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Robust optimization for load scheduling of a smart home with photovoltaic system ☆

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ABSTRACT

In this paper, a robust approach is developed to tackle the uncertainty of PV power output for load scheduling of smart homes integrated with household PV system. Specifically, a robust formulation is proposed and further transformed to an equivalent quadratic programming problem. Day-ahead load schedules with different robustness can be generated by solving the proposed robust formulation with different predefined parameters. The validity and advantage of the proposed approach has been verified by simulation results. Also, the effects of feed-in tariff and PV output have been evaluated.

1. Introduction

Residential homes are getting smarter and smarter with wider use of smart appliances and integration of information and communication technology. On one hand, traditional home appliances are being replaced by smart appliances with communication module and automatic control function; on the other hand, home area networks are established in smart homes, which connect all household appliances and sensors together for easier monitoring and smarter control. Besides, smart homes are being faced with diverse pricing mechanisms where flexible pricing schemes such as time of use, real time pricing and critical peak pricing are being implemented in many countries all around the world. Therefore, there is a great opportunity for residential users to improve their life quality through smart home techniques under flexible pricing mechanisms. But general residential users do not have sufficient time and knowledge to manage all the devices of smart homes by their own. Thus, home energy management systems are often expected to be installed in smart homes to help users manage all the devices and data, and load scheduling is often running in home energy management systems to arrange the work of home appliances optimally.

In the future, energy sources of smart homes will be more diverse as well. Besides electricity from the bulk power grid, more and more distributed generation using renewable energy will be encouraged to be installed in smart homes. Household photovoltaic (PV) system is an important type of renewable distributed generation, which converts solar energy to electrical power for residential users. However, the integration of PV system presents new challenges to smart home energy management because of the randomness of solar energy. Researchers have done some work to tackle PV integration issues in household load scheduling: [1–3] involved PV system in the optimization of smart home energy services, but did not consider the forecast uncertainty of its power output. Pedrasa et al. [4] concluded that there is no value in making accurate solar insolation forecasts when the feed-in tariff equals to the time-of-use tariff exactly at every minute of the day, whereas that is a quite special scenario and the real situations are far more diverse and complicated. Chen et al. [5] tackled the forecast error of PV system output by online adapting the operation schedule during the execution, but only heuristic rules are referred when making the adaption, which is not the optimal way. Hubert and Grijalva [6] took the lower limit of the 95% confidence interval for the solar irradiance forecast in the optimization, through which the schedule was robust but only the worst situation was considered. These existing researches have made positive attempts to digest the integration of household PV system, but due to their respective limitations, further research is still needed to deal with the challenge of PV output uncertainties in household load scheduling.

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Nomenclature

Variables

x	power of an appliance (kW)
z, q, m, n, u, v, r, s	auxiliary variables

Parameters

p	electricity price ($/kWh)
b	allowed beginning time of a task (h)
L	time length of a task (h)
d	demand of hot water drawn (kg)
θ	temperature (°C)
α	constant (1/3,600,000) for unit conversion
P	appliance/PV power (kW)
e	deadline of a task (h)
E	energy demand of a task (kWh)
c_{water}	specific heat of water (J/kg/°C)
M	mass of water in full storage (kg)
Γ	parameter that controls the robustness

Subscripts

i, j, n	time step index
buy	buy electricity from the power grid
NL	noninterruptible loads
TCL	thermostatically controlled loads
e	environment
0	initial state
day	day index
PV	household photovoltaic system
sell	sell electricity to the power grid
IL	interruptible loads
req	requested by users
up	upperlimit
group	index of high/medium/low group

Others

N	number of all the time steps of a day
Δt	length of a time step (h)
J	set of all the N time steps
AP	average electricity payment ($)
D	total days of a group
SDAP	standard deviation of average payment ($)
$\boldsymbol{A}$	set of all the household appliances
S	subset of J
K	number of time steps with solar radiation
EP	practical electricity payment of a day ($)
EAP	expectation of average electricity payment ($)

Robust optimization is a promising method to deal with data uncertainty in optimization problems, thus naturally to be a potential solution to PV output uncertainties in household load scheduling. Till now, three major steps have been made in the field of robust optimization: the first step by Soyster [7]; the second step by Ben-Tal and Nemirovski [8–10], El-Ghaoui and Lebret [11], and El-Ghaoui et al. [12]; and another step by Bertsimas and Sim [13,14]. Robust optimization method proposed by Soyster keeps the linearity of linear programming but proves to be too conservative. Method proposed by Ben-Tal et al. considers linear programming with ellipsoidal uncertainties and solves the robust counterpart in the form of conic quadratic programming, being less conservative. Method proposed by Bertsimas and Sim is capable of keeping the linearity of linear programming and is characterized by introducing a predefined number Γ to flexibly control the conservative level of final solutions. In terms of the application of robust optimization methods in smart homes, Chen et al. [15] and Conejo et al. [16] used the method proposed by Bertsimas and Sim to tackle the real-time demand response issue with price uncertainty. However, to the best of our knowledge, there was little work done in using robust optimization methods to tackle the PV output uncertainty challenge in household load scheduling.

In this paper, robust load scheduling is studied for smart homes integrated with PV systems. The main contribution of this paper is to use robust optimization method to solve the PV output uncertainty problem in smart homes for the first time. Load scheduling problem in smart homes with PV systems has a special nonlinear form, and thus conventional robust optimization method proposed by Bertsimas and Sim cannot apply directly. To tackle this challenge, a robust formulation of load scheduling considering PV output uncertainty is established in this paper, and further transformed to an equivalent quadratic programming problem that can be solved by existing tools easily. By doing so, the uncertainty problem brought by the integration of household PV system is effectively tackled by the robust optimization method proposed in this paper.

The work of this paper is novel because it uses a method (robust optimization method) that has not been used in household load scheduling with PV integration before and tackles the uncertainty of household PV output to an extent that existing researches have not reached. Specifically, Pedrasa et al. [1,2] and Lujano-Rojas et al. [3] did not consider the household PV output uncertainty, but this paper does; Pedrasa et al. [4] only considered the PV output uncertainty under a special pricing mechanism, but this paper considers much general and diverse pricing mechanisms; Chen et al. [5] dealt with PV output uncertainty by adopting heuristic rules in the execution stage, but this paper dealt with the problem in an optimization way in the day-ahead scheduling stage; Hubert and Grijalva [6] only considered the worst situation, but the method proposed in this paper can control the robustness of final load schedules flexibly.

The rest of the paper is organized as follows. Problem description and modeling are presented in Section 2. Robust counterpart establishment and transformation are described in Section 3. Case study is presented in Section 4. Conclusions are summarized in Section 5.

2. Formulation of household load scheduling with the integration of PV system

2.1. System structure and problem description

Typical smart home with household PV system is shown in Fig. 1. Electricity of the smart home is supplied by two sources: local PV system and bulk power grid. Household devices such as smart appliances, sensors and smart plugs are connected to each other to form a home area network. Home energy management system uses the network to collect operation data of all the devices and send control signals back to control them. Load scheduling algorithm is running in the home energy management system to generate optimal load schedules based on device information, user settings and pricing mechanism.

The core of load scheduling is to utilize load flexibility according to PV output and pricing mechanism to minimize electricity payment under the premise of user comfort. The complexity of this problem is threefold: firstly, different types of loads have different