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A scenario-based planning framework for energy storage systems with the main goal of mitigating wind curtailment issue

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ABSTRACT

This paper provides a new multi-objective (MO) framework for expansion studies of energy storage systems (ESSs) in high wind penetrated power system. The proposed approach well considers the issues originated from the wind power curtailment via introducing expected of wind curtailment cost as an objective function of the studies. All other imposed costs of installing storage units are modeled as expected of total social cost. Also, the effect of uncertainties is modeled through an internal scenario analysis. In this regard, two criteria including maximum regrets of wind curtailment cost and total social cost are considered as the other objectives of the proposed MO optimization procedure. These all the crucial and maybe contradictory aspects of the ESSs expansion problem are treated via a Posteriori MO optimization algorithm, i.e. the Non-dominated Sorting Genetic Algorithm II (NSGA II). The proposed methodology is implemented on the modified IEEE 24-bus test system and its anticipated applicability is well verified.

1. Introduction

UNCERTAIN fuel prices and also global climate changes are accompanied by some state initiatives such as renewable portfolio standards (RPS) [1]. This has caused a fast growth in the amount of renewable energy installed worldwide over the last decades. Among various renewable energy technologies, wind power has experienced a remarkable development. The total installed wind power capacity at the end of 2017 was 539.6 GW which can be translated to more than 11% increase in the cumulative installed capacity compared to the corresponding amount in 2016 [2]. However, the intrinsic characteristics of wind farms output power, i.e. intermittency and being 'non-dispatchable' in output generation of wind turbine raises many new major technical and financial challenges for power system operators and planners [3]. Requiring more installed and operating reserve, increase in ancillary service cost, and also imposing new uncertainties in the operational and planning studies are some of these unavoidable challenges [4]. Up to these issues, the large level of wind power penetration causes a growing concern in wind energy curtailment issue.

Since the output generation of wind farms cannot be controlled; and due to transmission constraints, oversupply in low load periods, and also inaccurate wind speed forecast, the wind farm's operator may be forced to curtail the amount of extra wind power [5]. Based on a report published by national renewable energy laboratory (NREL), the level of wind curtailment experienced in the Electric Reliability Council of Texas (ERCOT) was more than 16% of wind generation in 2009. ERCOT has reduced this amount of wind curtailment by investing in the transmission network and redesigning the market, as the level of wind curtailment improved to the amount of less than 2% in 2013 [6].

In response to this restrictive issue, researchers have tried to suggest some short-term and long-term solutions to alleviate the curtailment issues. Amongst, employing energy storage systems (ESS) is introduced as an effective long-term solution to alleviate the wind energy curtailment problems [7]. It has been shown that presence of ESSs in a high wind penetrated power system can result in several benefits including renewable energy time-shift, renewable capacity firming as well as transmission and distribution reinforcement deferral [8]. This can be achieved by charging the ESS units during periods of wind farms excess generation and discharging at times there is neither enough transmission capacity nor low consumption of electrical energy. Nonetheless, the authors in [9] have shown that due to the additional capital cost of ESSs, employment of these units only with the goal of reducing the wind curtailment is not a viable and economical solution especially in a system with the low and medium level of wind power penetration. As a consequence, aimed to reach the beneficial features of ESSs, it is required to develop a well-organized multi-criteria framework for planning studies of the ESSs, which is the main concern of this paper.

Among all energy storage technologies, pumped hydro energy

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Nomenclature

Variables

$P_{w,rated}$	rated wind power output (MW)
P_j^{inj}	injected power at bus j (MW)
$P_{S_{i,t}}^{Sen}$	power of ith storage at hour t (MW) for sensitivity criterion calculation
$P_{W_{i,t}}^{\max}$	maximum available wind power of the ith wind farm at hour t (MW)
$P_{W_{i,t}}$	power output of the ith wind farm at hour t (MW)
$S_{i,t}$	energy stored in the ith storage at hour t (MWh)
$P_{S_{i,t}}$	power of ith storage at hour t (MW)
$P_{ij,t}$	active power flow in a branch in the right-of-way i-j
$S_i^{\max}$	maximum energy capacity of ith storage (MWh)
$P_{S_i}^{\max}$	power rating of the ith storage (MW)
$C_{s,OP}^A$	annualized operation cost of all storage systems in scenario s ($)
C_{OP}^A	annualized operation cost of all storage systems ($)
$C_{s,cong}$	total congestion cost in scenario s ($)
C_{cong}	total congestion cost ($)
$C_{s,LC}$	total load curtailment cost in scenario s ($)
C_{LC}	total load curtailment cost ($)
P_{WL}^t	total curtailed wind power at hour t (MW)
$D_{L_{i,t}}$	curtailed load at bus i at hour t (MWh)
$\overline{X}_s$	optimal solution in scenario s

