \tag{12}$$

$$p_{t,grid}^{+}(t) \geq 0, p_{t,grid}^{-}(t) \leq 0 \tag{13}$$

where, $p_{t,grid}^{+}(t)$ is the purchased power of customers in time t; $p_{t,grid}^{-}(t)$ is the sold power of customers in time t. $p^{+}(t)$ is the purchased power price for each time period; $p^{-}(t)$ is the sold power price for each time period; p_{t}^{grid} is the power of household-grid interaction for time period t.

In addition, the household load power, PV power, energy storage device charging and discharging power and household and grid interaction power are in balance for each time period of the household load, corresponding to the power balance constraint in the system as

$$p_{t,load} - p_{t,PV} - P_{dc,t}^{ESS} = p_{t,grid} + P_{ch,t}^{ESS} \tag{14}$$

Where, $p_{t,load}$ is the total power of household electric load, kW; $p_{t,PV}$ is the power of PV output, kW; $P_{ch,t}^{ESS}$, $P_{dc,t}^{ESS}$ is the charging and discharging power of energy storage device, kW.

The life of the energy storage system is related to the number of times the battery is charged, and its maintenance cost Fes is proportional to the total change of the battery, which can be equated as proportional to the total charge power of the energy storage, so Fes can be expressed as

$$F_{es} = \lambda_{es} \sum_{t=1}^{T} p_{es}^{+}(t)\Delta t \tag{15}$$

where, λ_{es} is the ratio of maintenance cost and storage charging power; $p_{es}^{+}(t)$ is the storage charging power at time t, kW.

The overall comfort of residents is weighted by the comfort of various types of household appliance loads.

$$U_{comf} = \sum_{i=1}^{a} w_{ai} U_{comf1} + \sum_{i=1}^{b} w_{bi} U_{comf2} + \sum_{i=1}^{c} w_{ci} U_{comf3} \tag{16}$$

Where, a, b, c denote the set of transferable load, temperature-controlled load and interruptible load, respectively; w_{ai}, w_{bi}, w_{ci} denote the comfort weights of transferable load, temperature-controlled load and interruptible load, respectively.

$$\sum_{i=1}^{a} w_{ai} + \sum_{i=1}^{b} w_{bi} + \sum_{i=1}^{c} w_{ci} = 1 \tag{17}$$

The model takes Eq. (9) as the objective function and Eqs. (1)-(8) and (10)-(17) as the constraints to build an optimization model for residential electricity consumption. The optimization model is in mixed integer linear form, and the CPLEX solver is invoked to solve it.

3. Case Study

3.1 Optimization of electricity consumption by residential customers under real-time tariffs

The simulation results of transferable and temperature-controlled devices are shown in Figure 1. Figure 1 gives the optimal scheduling results of household devices. The working interval of the washing machine is 19:00-22:00, and the most comfortable time is 21:00. The working interval includes the usual and peak tariff periods, and after optimal scheduling, the washing machine is scheduled to run at 21:00-22:00 when the tariff is lower; the working interval of dishwasher A is 12:00-14:00, and the most comfortable time is 13:00. Dishwasher A is scheduled to run at 13:00 after optimal scheduling; Dishwasher B is set to run from 20:00-24:00 with the most comfortable time being 23:00, and after optimal scheduling, Dishwasher B is set to run at 23:00; similarly, the sanitizer and dryer work zones contain multiple tariff periods, and after optimal scheduling, they are both scheduled to run at 00:00. The water heater works according to the demand for hot water at different times of the day, and since the demand for hot water is greater at 20:00 in the evening than at 08:00 in the morning, the water heater works at a higher power compared to the water heater; the air conditioner works according to the difference between indoor and outdoor air temperature and the comfort temperature range to be maintained.

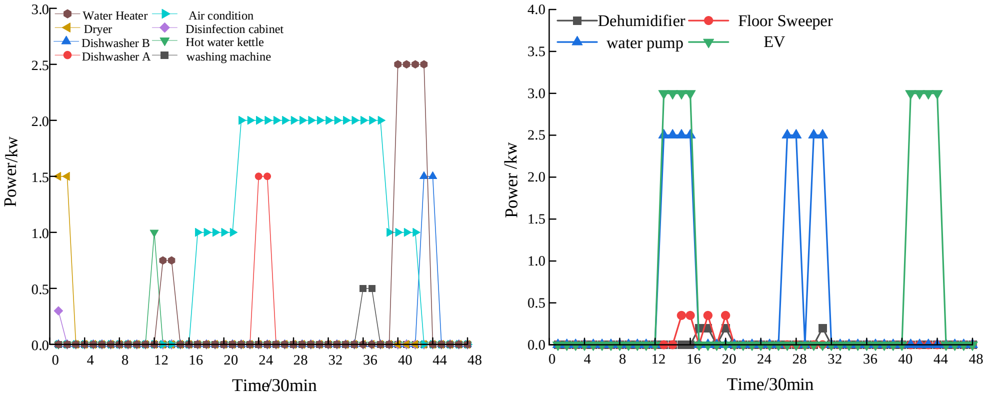

Figure 1: Home equipment scheduling.

