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Cost analysis of a power system using probabilistic optimal power flow with energy storage integration and wind generation

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ABSTRACT

This paper examines the storage application and its optimal placement for the social cost and transmission congestion relief of wind integration. Probability density functions (PDFs) are used to characterize the uncertainties of wind speed and load. A probabilistic optimal power flow (POPF) is developed using two-point estimation which incorporates the storage system either as a variable load or as a variable generator. Storage systems are optimally placed and adequately sized using a particle swarm optimization (PSO) to minimize the sum of operation and congestion costs over a scheduling period. A technical assessment framework is developed to enhance the efficiency of wind integration and evaluate the economics of storage technologies and conventional gas-fired alternatives. The proposed method is used to carry out a cost-benefit analysis for the IEEE 24-bus system and determine the most economical technology. Optimal storage distribution and its potential to relieve the transmission congestion are evaluated for higher wind penetration levels.

1. Introduction

Recent developments in advanced energy storage technologies combined with the associated technical, economic and environmental benefits provide energy storage systems with a broad range of potential to optimize grid connected wind power resources [1]. Integration of wind generation with more than 20% penetration levels requires additional regulation and spinning reserve resources for grid stability purposes. These services incur some costs which have been the subject of several investigations in the US and Europe [2–6]. Increasing amounts of these costs with wind penetration levels gives an opportunity for energy storage systems to provide all or some portion of these ancillary services. Rated capacity of the wind power is the determining factor in calculating the amount of grid capacity required to accommodate the full wind power resource. However, average capacity of wind power is typically between 30% and 40% of rated capacity. This is due to the intermittent nature of wind power which makes it a variable and uncertain energy resource. Therefore, when compared with conventional generating technologies, more transmission capacity per unit of delivered wind energy is assigned to deal with wind power intermittency [1]. Wind power may be curtailed during high wind periods to avoid transmission congestion. This may impose an extra cost to the grid operators or a loss of revenue to the wind generators. Energy storage can be used to store the wind energy in excess of transmission capacity and dispatch it later when transmission capacity is available. Effective utilization of transmission capacity could be realized by optimizing the placement and scheduling of energy storage. This results in transmission congestion relief and/or transmission expansion deferral [7]. Adequate sizing of energy storage is also required to efficiently integrate renewable resources and justify the cost of storage deployment over the more conventional alternatives [8]. Therefore, application of large-scale energy storage for renewable integration calls for a techno-economic assessment framework to enhance grid operability and reduce operation cost [9–11]. This is particularly essential for transmission congestion relief application whose lack of operational practices limits the knowledge about operating, siting, sizing, and optimal scheduling of energy storage technologies in power systems with renewable energy sources. This has been the subject of investigation in few publications [12,13]. Wind uncertainties are not considered in [12], which questions the applicability of the proposed methodology for real world problems. In addition, the compressed air energy storage (CAES) is arbitrarily placed close to the wind resource and/or load center, with no attempt at optimizing its location and size to minimize congestion-related costs. Ref. [13] concludes with installing storage systems at locations that are downstream from the point of congestion in a transmission system. This would allow for the transmission of energy for charging when there is no congestion. The stored energy can be later discharged to reduce transmission capacity requirements during peak load periods. However, this conclusion cannot be generalized for a transmission network where the presence of several transmission lines and load centers complicates the optimal placing problem.

