A calculation method of user response potential on demand side response in integrated energy system

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Abstract. The current Integrated Demand Response (IDR) strategies cannot accurately evaluate the user's maximum response which ignore the user terminal equipment response model. At the same time, the optimization target of the current IDR strategies is mostly electric energy, and other energy response requirements such as natural gas are not considered. This paper establishes an IDR strategy model based on energy models for different equipment terminals of residential users. And calculate the theoretical maximum response potential value of different users according to the response strategy formulated by different energy response requirements with the GA-SQP hybrid algorithm. The example analyses the user response potential in typical scenarios and time periods. The results verify the effectiveness and feasibility of the proposed method.

1. Introduction

By utilizing the complementary coupling among different energy sources like electricity, gas, heat and cold, Integrated Demand Response [1] co-optimize at the user demand side energy storage, energy conversion, and load regulation in the electric power grid. The IDR potential is the user's theoretical maximum response. The potential calculation is the basis for evaluating the users’ ability of response. It is not only an important basis for the energy supply side to formulate the response strategy and the park's comprehensive energy optimization operation strategy, but also is an important component of the users' portrait.

The concept of IDR was officially published in the literature [2] for the first time in 2015. Literature [3-12] conducted a model analysis of the IDR response randomness model, the resource coordination operation mechanism and its benefit evaluation, and the demand side economic model in the integrated energy system.

However, the current research doesn’t consider the constraints of the user's actual maximum response, and there is no specific model calculation for the user terminal equipment. At the same time, the optimization target of the current IDR strategies is mostly electric energy, and other energy response requirements such as natural gas are not considered.

This paper takes the residential building users as the research object, considers the randomness of the residents, and builds the energy usage model of the user's commonly used equipment. Establishing the user side IDR strategy optimization model which takes the maximum response as the optimization goal, and the maximum response potential of the user is calculated. Taking the actual electricity
consumption of one household in an intelligent community in North China in the summer as an example, calculating the response potential of different energy sources as the main part of response, and conducting sensitivity analysis on the comprehensive response potential of different terminals.

2. User terminal equipment energy model

2.1. Air conditioning

The air conditioning load is processed at a fixed frequency and the periodic start-stop compressor can realize the function of the fixed-frequency air conditioner to adjust the indoor temperature. According to the state queue model[13], the dynamic process of air conditioning operation is as follows:

\[
\begin{align*}
T_{in}^{t+1} &= T_{out} - (T_{out} - T_{in}^t) \times e^{-\Delta t/T_c}, s = 0 \\
T_{in}^t &= T_{out} - \eta_1 P/A - (T_{out} - \eta_1 P/A - T_{in}^t) \times e^{-\Delta t/T_c}, s = 1 \\
t_{off} &= ln \left[ \frac{T_{out} - T_{set} - \delta}{T_{out} - T_{set} + \delta} \right] / (-\Delta t/T_c) \\
t_{on} &= ln \left[ \frac{T_{out} - T_{set} + \delta - \eta_1 P/A}{T_{out} - T_{set} - \delta - \eta_1 P/A} \right] / (-\Delta t/T_c) \\
P_{air}(t) &= \begin{cases} 
P_{air-on}, & t \in t_{on} \\
P_{air-off}, & t \in t_{off}
\end{cases}
\end{align*}
\]

\(T_c\) is time constant, \(\Delta t\) is simulation duration, \(T_{out}\) is outdoor temperature, \(T_{in}\) is indoor temperature at time \(t\), \(T_{in}^{t+1}\) is indoor temperature at time \(t+1\), \(P\) is rated power, \(s\) is on/ off status, 0 for on status, 1 for off status, \(\eta_1\) is energy efficiency ratio of fixed frequency air conditioner, \(A\) is thermal conductivity, \(T_{set}\) is set temperature, \(\delta\) is control accuracy, \(t_{off}\) is off state duration, \(t_{on}\) is on state duration, \(P_{air-on}\) is operation power, \(P_{air-off}\) is standby power.

