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The value of energy storage in optimal non-firm wind capacity connection to power systems

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ABSTRACT

Wind is a variable and uncontrollable source of power with a low capacity factor. Using energy storage facilities with a non-firm connection strategy is the key to maximum integration of distant wind farms into a transmission-constrained power system. In this paper, we explore the application of energy storage in optimal allocation of wind capacity to a power system from distant wind sites. Energy storage decreases transmission connection requirements, smoothes the wind farm output and decreases the wind energy curtailments in a non-firm wind capacity allocation strategy. Specifically, we examine the use of compressed air energy storage (CAES) technology to supplement wind farms and downsize the transmission connection requirements. Benders decomposition approach is applied to decompose this computationally challenging and large-scale mixed-integer linear programming (MILP) into smaller problems. The simulation results show that using energy storage systems can decrease the variation of wind farms output as well as the total cost, including investment and operation costs, and increase the wind energy penetration into the power system.

1. Introduction

Wind power has been experiencing very rapid growth around the world. However, there are some issues associated with the wind power that should be considered when planning these resources. One important issue is the variability of wind speed that leads to partially dispatchable nature of wind farms [1]. Also, the remoteness of the wind-rich areas requires long transmission lines for connection to the existing network. Furthermore, wind-rich sites are in open areas with low population density. Transmission networks in these areas are not best designed to absorb all the power from these new power producers [1].

To increase wind energy penetration in a power system, optimal wind capacity allocation strategies should be used to cope with above-mentioned problems. However, due to the fluctuating output and site dependent characteristics, as well as the possibility of wind speed profile in a direction opposite to the load profile, a comprehensive analysis over an extended time is needed to find the optimal locations for wind farms [2]. In Refs. [2,3], the authors proposed a model for wind capacity allocation to potential wind sites to maximize firm wind connection to the transmission network. However, they conclude that a firm connection is not the best choice for connecting a wind farm to a power system. By definition, a firm connection for a wind farm does not involve any wind curtailments due to network capacity limitation. In contrast, when a non-firm connection is assumed, the independent system operator is allowed to curtail wind energy in some situations due to power system security constraints. In Ref. [4], a model for optimal non-firm wind capacity connection to the congested transmission systems is presented. In this study, extensive wind profile, load demand profile, fuel price and contingency management sensitivities are examined and their effects on the optimal wind capacity allocation is shown. These studies do not consider the transmission connection requirements for wind farms, which is a significant cost component of remote wind farms with capacity factor between 20 and 50%. In our previous work [5], a model for optimal wind power

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Nomenclature

Constants

IC_f^W	annualized investment cost for 1 MW wind farm for site f
IC_f^{Tl}	annualized investment cost for 1 MW transmission line for site f
IC_f^C	annualized investment cost for 1 MW CAES compressor for site f
IC_f^E	annualized investment cost for 1 MW CAES expander for site f
IC_f^S	annualized investment cost for 1 MWh CAES storage for site f
η_C	CAES compressor efficiency
η_E	CAES expander efficiency
v_i	cut-in wind speed of wind turbine
v_o	cut-out wind speed of wind turbine
v_r	rated wind speed of wind turbine
C_T	total wind farm capacity desired to be installed
v	wind speed
$G(v)$	nominal 1-MW wind power output function
P_{WF}	wind farm power output function
d_f	distance of wind site f from grid

Variables

$F_k(w,h)$	production cost of unit k in period (w, h)
$SD_k(w,h)$	shutdown cost of unit k in period (w, h)
$SU_k(w,h)$	startup cost of unit k in period (w, h)
OC^n	total operation cost in iteration n
$C_{f,\max}$	maximum wind farm capacity of site f
C_f^W	wind farm capacity optimization variable for site f (MW)
C_f^{Tl}	transmission line capacity optimization variable for site f (MW)
C_f^C	CAES compressor capacity optimization variable for site f (MW)
C_f^E	CAES expander capacity optimization variable for site f (MW)
C_f^S	CAES storage capacity optimization variable for site f (MWh)
$P_{f,w,h}^W$	wind power production of farm f in period (w, h)
$S_{f,w,h}$	amount of energy stored in CAES of site f in hour h
$P_{f,w,h}^{Inj}$	amount of power injected into grid from site f in period (w, h)
$P_{f,w,h}^E$	CAES expander power production of site f in period (w, h)
$P_{f,w,h}^C$	CAES compressor power consumption of site f in period (w, h)
$P_{f,w,h}^{Cur}$	amount of wind curtailment of farm f in period (w, h)
$\pi_{W,f}^n(w,h)$	dual multiplier of wind farm capacity constraint of site f in period (w, h) and iteration n
$\pi_{Tl,f}^n(w,h)$	dual multiplier of transmission line capacity constraint of site f in period (w, h) and iteration n
$\pi_{C,f}^n(w,h)$	dual multiplier of CAES compressor capacity constraint of site f in period (w, h) and iteration n
$\pi_{E,f}^n(w,h)$	dual multiplier of CAES expander capacity constraint of site f in period (w, h) and iteration n
$\pi_{S,f}^n(w,h)$	dual multiplier of CAES storage capacity constraint of site f in period (w, h) and iteration n

Sets

W	set of index of all weeks
K	set of index of all units
F	set of index of all wind sites
H	set of index of all hours in a week
N	set of index of all iterations

capacity allocation considering transmission connection requirements is presented. It simultaneously optimizes the wind farms and their transmission connection requirements capacities. Its results suggest that downsizing the transmission connection would be beneficial for remote wind farms. However, downsizing the transmission connection would cause wind energy curtailment. Storage technologies can provide a solution to wind farm integration problems. Energy storage systems have many benefits for remote wind farms; they increase the overall capacity factor of the wind farm transmission connection, decrease wind curtailments, provide firm capacity, provide ancillary services, and can be used to shape wind farm output [6]. However, the joint planning of wind farms and energy storage facilities has not been explored yet, which is the subject of this paper.

There are different storage technologies, which are economical at different scales. At present, few technologies such as pumped hydro storage and CAES are economical and practical for storing large amounts of wind energy [7]. Since the pumped-hydro storage units are site-dependent, they cannot be used for supplementing wind farms at their sites. In CAES the air can be compressed underground in a solution-mined salt cavity, mined hard rock cavity or in a tank above the ground. A typical CAES unit has electrical round-trip efficiency of %77 to %89 [7]. Remote CAES units also have the benefits of using alternatives to natural gases such as coal and biomass [6].

The benefits of using CAES to supplement the wind energy from a remote wind farm are investigated in Ref. [7]. In this study, two cases with different conditions are studied and compared for supplementing the wind farms: CAES and gas turbines. In Ref. [6], the importances of CAES units for supplementing wind farms in a transmission constrained power system are studied. This study considers two options for locating CAES units: near load centers and near wind farms, and investigates the advantages and disadvantages of each choice. Several other studies have explored the use of energy storages for a variety of goals [6–10].

In this paper, we allocate a fixed amount of wind power capacity between candidate wind sites to minimize the investment cost and the power system operation cost. The use of CAES units is explored to supplement the wind farms and increase the transmission connection lines capacity factor. We optimize the transmission lines and CAES components capacities along with wind farms capacity simultaneously. The proposed model is applied to IEEE 24 bus test system and the results are presented and discussed. The rest of the paper is organized as follows: the combined model of wind farm and CAES is presented in Section 2. Section 3 describes the problem and the proposed methodology to solve it. The simulation results and conclusion are given in Sections 4 And 5 respectively.