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Robust scheduling of building energy system under uncertainty

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HIGHLIGHTS

- We model a building energy system with chillers and ice thermal energy storage.
- A two-stage robust strategy is proposed to schedule the system operation.
- The robust strategy with proper parameters is superior to the deterministic method.
- The performances of the robust strategy and the MPC method are similar.

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ABSTRACT

This paper proposes a robust scheduling strategy to manage a building energy system with solar power generation system, multi-chiller system and ice thermal energy storage under prediction uncertainty. The strategy employs a two-stage adjustable robust formulation to minimize the system operation cost, wherein a parameter is introduced to adjust the level of conservatism of the robust solution against the modeled uncertainty. Then a column and constraint generation algorithm with modified initialization strategy is adopted to solve this optimization model along with mixed-integer linear programming. Further, we evaluate the performance of the proposed strategy by hourly simulating the system operation of a practical project with Monte Carlo simulation. Numerical results show that the robust scheduling with a proper parameter can be superior to the deterministic strategy in all the studied cases. Additionally, the proposed strategy has similar results with the model-based predictive control strategy while the former only needs to be implemented once. Even in the highest load case, the relative deviation between the two strategies is less than 2%.

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1. Introduction

Integrated energy systems (IES) provide a promising approach for the new or existing buildings, which are one of the primary energy consumers in the world [1]. The IES is a complex system with the goal of supplying electrical, space cooling, space heating loads and other loads, such as hot water and steam at the same time [2,3]. In such a system, electrical energy can come from distributed energy resources like solar power, wind power and combined heat and power system, while cooling energy can be provided by adsorption chillers using waste heat or ground source heat pumps exploiting geothermal energy. The energy bought or produced can also be stored in electrical or thermal energy storage systems and then released to meet the demands at other time. To fully exploit the potential and advantages of the IES, it is essential to develop an effective operation strategy. Note that energy storages couple the scheduling problem across multiple time periods, which increases the complexity of the system operation. In this paper, we focus on developing an optimal operation method for the building IES that integrates solar power generation system (SPGS), multi-chiller system and ice thermal energy storage (ITES) system.

For a building energy system, space cooling accounts for a large portion of energy consumption in hot weather [4]. In order to lower the energy consumption cost, especially the cooling cost, considerable work has been done on the application and optimal control of multi-chiller system and thermal energy storages [5–8]. The multi-chiller system can meet diverse load demands due to its flexible operation, and the thermal energy storages have the potential to shift electrical load from peak to off-peak periods under dynamic electricity pricing [9]. Fan et al. [5] divided the probability density distribution profile of cooling load ratio into

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several ranges, and furthermore separately optimized the operation of the chillers in terms of different load demands. The results showed that such a strategy can save more power consumption than the original sequence control strategy. In [6], Ma et al. proposed an online adaptive optimal control strategy for central chiller plants and obtained the similar results. For the energy system with thermal energy storage, Wang et al. [7] applied the storage-priority strategy to coordinate the chillers and the storage. However, such a deterministic method cannot make full use of the thermal energy storages to lower the operation cost.

To make the system responsive to the change of cooling load in time and to fully utilize the thermal energy storages, many researchers have applied the model-based predictive control (MPC) method to the operation of building energy systems [10–17] and microgrids [14,18]. Owing to the feedback of actual operation and the rolling mechanism, the MPC can properly adjust the operation scheduling during the prediction horizon. Zhao et al. [13] used the MPC strategy to optimize the scheduling of a building with thermal energy storages and achieved the desired performance. Besides the nonlinear characteristics of the energy systems studied in [13], Lu et al. [9] proposed a MINLP-based optimal scheduling strategy to consider discrete features like on/off number of some devices, which is more competitive than the NLP method. In [16], the authors developed a mixed-integer nonlinear programming model to simulate the operation of a central chiller plant with thermal energy storage by means of the MPC strategy and proposed a heuristic algorithm to solve the problem. Note that the inaccurate predictions of load demands [19] and renewable energy sources [20] may affect the performance of the MPC strategy. In terms of the prediction uncertainty, adaptive multiple MPC approach [21], MIN–MAX MPC robust optimal control method [22] and stochastic programming [23] are proposed or used to handle the uncertainty. However, the solution obtained in [22] may be over-conservative; the distributions of uncertain variables have to be known in advance in [23], which makes it difficult to be implemented in practice. In contrast, the robust model given in [24] does not require the distributions of uncertain variables and allows the decision makers to adjust the conservatism level of the solutions by themselves. For this reason, the method has been gaining increasing interest in recent years [25–29]. Alessandra et al. [26] presented a robust model for the operation management of energy hub and obtained a robust solution considering the uncertain parameters of the model, but they failed to consider the load uncertainty. The authors in [27,29] utilized two-stage robust optimization methods to solve unit commitment problems in the area of power system operation. Robust location transportation problems are studied in [28] considering uncertain demands. However, little work in existing literature has been done on scheduling the building energy systems under uncertainty by means of the robust optimization with adjustable conservatism levels, especially the two-stage robust optimization.

