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Optimal residential community demand response scheduling in smart grid

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HIGHLIGHTS

- Propose optimal scheduling scheme for smart residential community.
- Classify smart residential loads into different categories according to different demand response capabilities.
- Reduce the peak load and peak-valley difference of residential load profile without bringing discomfort to the users.
- Provide support for the decision of electricity pricing strategy under electric power market development.

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ABSTRACT

With the reformation of electric power market and the development of smart grid technology, smart residential community, a new residential demand side entity, tends to play an important role in demand response program. This paper presents a demand response scheduling model for the novel residential community incorporating the current circumstances and the future trends of demand response programs. In this paper, smart residential loads are firstly classified into different categories according to various demand response programs. Secondly, a complete scheduling scheme is modeled based on the dispatch of residential loads and distributed generation. The presented model reduces the cost of user's electricity consumption and decreases the peak load and peak-valley difference of residential load profile without bringing discomfort to the users, through which residential community can participate in demand response efficiently. Besides, this model can also provide support for the decision of electricity pricing strategies under power market development.

1. Introduction

Demand response (DR), the main method of interaction between the power grid and customers under power market development, has been widely applied in recent years. In perspective of the grid utility, DR can improve load profile by reducing peak load and peak-valley difference, thus decreasing the operation cost of the system, and alleviating the pressure of the grid investment on load increase. On the other hand, for the electricity consumers, DR reduces cost of customers' electricity consumption without affecting their satisfaction. Among loads that can participate in DR, residential load has great potentiality, and can effectively ameliorate the demand-side load curve [1,2].

With the development of smart grid technology, controllable loads and distributed generation (DG) have been gradually integrated into residential side. Smart meters, in addition, have been gradually applied to residential buildings. Therefore, a new DR participant with considerable load flexibility arises from residential side, which is smart residential community. Fig. 1 shows the components of the load and DG in smart residential community that include interruptible load, controllable load, roof-top solar panel, and storage battery. In comparison to conventional residential loads, smart residential community has greater DR potentiality leading to that it can smooth the load curve more dramatically owing to its load flexibility. In addition, DR of smart residential community is also crucial for ancillary service entities to get involved in power market. Since smart residential community arises freshly, few studies have been done upon DR of this specific entity. Thus, it is meaningful and necessary to study the DR strategy of smart residential community.

China has initiated numerous demonstration projects of smart residential community during the past several years aiming to reduce the peak load, load peak-valley difference and energy

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Nomenclature

Indices
l superscript for interruptible load
a superscript for adjustable load
b superscript for shiftable load
i index for power generation unit
j, k index for load unit
t index for time

Parameters
$P_j^{l,\max}$ maximum curtailable power of interruptible load j at each hour (kW)
$X_j^{l,\max}$ maximum daily curtailable hours of load j (h)
$P_{j,t}^L$ original load power of load j at hour t (kW)
$P_{j,t}^{a,base}$ original power of illumination load j at hour t (kW)
$\rho_j^{a,\min}$ price threshold of illumination load j (¥/kW h)
$P_{j,t}^{a,\min}$ adjusted power of illumination load j at hour t (kW)
ρ_t power price of grid at hour t (¥/kW h)
ε small positive constant (which equals to 0.001 in this paper)
$T_{k,t}^{\alpha}$ ambient temperature of air conditioner k at hour t (°C)
α_k system inertia of air conditioner k
Δt control interval (1 h)
C_k thermal capacitance of air conditioner k (kW h/°C)
R_k thermal resistance of air conditioner k (°C/kW)
η_k working efficiency factor of air conditioner k
$P_k^{\min}$, $P_k^{\max}$ minimum and maximum power of air conditioner k at each hour (kW)
$T_{k,t}^{s,\text{base}}$ original temperature set point of air conditioner k at hour t (°C)
$T_{k,t}^{s,\max}$ adjusted temperature set point of air conditioner k at hour t in cooling mode (°C)
$\rho_k^{a,\min}$ price threshold of air conditioner k (¥/kW h)
$P_j^{b,\text{average}}$ average power of shiftable load j (kW)
$X_{j,t}^{b,\text{on}}$ total operated hours of shiftable load j at hour t (h)
U_j^b cycle duration of shiftable load j (h)
τ start hour of time window set by user (h)
T end hour of time window set by user (h)
$P_k^{b,\min}$, $P_k^{b,\max}$ minimum and maximum charge power of EV k at each hour (kW)
T_a users EV home arrival time (i.e. EV plug-in time) (h)
T_b end of users EV charge time (h)
$E_k^{\max}$ battery capacity of EV k (kW h)
D maximum mileage of EV
ρ_j^l interruptible load curtailment tariff (¥/kW h)

