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Developing a multi-objective framework for expansion planning studies of distributed energy storage systems (DESSs)

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ABSTRACT

This paper presents a framework for expansion planning studies of distributed energy storage systems (DESSs) in high wind penetrated power systems. The main objective is to find optimal location and capacity of DESSs in the viewpoint of independent system operator (ISO) while ensuring the maximum usage of wind farms output generation. Three different criteria are introduced for expansion planning studies. Minimizing wind curtailment cost together with transmission congestion cost are considered to properly deal with the issues associated with the curtailment of wind energy and constraints of transmission network. Furthermore, the minimum normalized profit for all DESSs' owners needs to be maximized to model the requirements of DESSs' owners in the studies. These all the crucial aspects of the DESSs expansion problem are treated via a well-organized posteriori multi-objective (MO) optimization algorithm, i.e. the Non-dominated Sorting Genetic Algorithm II (NSGA-II). The proposed method is applied to the modified IEEE 24-bus test system, and the results are presented to verify the applicability and efficiency of the proposed DESSs planning in a renewable-based power system.

1. Introduction

Variability and unpredictability nature of renewable energy sources (RESs) especially wind energy pose significant challenges in operation and planning studies of power system [1]. Energy storage systems (ESSs) have been introduced as a sustainable solution to mitigate these challenges [2], and therefore facilitate the integration of wind energy in generation sector of power systems [3]. Based on a report, California passed an ESS mandate calling for 1325 MW of energy storage by 2020 aims to reach 33% of its power supply from RESs [4].

ESSs can be classified into two main categories, centralized energy storage system (CESS) and distributed energy storage system (DESS). CESSs can be described as some large-scale storage systems that could be placed along sub-transmission and transmission networks, and be dispatched by independent system operator (ISO). On the other hand, DESSs tend to be smaller units, in a numerous number, and connected to distribution and electric utility customer levels, and often controlled by load aggregators with the main goal of obtaining maximum profit [5]. The most common commercialized ESSs technologies are CESSs. These technologies are known as bulk ESSs because of their high technical maturity and large energy capacity. However, because of some superiorities of DESS compared to CESS, these technologies are very close to commercialization stage [6]. An important superiority of DESS compared to CESS is that DESS is not subject to geographical restrictions. For instance, pumped hydro energy storage (PHES), the most promising CESS technology, is only available in mountainous areas [7]. However, battery or flywheel as DESS technologies can be placed everywhere on the power grid either near the generators or near the customers. The main technologies of DESS include flywheel, battery, and electric vehicle (EV). The battery of EVs can be used as distributed energy storage resources taking into consideration this fact that most EVs are plugged in for over 90% of the time in a day [8]. In recent years, with the rapid growth of battery technology, battery energy storage systems (BESSs) and EVs have become the most popular types of DESS.

Deployment of ESSs in electricity industry as an energy resource, however, is dependent on several services provided by them. Some of these services such as ancillary services and temporal arbitrage have no relation with the place of ESSs. In contrast, other services like mitigating congestion in transmission lines and

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Nomenclrure

A. Variables

$D_{i,t}^{\mathrm{mod}}$	Adjusted demand of the ith aggregator at hour t (MW)
$P_{i,t}^{C}$	Charge power of the ith storage at hour t (MW)
$P_{i,t}^{D}$	Discharge power of the ith storage at hour t (MW)
$S_{i,t}$	Energy stored in the ith storage at hour t (MWh)
$S_i^{\min}$	Minimum energy stored in the ith storage (MWh)
$S_i^{\max}$	Maximum energy stored in the ith storage (MWh)
$P_{W_{i,t}}$	Power output of the ith wind farm at hour t (MW)
$P_{G_{i,t}}$	Power output of the ith conventional generator at hour t (MW)
$U_{i,t}$	0/1 for charge/discharge of the ith storage at hour t
$P_{S_i}^{\max}$	Power rating of the ith storage (MW)
P_{WL}^{t}	Total curtailed wind power at hour t (MW)
$C_{D,NS}^{A}$	Annual paid cost without storages ($)
$C_{D,WS}^{A}$	Annual paid cost with storages ($)
C_{OP}^{A}	Annual operation cost of all storages ($)
C_{Inv}^{A}	Annualized investment cost of all storages ($)

