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A probabilistic determination of required reserve levels in an energy and reserve co-optimized electricity market with variable generation

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ABSTRACT

The determination of the required reserve levels due to the incremental trend of injecting wind energy into the power grid with a high level of wind energy penetration is complicated because of the variability of wind energy. This study proposes a method, based on the logarithmic barrier interior point method for optimal power flow and Monte Carlo analysis, to evaluate the required reserve levels for a grid with variable generation. A Gaussian distribution was used to model the dynamic load demand, while a unique linearized least-square approximation was used to model the wind turbines. In order to demonstrate the capability of the proposed algorithm, the methodology was applied to a modified IEEE 30-bus system with two wind-farms. The simulation results showed that the determined reserve requirement was considerably reduced compared with that obtained with classical approaches. The proposed method also satisfies all the considered constraints and maintains system reliability.

1. Introduction

Reducing the impact of conventional generation resources and their impact on the environment in the past decades led to the increased use of renewable energy [1]. In comparison with other types of renewable energy, wind is more variable and uncertain. Wind power has zero fuel cost and its emission-free output provides numerous advantages for consumers [2]. Due to the rapid rate of wind energy utilization, there is a substantial interest in large-scale wind power integration into power systems [3].

Due to the injection of high level of wind energy into power grids, system planners, schedule planners, and power system operators are becoming concerned about new challenges being posed by wind power. One of these challenges is how to deal with the variable nature of wind and its effect on the power system reliability [4].

In order to have a reliable system there must be adequate capacity reserve. Moreover, there is a direct relation between offering a high level of reliability and cost, while it is possible to reduce cost with optimal determination of the required reserve level [5].

Determination of optimal reserve is a mature topic, and there has been great deal of emphasis in this area [6]. This problem has been solved by different approaches, i.e.; heuristic, probabilistic, system simulation and empirical approaches [7]. In heuristic or classical approaches, the amount of operating reserve should be equal to the size of the largest generating unit [8], or to the fraction of total load demand or both. These methods have used deterministic approaches to find the required reserve level. Pousinho et al. [9], used a deterministic method such as mixed-integer linear programming (MILP) for determining the self-scheduling of the power producers which they participating in the joint, day-ahead and the reserve market for the short term planning while the uncertainties of the wind and solar power have been taken into account. In that study, as in most studies for modeling of wind power,

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Nomenclature

Indexes

CSM	Continuous-trading market
ISO	Independent system operator
KKT	Karush-Kuhn-Tucker
LBIPM	Logarithmic barrier interior point method
LMP	Locational marginal price
MCS	Monte Carlo Simulation
OPF	Optimal power flow
PDF	Probability distribution function
SUMT	Sequential unconstrained minimization technique
TARC	Total average reserve cost
WESM	Wholesale electricity spot market

Variables

$D_{FC,i}$	Fixed energy cost for served load *i*
$D_{PC,i}$	Proportional energy cost for served load *i*
$D_{QC,i}$	Quadratic energy cost for served load *i*
$G_{FC,i}$	Fixed energy cost of generation unit *i*
$G_{PC,i}$	Proportional energy cost of generation unit *i*
$G_{QC,i}$	Quadratic energy cost of generation unit *i*
P_{Gi}	Energy schedule of generation unit *i*
$P_{Gi,min}$	Min active power limits of generation unit *i*
$P_{Gi,max}$	Max active power limits of generation unit *i*
$P_{Lij,min}, P_{Lij,max}$	Min and max ratings of line *i-j*
$Q_{Gi,min}, Q_{Gi,max}$	Min and max reactive power limits of generation unit *i*
R_{GiK}	Reserve schedule of generation unit *i* of reserve category *K*
$R_{G_{i,K,a}}$	The reserve schedule of generator reserve source *i* in area *a* for reserve category *K*
$R^{req}_{K,a}$	The reserve requirement for area *a* and reserve category *K*
$R_{i,K,sched}$	The scheduled reserve for generation unit *i* in reserve category *K*
$R_{i,K,max}$	The maximum reserve capability of generator *i* in reserve category *K*, where *K* is either regulating reserve or contingency reserve
$R_{FC,iK}$	Fixed reserve cost of generation unit *i* in reserve category *K*
$R_{PC,iK}$	Proportional reserve cost of generation unit *i* in reserve category *K*
$R_{QC,iK}$	Quadratic reserve cost of generation unit *i* in reserve category *K*
$V_{i,min}, V_{i,max}$	Min and max voltage limits of generation unit *i*

