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Multi-objective market clearing of electrical energy, spinning reserves and emission for wind-thermal power system

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ABSTRACT

This paper proposes energy and spinning reserve market clearing mechanism for wind-thermal power system, including uncertainties in wind power generation and load demand forecasts. The impact of wind power and load demand volatility on the energy and spinning reserve market is taken into account. This paper considers reserve offers from the conventional thermal generators. The stochastic behavior of wind speed, and wind power is represented by Weibull probability density function (PDF), and the load demand uncertainty is represented by Normal PDF. This paper considers two objectives: energy and spinning reserves cost minimization, and emission minimization. The energy and spinning reserves cost minimization objective includes cost of energy provided by conventional thermal generators and wind generators, cost of reserves provided by conventional thermal generators. It also includes costs due to over-estimation and under-estimation of available wind power, and load demand. The proposed market clearing model provides a compromise solution by optimizing both the objectives simultaneously using multi-objective Strength Pareto Evolutionary Algorithm 2+ (SPEA 2+). The effectiveness of the proposed approach is established from the results on IEEE 30 bus system.

1. Introduction

In recent years, wind energy is becoming a significant component of the power generation throughout the world. It's stochastic nature affects the system operation in many different aspects. Wind is a relatively cheap form of renewable energy, but is variable and uncertain. Therefore, its large scale integration into an electric power system poses challenges to power system operators and planners. At present, the penetration of intermittent renewables in most power grids is low, but wind power provides nearly 20% of the electricity generated in Denmark [1,2], 11% of electric energy in Spain and Portugal [3], 9% in the Republic of Ireland [3], and 7% in Germany [4]. The US Department of Energy's report, *'20% Wind Energy by 2030'*, envisioned that wind power could supply 20% of all US electricity, which included a contribution of 4% from offshore wind power [5]. With the growing of wind power in the system, the uncertainty of wind power will bring more adventure to the power system, and increase the demand for reserve capacity. In order to accommodate the unpredictable nature of wind power, the productions and consumptions scheduled in an electricity market need to be modified during the actual operation of the power system. As more and more wind power is installed on the system, the operation of conventional plant on the system will be dramatically different. The volatility, intermittence and unpredictability of wind speed result in the great randomness to the output of wind power units. Great challenge has been imposed on the system operator due to variable nature and integration of wind power.

Worldwide power generation sector contributes more than 30% of carbon dioxides (CO_2) emissions, and the collective efforts are needed from the power sector for this global warming issue. Reductions of the global emissions of CO_2 into the atmosphere of at least 80% will be needed to stabilize the climate against global warming. Wind power considered to have a key role to play in the evolution of less carbon intensive, and more environmentally sustainable electricity supply systems.

Wind generation is strongly dependent on wind speed, hence fluctuations of wind generation receive great attention. Further, future load demand is a random variable and cannot be predicted accurately. The difficulty with wind power generation and load demand is uncertainty/variability at any time. System operator can predict the uncertainty of the wind power/load demand by using wind/load demand forecast data. Usually, probability distribution curves are used to model the related uncertainties.

Wind uncertainty increases the need for reserve capacity. The reserves are the services traded in the market to materialize physically the required adjustments. The question of determination of optimal reserve in a power system is an old one. Traditionally, the spinning reserve (SR) requirement has been based on protection against the loss of largest online generator. Such deterministic

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Nomenclature

$a_i,\ b_i,\ c_i$	cost coefficients of ith thermal generator
$c,\ k$	scale factor and shape factor of the Weibull distribution at given location
$C_{p,Dk}$	penalty cost function for kth load/demand
$C_{p,wj}$	penalty cost function for not using all available power from the jth wind power generator
$C_{r,Dk}$	reserve cost function for kth load/demand
$C_{r,wj}$	reserve cost function relating to uncertainty of wind power. This is effectively a penalty associated with over-estimation of the available wind power
CG	conventional thermal generator
d_j	direct cost coefficient of wind generator j
$f_l(l)$	load PDF (normal distribution)
$f_p(p)$	WEG/wind power PDF
l	uncertain load
n	number of buses in the system
N_G	number of conventional thermal generators
N_L	number of loads/demands
N_W	number of wind generators/farms
p	wind energy generator (WEG) power output
$P_{Dk,av}$	available power demand from kth load. This is a random variable, with a range of $P_{Dk}^{min} \leqslant P_{Dk,av} \leqslant P_{Dk}^{max}$
P_{Dk}	scheduled power demand from kth load in MWs
P_{Dk}^{max}	maximum level of load forecast for kth load
P_{Dk}^{min}	minimum level of load forecast for kth load
P_{Gi}	scheduled power from ith conventional thermal generator in MWs
P_{Gi}^{0}	power output of ith conventional thermal generator at previous hour in MWs
P_{rj}	rated wind power from jth wind generator
P_{SRi}	amount of spinning reserve (SR) provided by ith conventional thermal generator in MWs
P_{wj}	scheduled wind power from jth wind power generator in MWs
$P_{wj,av}$	available wind power from jth wind power generator. This is a random variable, with a range of $0 \leqslant P_{wj,av} \leqslant P_{rj}$
RR_{Gi}^{down}	ramp down limits of conventional thermal generators (MW/h)
RR_{Gi}^{up}	ramp up limits of conventional thermal generators (MW/h)
v	wind speed (m/sec)
$v_r,\ v_i,\ v_o$	rated, cut-in and cut-out wind speeds (m/sec)
WG	wind generator
$x_i,\ y_i$	cost coefficients of SR provided by ith thermal generator