2.2. Hanging gas heater

The thermodynamic equation of the hanging gas heater is as follows[14]:

\[
F \times K \times (T_{out}(t) - T(t)) + P_{san}(t) - s \times \eta \times P_{rg}(t) = mc \frac{dT}{dt}
\]

\(F\) is heat conduction area of the hanging gas heater \((m^2)\), \(K\) is thermal conductivity of the hanging gas heater \((kW/m^2/C)\), \(T_{out}(t)\) is outdoor temperature \((C)\), \(T(t)\) is room temperature \((C)\), \(P_{san}(t)\) is indoor cooling power \((W)\), \(s\) is state variable, 1 is on state, 0 is off, pause or standby state, \(\eta\) is energy efficiency ratio of the hanging gas heater, \(P_{rg}(t)\) is the rated heating power of the g hanging gas heater at t time \((W)\).

The operation time and standby time of the hanging gas heater are:

\[
\begin{align*}
t_{off} &= \frac{1}{\mu} ln \left[ T_{min} - T_{out}(t) - P_{san}(t) / A \right] \\
t_{on} &= \frac{1}{\mu} ln \left[ T_{max} - T_{out}(t) - P_{san}(t) / A \right]
\end{align*}
\]

\(t_{off}\) is duration of the standby process during a work cycle, \(t_{on}\) is duration of the heating process during a work cycle, \(T_{max}\) is the highest temperature when the hanging gas heater is working, \(T_{min}\) is the lowest temperature when the hanging gas heater is working, \(\mu\) is a constant related to the heat transfer area and thermal conductivity, \(A\) is system thermal conductivity of the hanging gas heater \((kW/C)\).

The power of the hanging gas heater can be expressed as:

\[
P_{rg}(t) = \begin{cases} 
P_{rg-on}, & t \in t_{on} \\
P_{rg-off}, & t \in t_{off}
\end{cases}
\]

\(P_{rg-on}\) is operation power, \(P_{rg-off}\) is standby power.
2.3. Lighting
The proportion of lighting electricity accounts for 10% to 25% of the total building electricity consumption. The annual lighting energy consumption of buildings is as follows:

\[ P_L(t) = \overline{P}_L \cdot A_L \cdot \lambda_L(t) \]  

\( \overline{P}_L \) is average lighting power per unit area, \( A_L \) is Lighting area, \( \lambda_L(t) \) is lighting time distribution, its distribution law is related to living habits of residents.

2.4. Household electric appliance
The main household electric appliances in the family include TVs, washing machines, refrigerators, personal laptops, ventilation fans in the washroom, and ventilation fans in the kitchen. In theory, the energy consumption of each appliance can be expressed as:

\[ P_{EH-i}(t) = P_{EH} \cdot \lambda_{EH-i}(t) \]  

\( P_{EH-i}(t) \) is electrical appliance \( i \) operation power, \( \lambda_{EH-i}(t) \) is the possibility that the appliance \( i \) is used at time \( t \), and its value is related to the automation level of the appliance itself, the division of the appliance type, the user's habit, and the appliance usage mode.

2.5. Cooking
The energy consumption of cooking can be divided into gas energy consumption and electric energy consumption. The cooking energy consumption can be described by the following formula:

\[ T_{c-i} \cdot P_{c-i}(t) = Q_c \cdot \eta_{c-i} \]  

\( T_{c-i} \) is duration of cooking, \( T_{c-i} \) is the duration of gas cooking in a day, \( T_{c-i} \) is the duration of electric cooking in a day, \( P_{c-i} \) is cooking power, \( P_{c-i} \) is gas cooking power, \( P_{c-i} \) is electric cooking power, \( \eta_{c-i} \) is conversion efficiency, \( \eta_{c-i} \) is the efficiency of gas energy conversion into cooking energy, \( \eta_{c-i} \) is the efficiency of electrical energy conversion into cooking energy, \( Q_c \) is average energy consumption of cooking.

2.6. Domestic hot water energy consumption
The hot water in the residents' homes is mainly consumed in the bathing area. The state of the electric water heater can be divided into a non-water use period and a water use period, and the hot water temperature in the storage tank reciprocally changes within a certain range of the temperature set point[15].