Parameters

V_{ci}, V_{co}, V_r	cut-in, cut-out, and rated wind speeds (m/s)
$\eta_{c,s}$, $\eta_{d,s}$	charging and discharging efficiencies
d_s	hourly self-discharge rate of the storage
RU_{S_i}, RD_{S_i}	ramp up and ramp down of the ith ESS (MW)
P_s	occurrence degree of scenario s
λ_w	wind curtailment penalty cost ($/MWh)
λ_D	load curtailment penalty cost ($/MWh)
T	simulation time horizon (h)
d	discount rate
N	life time of investment
μ_{d_i}	desirable level of ith objective function
μ_{f_i}	satisfaction level of ith objective function

Sets

Ω_W	set of wind farms
Ω_L	set of transmission lines
Ω_D	set of load buses
Ω_S	set of scenarios
Ω_B	set of all buses
Ω_N	set of non-dominated solutions

storage (PHES) and compressed air energy storage (CAES) are the most promising and commercially acceptable grid-scale energy storage technologies for wind integration purposes because of their large power capacity, long lifetime, and low operation costs. The major difficulty in integration plans of the PHES units is their dependence on specific geographical location. It is usually difficult to identify a suitable site for the PHES with two large reservoirs located at different elevations and be close to the electric grid [10]. In contrast, the geographical location is not a bounding constraint for installing new CAES units. It has been shown that over 80% of the United States is geographically suitable for CAES technology [11].

In the literature, many studies have been conducted on optimal placement and sizing of ESSs in renewable-based power systems. Zhao et al. [12] proposed a deterministic model for optimal siting and sizing of ESSs with the main goal of mitigating the wind power fluctuations during the interval between two rolling economic dispatches. Park and Baldick [13] proposed a mixed integer programming (MIP) planning framework to determine the optimal locations and capacity of CAES to increase wind power production satisfying 20% RPS. Then, the proposed method implemented on the ERCOT transmission system. Hozouri et al. [14] introduced a combinational planning framework to identify the optimal placement and sizing of the PHES units as well as reinforcement plans of the transmission grid. Ghofrani et al. [15] proposed a two-stage probabilistic model for optimal siting of CAES units with the objective function of minimizing hourly social cost and maximizing wind power utilization. Zhang et al. [16] described a chronological production simulation platform and its application in identifying optimal sizing of pumped storage for the Jiangsu (China) considering the sum of operating and investment costs as the objective function. Ghofrani et al. [17] proposed an optimization framework to stochastically model wind generation, load, and equipment availability to find the optimal siting and sizing of ESSs by minimizing the sum of operation and load curtailed costs over a planning period. Jabr et al. [18] proposed a tool for ESS planning problem by a robust optimization method. The proposed optimization problem has been developed to minimize the investment cost of ESSs without load and wind power curtailment. Finally, the proposed ESS planning obtain the optimal placement and sizing of ESSs in transmission network level. Wang and Yu [19] proposed an effective method to determine the optimal power rating and capacity of a CAES system in high wind penetrated power system with the main goal of maximizing economic profit. The result of this study indicated that the optimal CAES system's size is influenced by gas price, discount rate, and carbon compensation policy.

In all the above-reviewed papers, the authors have assumed that wind farms location and capacities are known and firm. In other words, all these papers have ignored uncertainties associated with the expansion of generation sector, especially uncertainty in the expansion of wind farms. In unbundled power systems, the system operators cannot certainly predict the expansion plans decided by the private investors. This escalates the available uncertainties and imposes new uncertainties. The uncertainties which system planners are dealing with them can be classified into two main categories, random (probabilistic) and non-random (bounded) uncertainties [20]. For instance, the uncertainty of the generation expansion plan has a nonrandom behavior and belongs to nonrandom uncertainty category which scenario-based approach should be used to tackle with this type of uncertainty [21].

To fill this gap, this paper proposes a scenario-based multi-objective (MO) framework for the problem of the ESSs expansion planning studies in high wind penetrated power system. The main contributions of this paper can be accounted as follow:

- The issues associated with the curtailment of wind farms are properly considered in the expansion studies via introducing an objective function of the optimization problem, i.e. expected of wind curtailment cost.
- The uncertainties associated with the expansion plans of the generation sector are properly modeled via an internal scenario analysis.
- A sensitivity analysis criterion has been developed to determine some candidate buses for installing of ESSs and limit the numbers of decision variables.
- A well-organized MO algorithm is proposed to effectively deal with different aspects of the expansion studies.
- A strong Posteriori optimization tool, i.e. Non-dominated Sorting Genetic Algorithm II (NSGA II) is used to solve the modeled MO optimization problem.