The aforementioned researches either schedule the building energy systems with deterministic method, or roll to operate the chillers and thermal energy storages with MPC method. Although the MPC method has the potential to adjust the scheduling in time, the rolling optimization is still deterministic and significantly depends on the predictions of load demands and renewable energy generation [14]. Some of the above strategies are capable of making the system more robust against uncertainty, but those solutions may be over-conservative, which is possible to raise the operation cost to deal with the worst-case scenarios that rarely occurs. In this paper, for a building energy system with solar power generation system, multi-chiller system and ice thermal energy storage system, we develop a two-stage robust optimization model to study the impacts of uncertain cooling load, electric load and solar power on the system operation. The two-stage robust approach intends to consider two sets of variables. The first set is "here and now" variables, such as the on/off statuses of the chillers and the discharge/charge mode of the ice thermal energy system, which needs to be determined before the disclosure of the uncertainty. In contrast, the second one is "wait and see" variables, like the outputs of the chillers, which can be decided after the uncertainty has been revealed [28]. A column-and-constraint generation algorithm [30] is adopted to solve the proposed two-stage robust model with a modified initialization strategy. The studied building energy system has a two-level control structure [16,17]: supervisory control and local control. The supervisory control layer is responsible for optimizing the system operation in the look-ahead periods based on predicted solar power and load demands. The local control layer manages the equipment according to the operation scheduling from the supervisory control layer. We focus on the supervisory control of the building energy system in this paper.

The remainder of this paper is organized as follows: Section 2 models the main devices related to the building energy system and presents a deterministic formulation of its operation optimization. In Section 3, we develop a two-stage robust counterpart of the deterministic problem and give a solving algorithm. Numerical results are shown in Section 4. Finally, Section 5 summarizes our research.

2. System modeling

The studied building energy system is located in the north base of the Customer Service Center of State Grid Corporation of China, Tianjin, China, as shown in Fig. 1. The base is a call center and a research and development center for power supply technologies, which has ten buildings (total net floor area of 113,485 m^2) including 5 office buildings and 5 apartment buildings. The buildings have diverse energy demands, such as electrical load, space cooling in summer, space heating in winter, hot water. Here we focus on their electrical and space cooling demands. In the system, a solar power generation system and the utility grid supply electric power to the entire base; a central chiller system cools the buildings in summer, which involves three ground source heat pumps (GSHP), two water-cooled chillers (WCC) and an ice thermal energy storage system. The ITES with chiller upstream consists of two chillers and an ice storage tank. The central chiller system applies constant primary flow and chilled water supply temperature, which means that the on-line chillers as well as the ITES will share the load according to some rules like the same part load ratio (PLR) described in [5]. As mentioned earlier, we study the system operation in the supervisory control level. In the following section, to optimize the commitment of the chillers and the discharge and charge plan of the ITES, we model the hourly operation of the building energy system with the objective of minimizing the energy cost during the look-ahead periods. Note that the building model is described by the hourly total predicted energy demands in this paper rather than the physical properties of buildings.

2.1. Ground source heat pumps and water-cooled chillers

Ground source heat pumps are environmentally friendly using geothermal energy for space heating and cooling, and here the cooling mode is considered. The hourly amount of cooling supplied by the ith heat pump and its energy consumption at hour t, denoted as $Q_{t,i}^{HP}$ and $W_{t,i}^{HP}$ respectively, are calculated using the following equations:

$$Q_{t,i}^{HP} = U_{t,i}^{HP} \cdot PL_t \cdot \overline{Q}_i^{HP}, \quad t = t_0, t_0+1, \cdots, T, \quad i = 1, 2, \cdots, N^{HP} \tag{1}$$

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