This paper believes that the temperature of the hot water in the water tank of the electric water heater is the same.

\[ \left\{ \begin{array}{l}
C \frac{dT}{dt} + G \times (T_r(t) - T_{out}) + B \times (T_r(t) - T_{in}) = P_i(t) \\
C = \rho c_p V, H = \rho c_p G = A/R, B = HWD(t)
\end{array} \right. \]  

\[ \left\{ \begin{array}{l}
C \frac{dT}{dt} + G \times (T_r(t) - T_{out}) + B \times (T_r(t) - T_{in}) = P_i(t) \\
C = \rho c_p V, H = \rho c_p G = A/R, B = HWD(t)
\end{array} \right. \]

\( WD(t) \) is resident users consume water in real-time(m³/s), \( T_r(t) \) is water temperature of the water tank in real-time(°C), \( P_i(t) \) is power of electric water heater in real-time(W), \( V \) is water tank volume(m³), \( T_{out} \) is ambient temperature of the water heater tank(°C), \( T_{in} \) is water temperature entering the water heater tank(°C), \( \rho \) is water density(kg/m³), \( c_p \) is specific heat capacity of water(J/kg·°C), \( A \) is the heater storage tank surface area(m²), \( R \) is the water heater storage tank thermal resistance (m²·°C/W).

The electric water heater implements this control logic by a thermostat controller with a hysteresis link, and the specific control logic is as shown in equation (12).

\[ P_i(t) = \begin{cases} 
0 & T \geq T_{high} \\
P_{so} & P_{so} \leq T_{low} < T < T_{high} \\
P_i(t - \Delta t) & T_{low} < T \leq T_{low}
\end{cases} \]  

\( T_{high} \) is the maximum working temperature (°C), \( T_{low} \) is the minimum working temperature (°C), \( P_{so} \) is the rated power(W), \( P_i(t - \Delta t) \) is power at the previous moment(W).
3. User side IDR strategy optimization model

3.1. Objective function
In this paper, the user response $P_{pot}$ is used as the optimization target to calculate the theoretical response potential of the user.

$$\max P_{pot} = \max \int_{t=T_{start}}^{T=T_{end}} (P_i'(t) - P_i(t)) P_i(t) dt = \begin{cases} 0, & T \geq T_{high} \\ P_{so_i}, & T_{low} \leq T \\ P_{i}(t - \Delta t), & T_{low} < T < T_{high} \end{cases}$$ (13)

$T_{start}$ represents the start time of the demand response event, $T_{end}$ represents the stop time. $P_i'(t)$ is the original power of terminal $i$ at time $t$, and $P_i(t)$ is the power of terminal $i$ responding at time $t$.

3.2. Constraints
Constraints which considering the terminal equipment and user demands as follows:

3.2.1. Energy demand constraint
(1)Room temperature constraint
$$T_{in-min} < T_{in}(t) < T_{in-max}$$ (14)
(2)Water temperature constraint
$$T_{w-min} < T_{w}(t) < T_{w-max}$$ (15)
(3)Lighting constraints
$$A_{L-min} < A_L(t) < A_L-max$$ (16)
(4)Cooking constraints (total energy load is equal)
$$\sum q_i(t) = Q_c$$ (17)
(5)Electrical appliances constraints
$$0 \leq \lambda_{EH_i}(t) \leq 1$$ (18)
(6)Heating constraints:
a. Air-conditioning running time: start-up time limit of the refrigeration unit of the air-conditioning.
$$t_{on} > t_{on-min}$$ (19)
b. Hanging gas heater running time: start-up time limit of the gas-fired boiler.
$$t_{on} > t_{on-min}$$ (20)
c. The remaining electrical appliances running time is less than 24h.

