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Schedule of air-conditioning systems with thermal energy storage considering wind power forecast errors

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ABSTRACT

As the penetration of uncontrollable renewable energy sources (RESs) increases, energy storage and flexible demand will play a more important role in future power systems. In this paper, air-conditioning systems with thermal energy storage (A/C storage systems) are studied as a way of compensating uncertainties from wind power. Wind power forecast errors are analyzed from different perspectives in order to better assist the schedule of storage devices. An operation scheme is proposed for A/C storage systems for both day-ahead scheduling and real-time operation, based on the features of wind power forecast errors. The targets include load management and compensation of wind power forecast errors. Simulations illustrate the effectiveness of the proposed scheme to support power systems with high wind penetration.

1. Introduction

The penetration of renewable energy sources (RESs) is continuously growing to support the sustainable development of human society. More flexibility is required for power systems to handle variable RESs, such as wind and solar generation. Energy storage systems is a possible solution that has been widely discussed [1–4]. However, effective storage of electricity has been a challenging problem for a long time. The concerns include cost, efficiency, cycle life and other limitations.

On the other hand, various types of indirect and equivalent storage options could be available to improve the flexibility at the demand side of power systems. For example, electric vehicles can act as storage devices for power systems under proper charging control strategies [5,6]. Electric load for cooling and heating can be managed for demand response if the system has inherent thermal inertia [7–10].

Air-conditioning (A/C) systems with real thermal energy storage (TES) have been studied and utilized for load shifting since 1980s [11–14]. The effectiveness of this type of system as a storage option for power systems is also illustrated by the authors previous work [15]. In this study, A/C systems with TES (denoted as "A/C storage systems") is select as a representative of promising storage systems. Due to the increasing penetration of RESs and the corresponding challenges, it would be valuable to design an operation scheme for A/C storage systems which can mitigate the impact of RESs more effectively.

Wind power is a major type of RES over the world. The uncertainties of wind power is another focus of this study. Numerous researches have been conducted on the properties of wind power forecast errors and their probabilistic distributions [16–18]. It is also reported that the statistics of wind power forecast errors is related to the wind power output level [18–20]. Besides, the scheduling of storage devices considering wind power forecast errors is widely studied [3,4,21,22]. Most of the studies focus on wind power and wind power forecast errors. However, since energy capacity is the major limitation of storage devices, it would be helpful if wind power forecast errors can be quantified in terms of energy.

In this paper, an operation scheme is proposed for both day-ahead scheduling and real-time operation of A/C storage systems. The cooperation with wind power generation is considered. The objective is to schedule and dispatch the energy capacity of the storage systems more effectively for both load shifting and compensation of wind power forecast errors. The major contributions of this paper are:

(1) The features of wind power forecast errors is analyzed from new perspectives. A novel concept called "wind energy forecast errors" is introduced to assist the schedule of energy capacity of the storage systems. Besides, a more specific

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relationship between wind power output levels and forecast errors is investigated. These provide critical information to schedule storage devices.

(2) Day-ahead scheduling and real-time operation strategies are proposed for A/C storage systems based on the identified features of wind power forecast errors. The strategies aim to support the operation of power systems more effectively by providing both load shifting and proper amount of energy reserves to handle the uncertainties from RESs.

The rest of the paper is organized as follows. Section 2 introduces the basic model and assumptions of A/C storage systems. Section 3 investigates the uncertainties of wind power. Section 4 presents the proposed operation scheme for A/C storage systems. Section 5 illustrates the simulation results with discussions. Finally, Section 6 concludes the paper.

2. Basic model of A/C storage systems in day-ahead and real-time operation

A central A/C system originally consists of a cooling device to produce cooling capacity, and Air Handling Units (AHUs) to feed the cooling capacity to the building. For each time interval t, denote P_C^t to be the cooling power of the cooling device, and P_{AHU}^t to be the cooling demand of the building which is supplied by AHUs (in equivalent electric power). Without additional storage, P_C^t is approximately equal to P_{AHU}^t. If P_C^t is adjusted, P_{AHU}^t and the indoor temperature are both affected. The range and duration of the indoor temperature deviation have to be limited considering the comfort of the users. This limits the flexibility to adjust P_C^t, especially for load shifting.

An A/C storage system is reconstructed by adding a real TES between the cooling device and AHUs, and shown in Fig. 1. The TES could be a chilled water storage system, or an ice storage system as suggested by [11]. The general benefits of A/C storage systems are discussed in [15], and a brief comparison on the capital cost are presented in Section 5.4 of this paper.

