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A real-time dispatch model of CAES with considering the part-load characteristics and the power regulation uncertainty

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ABSTRACT

Compressed Air Energy Storage (CAES) has its merits of large-scale, fast response, quick ramping and flexible operation, it can play an important role in power system real-time dispatch. However, there are very limited studies that focus on the real-time dispatch model of CAES. A specific model is developed in the paper for this purpose, which is based on a dispatch framework complied with the existing power control systems operated in China. The part-load characteristics of CAES and the power regulation uncertainty are considered in the developed model and thus it can mimic the practical situations. Then, an optimal real-time model for the power system with the CAES facility, the thermal unit and the wind farm is proposed. The concerned dispatch problem is converted into its equivalent deterministic linear formulation and then is solved. Numerical simulation results indicate that the CAES participation in the real-time dispatch can mitigate the wind curtailment and reduce the thermal unit's and the whole system's operation costs and the system Automatic Generation Control (AGC) cost. The results also show that the ignorance of the part-load characteristics and the power regulation uncertainty can result in the infeasibility of real-time scheduling decisions.

1. Introduction

Recently, large-scale Electrical Energy Storage (EES) attracts great attention in addressing the grid reliability and stability issues associated with a large amount of wind power integration. The total installed EES capacity in the US is forecasted to grow from 22 GW in 2014 to 103–152 GW by 2050, and the total installed EES capacity in China is forecasted to grow from 23 GW in 2015 to 53 GW by 2020 [1,2]. Among various EES technologies, Pumped Hydro Storage (PHS) and Compressed Air Energy Storage (CAES) are the two proven technologies suitable for large-scale operation [3]. However, the further development of the PHS has ceased due to the lack of suitable sites and high initial capital costs in some countries, e.g., UK and China [4,5]. Compared to PHS, the capital and maintaining costs of CAES can be relatively lower [5–7]. Thus, CAES is expected to be one of the most promising large-scale ESS technologies [5].

CAES technology has attracted much attention in research and industry [6–11]. At present, there are two successfully commercial CAES plants in operation: one is the Huntorf CAES plant in Germany built in 1978 and another is the McIntosh CAES plant in the US built in 1991 [8]. Both of them have been operated well over last two decades with high reliability [7]. In addition, some small-scale CAES demonstration facilities were recently built and some projects are underway around the world. General Compression constructed a 2 MW CAES project in Gaines, US, in 2012. It was claimed as the world's third CAES project [9]. A 1.5 MW adiabatic CAES demonstration facility located near Beijing, China, was recently built in 2015 and has been continuously operated [6]. In 2016, ALACAES built and tested an advanced adiabatic CAES plant in Swiss Alps, Switzerland [10]. Storelectric Ltd is planning to built a 40 MW 100% renewable energy pilot CAES plant in Cheshire, UK [11]. The construction of a 10 MW/40 MWh adiabatic CAES demonstration project is ongoing in Guizhou, China [8].

With the development of CAES technology, the optimal scheduling of CAES has became a very active research area in recent years. Jabari *et al* developed a methodology for day-ahead scheduling of a solar combined cool, heat and power system which is powered by a Stirling engine in the presence of an adiabatic CAES system [12]. Nojavan et al. proposed an optimal bidding and offering strategy of merchant CAES in day ahead electricity market with considering the electricity market as an uncertain parameter [13]. Soltani et al. proposed a stochastic multi-

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Nomenclature

A. Indices

t	index of time
k	index of compressor
j	index of turbine
i_{nA}	index of non-AGC unit
i_A	index of AGC unit

B. Sets

T	set of time periods
n_c	set of compressors
n_g	set of turbines
$N_{G,nA}$	set of non-AGC units
$N_{G,A}$	set of AGC units