$P^{g,\min}$, $P^{g,\max}$ minimum/maximum purchased power from grid at each hour (kW)
$P_{c,i}^{\min}$, $P_{c,i}^{\max}$ minimum/maximum charge power of battery i at each hour (kW)
$P_{d,i}^{\min}$, $P_{d,i}^{\max}$ minimum/maximum discharge power of battery i at each hour (kW)
η_i^S discharge/charge inverter efficiency
$E_i^{\min}$, $E_i^{\max}$ minimum/maximum stored energy of battery i (kW h)
NT total schedule hours (24 h in this paper)

Variables
$P_{j,t}^l$ curtailed power of user j at hour t (kW)
$I_{j,t}^l$ binary status indices of interruptible load j at hour t (if load is curtailed, $I_{j,t}^l = 1$)
$P_{j,t}^a$ power of illumination load j at hour t (kW)
$I_{j,t}^a$ binary status indices of adjustment of illumination load j at hour t (when hourly price is higher than $\rho_{j,t}^{a,\min}$, $I_{j,t}^a = 1$)
$T_{k,t}$ air conditioner temperature of air conditioner k at hour t (°C)
$T_{k,t}^g$ temperature adjustment of air conditioner k at hour t (°C) when it is turned on
$P_{k,t}^a$ load power of air conditioner k at hour t (kW)
$T_{k,t}^s$ temperature set point of air conditioner k at hour t (°C)
$I_{k,t}^a$ binary status indices of adjustment of air conditioner k at hour t (when hourly price is higher than $\rho_{k,t}^{a,\min}$, $I_{k,t}^a = 1$)
$P_{j,t}^b$ load power of shiftable load j at hour t (kW)
$I_{j,t}^b$ binary status indices of shiftable load j at hour t (when load is on, $I_{j,t}^b = 1$)
$P_{k,t}^b$ charge power of EV k at hour t (kW)
$I_{k,t}^b$ binary charge status indices of EV k at hour t (when EV is charged, $I_{k,t}^b = 1$)
$E_{k,t}^b$ SOC of EV k at hour t
P_t^g power purchased from grid at hour t (kW)
$P_{i,t}^V$ solar power generation of unit i at hour t (kW)
$P_{i,t}^S$ battery charge/discharge power of battery i at hour t (kW)
$P_{d,i,t}$,$P_{c,i,t}$ discharge power/charge power of battery i at hour t (kW)
$I_{d,i,t}$,$I_{c,i,t}$ discharge/charge binary status indices of battery i at hour t (when battery discharges/charges, $I_{d,i,t} = 1/I_{c,i,t} = 1$)
$E_{i,t}$ SOC of battery i at hour t

consumption in cities, and those projects are currently in high-speed progress. One of the projects has been conducted in Suzhou, Jiangsu Province, China, where the residential community participates in DR through advanced metering infrastructure (AMI) coordinated by load aggregator (LA). The DR structure of the community is shown in Fig. 2. Each particular interruptible load and controllable load of household is connected with smart meters. The smart meters record and transport the load data to LA, and delivers the scheduling signals from LA to controllers of each load such as smart plug, control module of air conditioner, etc. to realize the aggregation and direct dispatch of each load by LA. Time-of-use (TOU) and critical peak pricing (CPP) DR programs are currently considered to be tested on this community in different days, and the test of real time pricing (RTP) and interruptible loads (IL) programs are also concerned in the future. Therefore, this particular DR structure requests for a novel optimal scheduling tool to apply price-based and incentive-based DR programs, which dives and supports the work of this paper.

There are some researches on residential DR in recent years, most of which are from the United States and European countries. Ref. [3] presents a control strategy for all controllable loads in a single house based on TOU tariffs. Refs. [4,5] build DR control model for heating, ventilating and air conditioning (HVAC) system of one house. Ref. [6] presents a scheduling model for shiftable loads of household. Refs. [7,8] build a DR model for single house considering thermal storage system. Refs. [9–13] build specific DR models for HVAC, energy storage system (ESS), electric vehicle (EV), and shiftable loads respectively, and combine them to a complete DR model of single building. Ref. [14] presents a real-time DR management approach for household utilizing stochastic