The simulation results of interruptible equipment are shown in Figure 1. Due to the long working interval of EV and domestic water pump, considering the electricity cost of customers, EV is prioritized to run during low tariff time (20:00-22:00 and 06:00-08:00); the water pump is scheduled to run during low tariff time (06:00-08:00), and in order to meet its working hour requirement, the pump has Part of the work is scheduled to run during the time when the distributed power supply is sufficient (14:00-16:00). The dehumidifier and the floor sweeper are optimized to run during the low tariff period.

3.2 Impact of the number of interruptions on the optimization of customer electricity consumption

The number of interruptions allowed by the electricity-using equipment is also one of the factors that affect the cost of electricity and the comfort of customers. For the maximum allowable number of interruptions of interruptible load, the allowable number of interruptions of electricity consumption load is designed as shown in Table 1.

Table 1: Number of interruptions allowed for the electricity load

Case	Number of interruptions			
	Dehumidifiers	Floor Sweeper	water pump	EV
1	0	0	0	0
2	1	1	1	1
3	2	2	2	2
4	3	3	3	3

Based on the scenarios in Table 1, the simulation calculates the cost of electricity and customer comfort under the time-sharing tariff mechanism, as shown in Table 2. Scenario 1 has the highest electricity cost because it does not allow interruptions to occur, while scenario 2 has one interruption for each interruptible load and the electricity cost is reduced by 44.7%, i.e., the electricity cost in this scenario is $12.56, but the customer comfort is lost by 9.3% compared to scenario 1. This means that the number of interruptions in case 3 has made the distribution of electricity tasks flexible enough and made the cost of electricity and comfort of users minimal. This means that the number of interruptions in case 3 makes the distribution of tasks flexible enough and minimizes the cost and comfort, so there is no need to increase the number of interruptions. Therefore, it is important to arrange the number of interruptions of the interruptible load in a reasonable way, taking into account the economic and comfort objectives of the customers.

Table 2: Example results for each scenario

Case	Price/$	Comfort	Total Cost
1	22.72	0.472	24.496
2	12.55	0.516	16.678
3	10.76	0.594	15.512
4	10.76	0.657	16.016

3.3 Sensitivity analysis

Figure 2 shows the relationship between the number of interruptible load interruptions and the comfort weights of the number of interrupted loads in the household on the economy of energy use and comfort of residential customers. It can be seen that allowing interruptions to occur during the operation of household appliances can bring flexibility to the operating schedule of electrical equipment, and as the number of interruptions increases, the cost of electricity to the customer decreases, but the more comfort is lost to the residential customer. Therefore, HEMS can achieve the goal of reducing residential customers' electricity costs by scheduling equipment operation time according to the tariff signal and the number of interruptions of household interruptible equipment set by the customer, while ensuring customers' electricity comfort.

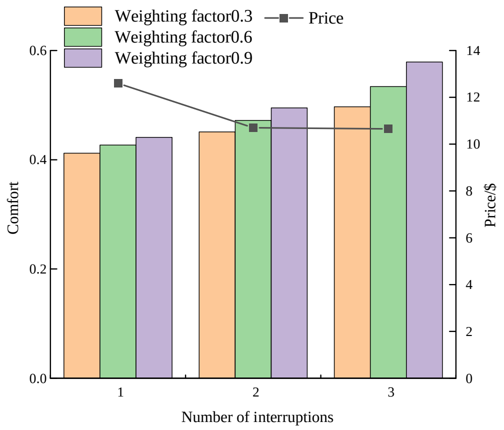

Figure 2: Comparison of electricity consumption cost and comfort under different weighting factors.

4. Conclusion

In this paper, the optimal operation strategy of residential household electrical equipment is studied. A mathematical model of typical residential household electrical equipment is established, and based on the real-time tariff designed in the previous section, an optimization model of dispatchable equipment in the customer's household is proposed. Based on the different requirements of each residential customer for operation time, the number of interruptions of interruptible household appliances is also limited, and the optimization simulation of each household appliance is carried out considering the economy and comfort as the target, and the impact of different interruptions of interruptible loads on the economy and comfort of customers is simulated and experimented. The results show that designing a reasonable number of interruptions of interruptible loads can reduce the electricity expenses and ensure the comfort of customers without harming other interests.

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