C. Abbreviations

EES	electrical energy storage
CAES	compressed air energy storage
PHS	pumped hydro storage
AGC	automatic generation control
HPC	high pressure compressor
LPC	low pressure compressor
HPT	high pressure turbine
LPT	low pressure turbine
MIP	mixed integer programming

objective day-ahead scheduling model for the power system which contains thermal generation units, plug-in electric vehicles, demand response programs, CAES units and renewable distributed generations [14]. Park et al. provided a four-week optimal operation model for CAES coupled with wind farms to investigate its long-term impacts of integration operation [15]. Attarha et al. proposed an adaptive robust self-scheduling model for a wind producer paired with a CAES system to participate in the day-ahead energy market [16]. Ghaljehei et al. proposed a stochastic security-constrained unit commitment model to study the integration of CAES and the wind power; a static voltage stability was considered in the proposed model to ensure its technical feasibility of the scheduling decision [17]. Shafiee et al. developed a self-scheduling model of CAES with considering the thermodynamic characteristics. The model is used to maximize the profit of CAES in the day-ahead energy and reserve markets [18]. A day-ahead scheduling strategy of the power system with a CAES facility as well as thermal units and renewable resources was addressed in [19–21]. Li et al. developed an optimal day-ahead energy dispatch model for studying a zero-carbon-emission micro energy internet integrated with a micro adiabatic CAES plant [22]. The economic scheduling models of CAES developed in above literatures were all considered to be used in the day-ahead or long-term scheduling. From the above literature review, so far there is no research on the dispatch model of CAES with considering the real-time operating characteristics.

The real-time dispatch is an important link between day-ahead scheduling and Automatic Generation Control (AGC) [23]. It can be used to perform the optimal load allocation and predefine the AGC participation factors [23]. The CAES plant has the merits of large-scale, fast response, quick ramping and flexible operation [18,24]. It is considered that CAES can have great potentials in AGC power regulation and can play an important role in power system real-time dispatch [7,18,24]. Therefore, the development of a real-time dispatch model of CAES is quite important and it can extend CAES applications in concerned areas.

The power system real-time dispatch is the final stage of the power system multiple time scale scheduling [23]. It is impossible for the scheduling centre to modify the schedules after the real-time dispatch. Therefore, the feasibility of the real-time scheduling decision is very important. In order to develop the model more realistic and to ensure the feasibility of the scheduling decision, the two factors must be considered in the modelling process: (1) when the CAES system operates in part-load conditions, some CAES operational parameters deviate significantly from their rated values [5,6]; (2) after the CAES plant participates in AGC regulation, the compressing and generating powers are adjusted automatically by the AGC system. In this paper, the part-load characteristics of CAES is considered in the developed model, including the compression ratio, the compressor efficiency, the expansion ratio, the turbine efficiency and the air temperature. The power regulation uncertainty is also considered in the real-time dispatch to keep the operational conditions of CAES away from their limitations in both the real-time dispatch and the AGC stage.

The main contributions of this paper are as follow:

(1) The part-load characteristics of CAES are considered in the modelling process and the corresponding mathematical descriptions are derived in the developed real-time dispatch model.
(2) The compressing power, the generating power, the air pressure and the gas consumption all have correlations to the power regulation uncertainty in the developed dispatch model.
(3) The dynamic constraints of CAES under the real-time dispatch time scale are modelled, and the optimal real-time dispatch model for the power system with a CAES plant is developed.
(4) The CAES real-time dispatch model is converted into its equivalent deterministic linear formulation. The converted formulation can be solved by conventional solver.

The rest of the paper is organized as follows. In Section 2, the real-time dispatch framework is introduced, and the real-time dispatch model of CAES with considering the part-load characteristics and the power regulation uncertainty is presented. In Section 3, the optimal real-time dispatch model for the power system with a CAES plant is presented. In Section 4, the equivalent deterministic linear formulation of the model is presented. In Section 5, case studies are carried out to analyse the impact of CAES on power system real-time operation, and the impact of the part-load characteristics and power regulation uncertainty on the feasibility of the scheduling decision. Finally, Section 6 concludes the paper.

2. Model formulation of CAES in real-time dispatch

This section begins with a brief introduction of the real-time dispatch framework for the power system with a CAES facility. The framework is developed based on a real-time dispatch framework complied with the existing power control systems in China [23]. Then a thermodynamic model of CAES considering the part-load characteristics and the power regulation uncertainty is developed, which is used to calculate the operational conditions of CAES in real-time dispatch. Finally, the operational and dynamic constraints of CAES are formulated.

2.1. Introduction of the real-time dispatch framework

This framework coordinates dispatch instructions among the wind farm, the AGC unit, the non-AGC unit, and the CAES facility. The wind farm operates using a maximum power-point tracking strategy. AGC units and the CAES facility are controlled by AGC systems with