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Study on unit commitment problem considering pumped storage and renewable energy via a novel binary artificial sheep algorithm

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HIGHLIGHTS

- The UC problem consisting of RE uncertainty and PHES has been studied.
- The Binary sheep algorithm has been proposed to solve the UC problem.
- Impact of RE uncertainties is comprehensively analysed by a new evaluation method.
- Influence of PHES on the UC problem is quantitatively evaluated.

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ABSTRACT

Wind power and photovoltaic power, two types of renewable energy (RE), have made large inroads into the power system. In this paper, we study a unit commitment (UC) problem that considers the uncertainty in RE and pumped hydro-energy storage (PHES). To improve the optimisation performance for this problem, we propose a novel heuristic algorithm called the Binary Artificial Sheep Algorithm (BASA) that is based on the social behaviour of sheep flock. To evaluate the effect of the uncertainty of RE, a scenario evaluation method is defined to assess quantitatively the stability and economy of the UC results with respect to different levels of RE forecasting errors. In addition, we investigate and analyse the effect of PHES on the UC problem. Three UC test systems with different RE and PHES combinations are used to verify the feasibility and effectiveness of the proposed BASA as well as its performance. The proposed BASA performed better than traditional fundamental metaheuristics in solving UC problems. Our results also demonstrated that the equivalent load fluctuation and operating costs of the thermal units will increase significantly with an increase in RE power forecast error, but the PHES can effectively counterbalance this adverse effect.

1. Introduction

Compared with traditional fuels, renewable energy (RE) has advantages with respect to the environment and economy. With the increase in demand for energy, RE, mainly wind power and photovoltaic power [1], has made inroads into the power system. All RE sources are regarded as clean and economical and play a significant role as input into the power system. However, the fluctuation and uncertainty of RE can have a negative effect on the power system. One way to deal with fluctuations and uncertainty is to store electrical energy [2]. Flexible storage characteristics enable redistribution of energy from the entire system. Pumped hydro-energy storage (PHES) units, one type of electrical energy storage system, is an effective tool for modulating and stabilising a power grid that contains intermittent RE. PHES units help maintain the stability of the power system by adjusting the quantity of water in the upper and lower reservoirs.

An important issue in the operation of a power system is the unit commitment (UC) problem, the goal of which is to obtain the optimal scheme that meets the power demand at a minimum operating cost by optimising the unit on/off state and the dispatch of the power load of corresponding units [3]. The focus of research on traditional UC problems is only thermal power-generating units. With the development of power systems that integrate RE sources with traditional sources, the UC problem has become more complex. Different factors have been considered in UC problems, including multiple types of resources [4], uncertainties of RE [5–8], the effects of PHES [9,10], and multiple objectives of the power system [11]. Although these issues have been studied, some issues still need to be investigated in depth.

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Nomenclature

s	index for scenario
T	number of scheduled hours
N	number of units
$I_{i,t}^s$	state (on/off) of unit i at time t in scenario s
$P_{i,t}^s$	output power of unit i at time t in scenario s
a_i, b_i, c_i	fuel cost coefficients of thermal unit i
$HSU_{i,t}$	hot start-up cost of unit i at time t
$CSU_{i,t}$	cold start-p cost of unit i at time t
$T_{i,t}^{off}$	continuously off time of unit i at time t
T_i^{cold}	cold start hours of unit i
F^s	total cost of unit
$P_{w,t}^s$	generation output of wind power at time t in scenario s
$P_{v,t}^s$	generation output of photovoltaic power at time t in scenario s
$P_{c,t}^s$	generating power of PHES at time t in scenario s
$P_{d,t}^s$	pumping power of PHES at time t in scenario s
$P_{i,ramp}$	generation output ramping up capacity of thermal unit i
L_t	system demand at time t
$\overline{P}_i$	maximum power generation of thermal unit i
$\underline{P}_i$	minimum power generation of thermal unit i
R_t	spinning reserve at time t
$rr_{i,t}$	continuously on time of unit i at time t
$zz_{i,t}$	continuously off time of unit i at time t
$T_{i,on}$	minimum up time of unit i
$T_{i,down}$	minimum down time of unit i
$\underline{P}_d$	minimum pumping power of PHES
$\overline{P}_d$	maximum pumping power of PHES
$\underline{P}_c$	minimum generating power of PHES
$\overline{P}_c$	maximum generating power of PHES
WE_u	capacity of upper reservoir
WE_{umax}	maximum capacity of upper reservoir
$WE_{d\,max}$	maximum capacity of lower reservoir