B. Parameters and Constants

$\rho_{i,t}$	Forecasted hourly market prices of the ith aggregator at hour t ($/MWh)
$P_{W_{i,t}}^{\max}$	Maximum available wind power of the ith wind farm at hour t (MW)
$P_{G_i}^{\min}, P_{G_i}^{\max}$	Minimum and maximum power of the ith conventional generator (MW)
$D_{i,t}$	Demand of the ith aggregator at hour t (MW)
$S_i^{initial}$	Initial energy stored in the ith storage (MWh)
$\eta_{c,i}$, $\eta_{d,i}$	Charging and discharging efficiencies
RD_i, RU_i	Ramp up and ramp down of the ith storage (MW)
λ_W	Wind energy curtailment penalty cost ($/MWh)
$f_{ij}^{\max}$	Maximum capacity of line ij (MW)
μ_{f_i}	Satisfaction level of the ith objective function
μ_{d_i}	Desirable level of the ith objective function
T	Simulation time horizon (h)
d	Annual discount rate
N	Life time of investment (year)

C. Sets

Ω_D	Set of load buses
Ω_G	Set of conventional generators
Ω_{DESS}	Set of storage systems
Ω_L	Set of transmission lines
Ω_W	Set of wind farms
Ω_N	Set of non-dominated solutions

minimizing wind energy curtailment can only be met by choosing proper capacity and location for the ESSs [9]. This can be translated to the crucial importance of ESSs siting problem in power system studies.

In recent years, many published papers can be found with the subject of ESSs utilization into modern power systems. Some published papers aim to determine the optimal location and capacity of CESSs in transmission network with the main purpose of mitigating the wind energy curtailment and transmission congestion. Pandzik et al. [9] proposed a three-stage planning procedure, that in the first and second stage, the optimal location, as well as energy and power rating, have been identified, respectively. Finally, in the third stage, the optimal operation of the storage systems is simulated to assess the benefits that they would provide by mitigating congestion of transmission lines. Hemmati et al. [10] proposed a new stochastic model for planning and scheduling of ESSs with the main goal of congestion management in transmission network including RESs. The proposed model finally determine the optimal capacity and charging schedule of ESSs. Cleary et al. [11] estimated the quantity of wind energy curtailment in Ireland power system for different scenarios such as with or without compressed air energy storage (CAES) on 2020 and concluded that the addition of CAES reduces wind farm's economic risk. Hozouri et al. [12] introduced a combinational multi-criteria 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. [13] proposed a two-stage probabilistic model for optimal siting of CAES units within a deregulated power system to minimize the hourly social cost by using the probabilistic optimal power flow, and maximize wind power utilization over the scheduling period using the genetic algorithm (GA).

All of the literature addressed above have not considered energy storage systems as independent entities, and have assumed that their installing and dispatching is governed by ISO to improve the operation of bulk power system. While the penetration of DESSs is increasing, it is essential to develop proper modeling procedure for these dispersed units in operation and planning studies of modern power systems.

Distributed energy storage technologies play a vital role in modern distribution systems. These technologies as promising resources help to reach more efficient smart grids. In addition, the development of DESSs enables load aggregators to store electricity at periods of lower prices and use that stored energy to supply the demands during peak periods instead of purchasing energy from the upstream network [14]. Therefore, the DESSs can support multiple applications for load aggregators, such as load management, price arbitrage, and improving power quality. Due to these wide applications, DESSs are receiving increasing attention in distribution level of power system.

The optimal sizing and siting of DESSs in distribution system level with the purpose of maximizing benefits for local distribution company are addressed in some studies. Celli et al. [15] proposed an optimal BESS allocation method based on the GA with the objective of minimizing overall network cost (summation of capital and operational costs of BESSs). This paper assumed that load aggregators are the operator of storage devices, and their optimal charge/discharge profiles are obtained by developing an inner algorithm based on dynamic programming. Sedghi et al. [16] presented a planning procedure for batteries in the distribution network to reach the optimal location, capacity, and power rating of these devices. In this paper, the optimal long-term planning that is based on the short-term probabilistic power flow solved by a hybrid Tabu search/particle swarm algorithm. Xiao et al. [17] proposed a bi-level optimization procedure to determine the optimal location and capacity of BESSs in distribution system level. In this bi-level optimization, the optimal location and capacity have been determined