The fundamental principle to control P_C^t is different for an A/C storage system. P_C^t is decoupled from P_{AHU}^t since the TES acts as a buffer. Whenever P_C^t is adjusted, the difference between P_C^t and P_{AHU}^t is covered by the charging or discharging of the TES. The supply of P_{AHU}^t and the indoor temperature are not affected. As a result, P_C^t can be adjusted freely (within its rated capacity) as long as the TES has enough energy capacity. The flexibility can be enhanced significantly.

In terms of the TES, the charging/discharging rate is determined by the difference between P_C^t and P_{AHU}^t. The TES should be able to be charged at the maximum cooling power or discharged at the maximum cooling demand at extreme conditions.

The cooling capacity stored in the TES is used directly and thus there is no further energy conversion losses. Thermal losses indeed exist. However, the percentage of the losses is assumed to be small, especially when the cooling demand is heavy (since the cooling capacity is only stored for a short period of time). Thus the losses are currently neglected.

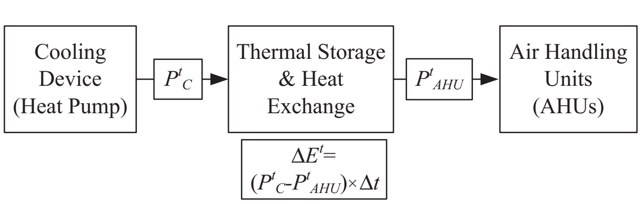

Fig. 1. Concept of A/C storage systems.

In this study, A/C storage systems are utilized to achieve two purposes: load shifting and compensation of wind power forecast errors. Energy capacity of the TES is the key limitation for the cooling power adjustment for both of the purposes. The proposed operation scheme divides the energy capacity of the TES into three parts, as shown in Fig. 2. The portions $[0, E_1]$ and $[E_2, E_{max}]$ are the upward and downward energy reserves to compensate wind power forecast errors, respectively. The portion $[E_1, E_2]$ is used for load shifting.

In day-ahead scheduling, P_C^t is optimized for load shifting. The dispatch of P_C^t is constrained so that the supply of P_{AHU}^t is guaranteed and the energy level of the storage device can only vary between E_1 and E_2. Besides, the upward energy reserve from 0 to E_1 is charged up and the downward energy reserve from E_2 to E_{max} is left empty.

In real-time operation, P_C^t is set according to the day-ahead schedule, and it may be further adjusted to cover the real-time wind forecast errors. If wind power is lower than the forecast, P_C^t may be decreased to serve regulation up, and the upward reserve (charged capacity) is used to cover the cooling demand; and if wind power exceeds the forecast, P_C^t may be increased to serve regulation down, and the downward reserve (uncharged capacity) is used to accept the excessive cooling capacity.

E_{max} is fixed for an A/C storage system, whereas E_1 and E_2 can be selected. The values of E_1 and E_2 should be determined by the features of wind power forecast errors. In the following sections, the proposed operation scheme is discussed in details with the analysis on wind power forecast errors.

3. Features of wind power/energy forecast errors

Historical wind data over two years, 2013 and 2014, from the European transmission system operator TenneT [23] is used for the analysis. The data includes the day-ahead forecasted and actual wind power outputs in 15-min time intervals.

The focus of this study is the methodologies to identify the features of wind power forecast errors from different aspects. The features themselves may be different for different locations and forecast methods. Thus, we do not attempt to fit the distributions of wind power forecast errors into specific analytical expressions.

Due to availability of data, wind data from TenneT is analyzed as an example, and the statistical results are fit into a hypothetical test system for simulation. To estimate the forecast errors of a specific wind farm, it would be better to apply the proposed methods to wind data from itself or nearby sites.

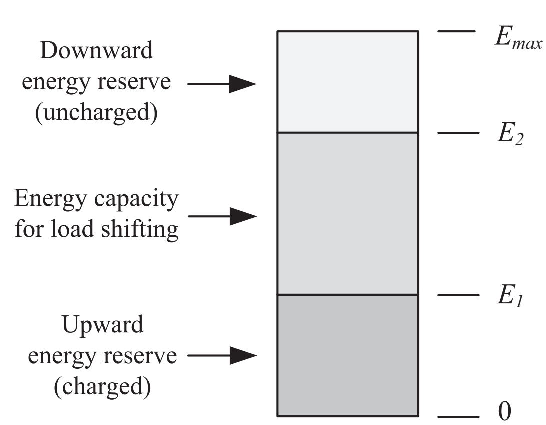

Fig. 2. Energy capacity of the thermal storage device.