Uncertainties in the forecasting of RE power greatly affect the solution of the UC problem and pose serious risks to the control and operation of the power system. Therefore, simulating the fluctuation in RE power is important to solving the UC problem with RE integration (UCRE). Ji et al. [5,6] introduced a model of the UC problem with wind power integration and applied chance-constrained programming to simulate the effect of wind power fluctuation, which was based on the joint probability distribution of wind power. However, the basis of chance-constrained programming is a Monte Carlo algorithm for which a large amount of data must be generated to ensure the reliability of the results, thus restricting the efficacy of the calculation. Rui et al. [12] proposed a robust optimisation method to handle the uncertainty of wind power by imposing constraint scenarios in the UC model while using a Monte Carlo method to automatically simulate the worst scenario to evaluate the greatest effect of RE on system operations. Wang et al. [13] proposed a novel security stochastic UC method that involves the effect of the worst-case scenario of wind power variability on UC. However, the worst-case scenario is not sufficient to represent the variability of wind power. In Refs. [14,15], a scenario tree represented the possible wind power outputs that were decided by the wind fluctuation rule. However, this method was considered inefficient because, even for a small scenario tree, it created numerous variables. In [16,17], the efficient method of Latin hypercube sampling (LHS) combined with Cholesky decomposition (LHS-CD) was utilised to generate different large scenarios to simulate the uncertainty of wind power. In addition to the theoretical distribution of this scenario simulation method, an empirical cumulative distribution function was used to characterise the uncertainty of wind power [18,19]. Although simulations of RE scenarios have been the focus of much attention, evaluation of scenarios has been inadequate, although this evaluation is important in UCRE for selecting a representative scenario. A performance index [16] for evaluating a scenario with respect to security and operating cost was applied in UCRE [16,17]. This index is sensitive only to the overall amount of RE power and cannot measure its variation. Thus, a scenario close to the upper boundary of the RE power interval will be selected as a typical difficult case to challenge the UC procedure. However, variation in RE power is also important in selecting the extreme scenario. The effect of large fluctuations in RE power on security and operating costs is great. To overcome the drawbacks of existing methods for scenario evaluation, we propose a new method that can comprehensively assess the effect of saving operating costs and restraining load fluctuation.

The effect of PHES on power systems is an important topic and their effect on UC problems has been studied previously [19–24]. In Ref. [19], the authors proposed a PHES-integrated UC model that minimises the fuel, start-up, and emission costs of a thermal system and considers variable start-up costs and constant start-up ramps of the thermal units. However, intermittent renewable power is not included in this model. Deane et al. [20] presents a model of a large PHES in a power system with high wind power penetration and shows how to formulate day-ahead and week-ahead reservoir targets in the context of uncertainty in wind forecasting. Khodayar et al. [21] studied the hourly coordination of wind power with PHES in a stochastic security-constrained UC while considering the errors in the wind and load forecasts [21]. In Ref. [22], the effect of PHES on the plans to expand the generating capacity of the Northern Ireland power system was analysed by considering different capacity levels of installed wind power and the costs of both fuel and emissions. Pérez-Díaz and Jiménez [23] proposed an interval UC formula for optimising both controllable generation and PHES based on a model of the Belgian power system to compare the resulting operating costs, reliability, and computational requirements. However, the quantitative effects of PHES on system operations were not analysed in these studies. Bruninx et al. [24] considered constant start-up costs and ramps for the thermal generating units in the assessment of the UC problem of a hydrothermal power system with penetration large amount of integrated wind power and quantitatively analysed the contribution of PHES to the reduction of scheduling costs. However, the forecast error level was not considered. Jiang et al. [25] proposed a robust optimisation approach to accommodate wind output uncertainty by considering the worst wind power scenario with the support of PHES unit. In Ref. [25], RE and PHES have been considered in UC problem, and the results revealed the impacts of increase of wind power penetration, however the influence of PHES was not evaluated. Although there are published studies on the effects of PHES, no previous work has evaluated the quantitative effect of PHES on operating costs, the load fluctuation of a UCRE problem for different levels of RE power forecast errors, and PHES capacity.

Researchers have designed different types of optimisation methods to solve UC problems effectively, including dynamic programming (DP) [26,27], mixed-integer linear programming (MILP) [28,29], Lagrangian relaxation (LR) [30], and the priority list method (PL) [31]. These traditional methods deal with the UC problem by using different calculation methods, but they still have