a number of assumptions have been made in predicting or modeling the wind speed variations through a normal distribution or a Weibull distribution [9]. In this study, real data has been captured and the respective power output of the considered wind farms has been modeled. One of the more popular deterministic methods for determination of reserve is cost-benefit analysis which has been employed to evaluate the optimum amount of spinning reserve requirement through a radial equivalent independent (REI) method in Ref. [10]. The developed REI method was coupled with the security constrained economic dispatch (SCED) to reduce the complexity of the large interconnected power systems for determining the required spinning reserve, and the results are compared in several scenarios. A comprehensive review on the mechanism of the joint energy and reserve markets by the consideration of the incorporation of intermittent resources has been done in Ref. [11]. The main emphasis of the paper is on the classification of the reserve types which have been introduced by the different implementation of equilibrium models of the joint markets and their respective dispatching methods for both conventional and non-conventional resources. Nevertheless, in the mentioned study the spinning reserve category has not been defined in more details or any other sub-categories.

System simulations can be done in several areas, such as evaluation of the reliability indices for a specific power system, determining the optimal generation based on historical data, economic dispatch and unit commitment. Doherty et al. [12], presented a comprehensive method to evaluate the capacity reserve with two different power system constraints, including load and wind fluctuations. The study also considered the possibility of losing generating capacity. The paper did not, however, consider reducing costs of capacity reserve by determining the exact required reserve level. Tong et al. [13], adopted a rigorous AC optimal power flow (OPF) method to specify the amount of ancillary services through the electricity market, while the focus of the study was on the pricing mechanism instead of on reserve determination. Sullivan et al. [14], implemented a technique based on a frequency reserve policy by economic dispatch for an autonomous power system, and the results were compared with a generator based reserve policy to prove the efficiency of the methodology. However, this method is not robust enough to deal with large-scale power systems. Holttin et al. [15], provided a thorough investigation in the area of operating reserves through the system simulations. In this study the operating reserve has been classified into three main sub-categories, namely normal operational reserve, contingency reserve and ramping reserve where each one of them have been formulated based on the empirical analysis of each category through to their considerable associated errors and probabilities.

While the system simulations and deterministic criteria attempted to define the appropriate level for required reserves, probabilistic methods are more able to specify quantitative measurements of system reliability and security based on the nature of generating units, generally characterized by unpredictability and random outages of system [16]. Lannoye et al. [17], illustrated that when changes in net load (predicted or unpredicted) cannot be covered by power system, insufficient ramping resource expectation (IRRE) can be observed. Security and reliability is the current challenge of many power system planners when high penetration levels of variable generation (VG) is integrated in to the system. To meet changes of VG and system load, an investigation of the system's flexibility over different time horizons is required and a means of measuring this flexibility is provided by IRRE to highlight the vulnerability of the system in a specific time horizon. Quan et al. [18], implemented a stochastic security-constrained unit commitment (SCUC) to analyze the reserve level and its associated risks while the renewable energies (REs) such as wind and solar have been incorporated into system. Their results were classified and compared in different scenarios, where the results show by addition of REs, the overall costs have been reduced. Ruiz et al. [19], have studied the utilization of stochastic methods to unit commitment with high level of wind power which its uncertainty has modeled by means of different scenarios while reserve requirements are enforced. They demonstrated that the sufficient amount of required reserve results to very robust solutions which lead to reduction of expected cost. They also showed the