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Nomenclature

a_i, b_i, c_i	cost function coefficients of the *i*th generating unit
A	equivalent annual cost of the investment
c_1	cognitive parameter for PSO
c_2	social parameter for PSO
C_C	cost of compressor for CAES
C_S	cost of reservoir for CAES
C_T	cost of turbine for CAES
C_{NG}	natural gas cost for CAES
C_{OM}	operation and maintenance cost for CAES
CC	congestion cost of the power system
d	discount rate
d_S	self-discharge rate of the storage system
$f_{ij,t}$	power flow from bus *i* to bus *j* at time *t*
$\bar{f}_r$	maximum flow of line *r*
G_W	wind output power
G_{W_r}	wind rated power
G_{W_t}	wind output power at time *t*
G_{S_t}	generation capacity associated with the storage at time *t*
$Gbest^m$	vector of global best position attained among all particles in the swarm at the *m*th iteration
H_{r-i}	generalized distribution factor of line *r* with respect to bus *i*
HR	heat rate of turbine for CAES
IC_S	total investment cost for the storage system
IC_G	investment cost for the gas-fired generators
L_{S_t}	variable load associated with the storage at time *t*
L_{M_t}	modified load of the system at time *t*
L_{T_t}	total load of the system at time *t*
L_{B_t}	base load of the system at time *t*
LF	Lagrange function for the OPF
LMP_i	locational marginal price at bus *i*
n	number of probabilistic variables
n_b	number of buses
n_g	number of generating plants
N	life time of the investment
OC	operation cost of the power system
OC_S	operation cost of the storage system
OC_G	operation cost of the gas-fired generators
$P_{d_{i,t}}$	load demand at bus *i* at time *t*
$P_{g_{i,t}}$	generation of the *i*th generating plant at time *t*
$P_{g_{i,t}-min}$	lower generation limit for the *i*th generating plant at time *t*
$P_{g_{i,t}-max}$	upper generation limit for the *i*th generating plant at time *t*
P_t	power of the storage system at time *t*
$P_{k,1}, P_{k,2}$	probabilities of concentrations for the *k*th input random variable
P_R	power rating of the storage system
P_R^d	power rating of the storage system for discharging
P_R^c	power rating of the storage system for charging
$Pbest_j^m$	vector of best position attained by the *j*th particle at the *m*th iteration
r_1, r_2	random numbers uniformly distributed within [0,1]
RD_i	ramp down of the *i*th generating plant
RU_i	ramp up of the *i*th generating plant
RD_S	ramp down of the turbine for the storage system
RU_S	ramp up of the turbine for the storage system
S_t	energy stored in the storage system at time *t*
$S_{\min}$	minimum storage capacity
$S_{\max}$	maximum storage capacity
SC	social cost of the power system
U_j^m	*q*-dimensional vector for the position of the *j*th particle at the *m*th iteration
v	wind speed
v_i	cut-in wind speed
v_o	cut-out wind speed
v_r	rated wind speed
V_j^m	*q*-dimensional vector for the velocity of the *j*th particle at the *m*th iteration
w	inertia weight
$x_{k,1}, x_{k,2}$	concentrations of PDF for the *k*th input random variable
X_k	*k*th input random variable
α	shape factor for Weibull distribution
β	set of buses
γ_r	Lagrange multiplier of the transmission constraint for line *r*
η_S^c	efficiency of the storage system for charging
η_S^d	efficiency of the storage system for discharging
λ	Lagrange multiplier of the power balance constraint
$\lambda_{k,3}$	coefficient of skewness for the *k*th input random variable
μ	expected value of the load
μ_{X_k}	expected value of the *k*th input random variable
$\mu_i^{\min}$	Lagrange multiplier of the lower limit for the *i*th generating unit
$\mu_i^{\max}$	Lagrange multiplier of the upper limit for the *i*th generating unit
$\xi_{k,1}, \xi_{k,2}$	locations of concentrations for the *k*th input random variable
σ	standard deviation of the load
σ_{X_k}	standard deviation of the *k*th input random variable
φ	scale factor for Weibull distribution
Ω	set of transmission lines

This paper proposes a POPF with energy storage integration and wind generation. The proposed methodology uses a PSO approach together with a two-point estimation to examine the storage applications for social cost and transmission congestion relief. The storage system is incorporated into the POPF model to store the extra wind power that would otherwise be curtailed. An economic assessment framework is also developed to evaluate the economic advantage of storage technologies over more conventional alternatives.

Section 2 explains the PSO and two-point estimation methods. It also presents probabilistic models of wind and load based on actual data. In addition, economic characteristics of storage technologies and gas-fired generators are discussed in this section. Section 3 investigates different case studies and conclusions are presented in Section 4.

2. Methodology

2.1. Stochastic modeling of wind and load

The stochastic nature of wind and the load characteristics impose some degree of uncertainty on power systems with wind energy resources. Wind uncertainties [14] and random changes in load [15] need to be modeled stochastically in order to reflect their characteristics. Wind speed variation is characterized using the Weibull distribution [15]:

$$f_V(v) = \left(\frac{\alpha}{\varphi}\right)\left(\frac{v}{\varphi}\right)^{\alpha-1} e^{-\left(\frac{v}{\varphi}\right)^{\alpha}}, \quad 0 \leqslant v \leqslant \infty \tag{1}$$