3.2.2. Equipment power constraints
$$P_{imax} > P_i(t) > 0$$ (21)

4. Algorithm
In this paper, a hybrid integer optimization model is established, which is solved by GA-SQP hybrid algorithm that combines the characteristics of the heuristic algorithm with the deterministic algorithm. The GA is used to search for the optimal set of integer variables in the outer layer. The inner layer NLP problem is solved by the SQP algorithm with quadratic convergence ability. Because the solution method of the NLP problem is now matured, the algorithm converges well.

GAMS can solve the nonlinear problem well, so it is integrated into the algorithm as a sub-problem loop solution. At the same time, the storage mechanism is introduced. When the integer set is repeatedly searched, the NLP solution result can be directly called to accelerate the convergence speed of the algorithm.

The GA-SQP algorithm, combined GA with SQP, not only utilizes the good global search ability of genetic algorithm, but also the gradient information based SQP algorithm, which is better than simple heuristic algorithm. Figure 1 shows the schematic diagram of the GA-SQP hybrid algorithm flow.
Start
Set genetic algorithm parameters
(Mutation probability, population size, number of iterations k=0)
Generate an initial population of peripheral integer variables Y
Calculate fitness values
Use SQP algorithm to solve NLP sub problems
Store fitness values and corresponding integer variable combinations
Choice, crossover, variation
End

Figure 1. Schematic diagram of the GA-SQP hybrid algorithm flow.

5. Analysis and comparison of examples

The example selects the actual electricity consumption data of a household in an intelligent community in North China in the summer [16], and simulates the above-mentioned regulation strategy on Matlab2019a. The user's building area is 100m². The outdoor temperature distribution of the user's area is shown in Figure 2. The indoor temperature distribution of the user's area is shown in Figure 3.

The user's different types of electrical appliances parameters are shown in Table 1.

| Types           | Equipments          | Parameters                                                                 |
|-----------------|---------------------|----------------------------------------------------------------------------|
| Air conditioning| Air conditioning    | \( P=2.5kW \), usage time 11:00-19:00, \( T_{in}\in[22^\circ C,28^\circ C] \). |
| Lightning       | Lightning           | \( P=0.83kWh/24h, \lambda_{EH\cdot R}=1 \);                                |
|                 | Refrigerator        | \( P=0.401kW, P_0=0.56W, \lambda_{EH\cdot C}=0.4 \);                        |
|                 | Computer            | \( P=0.14kW, P_0=0.3W, \lambda_{EH\cdot T}=0.5 \);                          |
|                 | TV                  | \( P=1.5kW, \lambda_{EH\cdot W}=0.5[17] \);                               |
|                 | Washing machine     |                                                                            |
| Cooking         | Induction cooker    | \( Q_c=0.242kWh, \eta_{cl}=90\%, \eta_{el}=63\%[18] \);                     |
|                 | Gas stoves          | \( P_{cl}(t)=2.2kW, P_{el}(t)=2.463kW \).                                |
| Electric heating| Water heater        | \( G=0.9, V=40L, T_{sw}=[40,60], P=1.2kW, \) customary usage time \( 19:00-22:00 \). |

The optimization results are shown in Figure 4, Figure 5 and Figure 6.

Figure 2. Outdoor temperature distribution of the user's area.

Figure 3. Indoor temperature distribution of the user's area.

Figure 4. User's different types of electrical appliances parameters.
The calculation results show that the optimized power transferable load can reach up to 2.27 kWh, which is 37.7% of the total electricity consumption of the user before optimization. Since most of the cooking energy can be replaced by electric energy, the gas transferable load is 0.236 kWh, which is 88.2% of the total gas consumption of the user before optimization. The reduction in lighting area and lighting duration may result in a decrease in user satisfaction. Due to the certain probability of use, household electrical appliances may lead to deviations in optimization results.

The optimization of cooking shows that it is more energy-efficient to use as much electric energy as possible since the conversion rate of electric energy to cooking energy is higher. Air-conditioning and electric heating appliances contribute significantly to the results in optimization, and there is a large space for optimization.

6. Conclusions
The importance of comprehensive demand side response is highlighted with the context of the rapid development of integrated energy systems. How to accurately calculate the response potential of different users and develop a scientific IDR strategy for energy suppliers has become an important part of promoting energy supply side reform.