approach does not consider the uncertainties in wind power, and load demand forecasts. But, these uncertainties must be taken into account while determining the requirements for SR, because this reserve is intended to protect the system against unforeseen events such as generation outages, sudden load changes or a combination of both. Wind turbine power output varies according to wind speed, and wind turbine units do not provide SRs.

Among six different ancillary services defined in Federal Energy Regulatory Commission (FERC) order 888 [6], SR is one important service for secure market operation, and should be accounted for while scheduling and operation. Generally, power system security is provided by ancillary services; among them, SR has significant role in providing system security [7]. SR is defined as the difference between present generation and the maximum capacity available. Various types of reserves and their definitions are presented in [8]. SR allows quick rescheduling of generation, within limits, such that security enhancement is possible.

In a market environment, day-ahead scheduling of energy and spinning reserves is required. Since the same generators provide both, there is strong coupling between the two, and simultaneous clearing of these provides more economic and secure solutions, than a sequential market clearing process [9]. Co-optimization of electrical energy and reserves has been implemented in Pennsylvania-New Jersey-Maryland Interconnection (PJM), New York Independent System Operator (NYISO), ISO-New England (ISO-NE) and Midwest ISO. The application of differential evolution algorithm for integrated energy and spinning reserve dispatch with uniform prices is proposed and discussed in [10]. A method for determining the spinning reserves (SRs) requirement in microgrids is presented in [11]. An improved particle swarm optimization to schedule generation and reserve dispatch in a multi-area electricity market considering system constraints to ensure the security and reliability of the power system is proposed in [12]. A stochastic linear programming model that can be used for pricing in electrical energy and reserve markets is presented in [13].

A methodology to identify the appropriate level of reserves, and their cost in a power system with high penetration of wind power is presented in [14]. In [15], an evolutionary iteration particle swarm optimization algorithm is applied to determine the SR requirements that best help a power system overcome unscheduled generator outages and major load forecasting errors without load shedding. A technique to calculate optimal amount of SR required for the system operator, which will respond to generation outages as well as forecast errors for load demand and wind power generation is proposed in [16]. In [17], day-ahead security constrained unit commitment model for electrical energy and ancillary services auction which can be used by an ISO to optimize reserve requirements in electricity markets is proposed. A stochastic security constrained multi-period market clearing problem with unit commitment is formulated in [18,19]. Uncertainty pertaining to wind availability and market prices at different trading stages is accounted in [20].

Modern electric utility companies can no longer dispatch electric power with minimum cost as the only objective. The increasing environmental concern pressures the utility towards multi-objective dispatch of electric power in meeting the load demand. Generation of electricity from fossil fuel releases several contaminants, such as sulphur dioxides (SO_2), nitrogen oxides (NO_X) and CO_2, into the atmosphere. In addition, increasing public awareness of environmental protection and the passage of the clean air act amendments of 1990 [21] have also forced utilities to modify the objectives of their electric power dispatch problems. The multi-objective stochastic economic dispatch problem, whereby the weighted sum technique and Newton–Raphson algorithm are used to generate the non-inferior solutions considering expected operating cost and expected risk associated with the possible deviation of the random variables from their expected values is solved in [22].

The main concern associated with wind energy generator (WEG) is uncertainty. To improve the reliable and economic operation of system every ISO and utility in North America, which are integrating a large amount of wind power uses wind power output forecasts [23]. Several studies were carried to forecast the wind speed profile. These investigations have been based on such