In this paper, the user's energy equipment terminals are taken as the research object, and an IDR potential calculation method is proposed. Considering the distributed energy and randomness of residents, based on the energy model of different equipment terminals, the IDR strategy model is established. The GA-SQP hybrid algorithm can be used to formulate the theoretical maximum response strategy for different energy response requirements. The value of the response potential of different users is obtained.

Finally, the user response potential in typical scenarios and typical time periods is calculated, which verifies the effectiveness and practicability of the proposed method. In the future research, the user and equipment terminal types will be further refined, and the impact of different energy system supply and operation modes on the integrated demand side response will be analyzed, perfecting the energy supply side IDR strategy formulation method.
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References
[1] Koeppel G, Andersson G 2009 Reliability modeling of multi-carrier energy systems[J] Energy 34(3) 235-244
[2] Sheikhi A, Bahrami S, Ranjbar A M 2015 An autonomous demand response program for electricity and natural gas networks in smart energy hubs[J] Energy 89(9) 490-499
[3] Xu X D, Jia H J, Jin X L, et al. 2015 Study on hybrid heat-gas-power flow algorithm for integrated community energy system[J] Proceedings of the CSEE 35(14) 3634-3642
[4] Zhang X, Shahidehpour M, Alabdulwahab A, et al. 2015 Optimal expansion planning of energy hub with multiple energy infrastructures[J] IEEE Transactions on Smart Grid 6(5) 2302-2311
[5] Mancarella P, Chicco G 2013 Real-time demand response from energy shifting in distributed multi-generation[J] IEEE Transactions on Smart Grid 4(4) 1928-1938
[6] Good N, Karangelos E, Navarro-Espinosa A, et al. 2015 Optimization under uncertainty of thermal storage-based flexible demand response with quantification of residential users' discomfort[J] IEEE Transactions on Smart Grid 6(5) 2333-2342
[7] Pazouki S, HaghiFam M R 2016 Optimal planning and scheduling of energy hub in presence of wind, storage and demand response under uncertainty[J] International Journal of Electrical Power & Energy Systems 89(1) 219-239
[8] Wang Q X, Liu D C, Wu J, et al. 2017 Comprehensive optimization including user behavior analysis for supply and demand sides of IES-MEC[J] Electric Power Automation Equipment 37(6) 179-185
[9] Shi J Y, Xu J, Zeng B, et al. 2016 A bi-level optimal operation for energy hub based on regulating heat-to-electric ratio mode[J] Power System Technology 40(10) 2959-2966
[10] Watson J P, Zhao C, Wang J, et al. 2012 Multi-stage robust unit commitment considering demand response uncertainties[J] IEEE Transactions on Power Systems 28(3) 2708-2717
[11] Yang N, Wang B, Liu D C, et al. 2013 Large-scale wind power stochastic optimization scheduling method considering flexible load peaking[J] Transactions of China Electrotechnical Society 28(11) 231-238
[12] Zhang H C, Hu Z C, Song Y H, et al. 2014 A prediction method for electric vehicle charging load considering spatial and temporal distribution[J] Automation of Electric Power Systems 38(1) 13-20
[13] Wang D, Fan M H, Jia H J 2014 User comfort constraint demand response for residential thermostatically-controlled loads and efficient power plant modeling[J] Proceedings of the CSEE 34(13) 2071-2077
[14] Yuan L X 2012 Study on gas consumption index, gas consumption law and daily load prediction of gas wall-hung boilers[D] Beijing University of Technology
[15] Zhou W J 2017 Study on electric water heater model construction and demand side frequency regulation control strategy[D] Harbin Institute of Technology
[16] Peng X J 2009 Research on energy constraint model of residential buildings[D] Chongqing University
[17] Hao S J 2017 Analysis of influence of power demand side management on power saving strategies of typical power users[D] Zhengzhou University
[18] Yin H 2013 Energy conservation and emission reduction environment power to substitute other energy evaluation method research[D] North China Electric Power University