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Environmental/economic power dispatch with wind power

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ABSTRACT

Economic environmental dispatch (EED) is a significant optimization problem in electric power system. With more wide spread use of wind power, it is necessary to include wind energy conversion system (WECS) in the EED problem. This paper presents a model to solve the EED problem incorporating wind power. In addition to the classic EED factors, the factors accounting for overestimation and underestimation of available wind power in both economic and environmental aspects are also considered. In order to obtain some quantitative results, the uncertain characteristic of available wind power and the performance of WECS are determined on the basis of the statistical characteristic of wind speed. The optimization problem is numerically solved by a scenario involving two conventional generators and two wind-powered generators. The results demonstrate that the allocation of system generation capacity may be influenced by multipliers related to the cost for overestimation and underestimation of available wind power, and by the multiplier related to the emissions for underestimation of available wind power. Nevertheless, the multiplier related to the emissions for overestimation of available wind power has little impact on the allocation. Taking account of economic factors, environmental factors and impacts of wind power penetration, the proposed EED model is beneficial to finding the right balance between radical and conservative strategy for wind power development.

1. Introduction

Economic dispatch (ED) problem which focuses on the economic issues of conventional electric power system is referred to allocate system load demand to each generating units. It tries to minimize total fuel cost while meeting varieties of operational constraints [1–3]. However, the requirement of adequate and secure electricity is not only cheaper cost, but also minimum pollution. With growing concern about environmental problem, economic environmental dispatch (EED) problem which adds emissions effect as the other objective is presented accordingly. It is a newly attractive alternative strategy that can minimize fuel cost and emission issues simultaneously without fuel switching [4,5].

Moreover, stricter global environmental regulations have posed great pressure on the conventional power generation industry. Distributed generation (DG), using renewable sources of energy which causes lower emissions and offers wider user choices has drawn significant attention from both academia and industry under such a situation [6–8]. Especially, wind power is one of the fastest growing types of renewable energy. The major benefit of wind power is that, after initial lands and capital costs, there is essentially no cost and no pollution emission involved during the production of electric power from wind energy conversion systems (WECS) [9–13]. After incorporating wind power, the deterministic models for conventional power system applications are incapable of expressing the uncertainties from basic parameters of wind power. The adoption of stochastic methods can provide a wider range of solutions which cover the above uncertainties [14–16]. In Ref. [17], the cost function includes the operating cost of the thermal power units together with the wind power plants, and the imbalance cost due to the mismatch between actual and scheduled power outputs of the wind power plants. In Ref. [6], the probability of stochastic wind power based on the Weibull probability density function is included in the proposed model as a constraint. In Refs. [9,18,19], some models are developed to include the WECS generators in the ED problem considering factors for both overestimation and underestimation of available wind power.

With more attention to environmental problems and more wide spread use of WECS, it is therefore meaningful to investigate how to

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dispatch the power properly for electric power system by taking into account economic factors, environmental factors and impacts of wind power penetration. However, few papers investigate the power dispatch problem including the above factors and impacts comprehensively. The objective of this paper is to incorporate WECS generators into the EED problem and to investigate this problem via numerical solutions. Besides the relationships between the penalty and reserve parameters in both economic and environmental aspects, this paper mostly focuses on the effects that different parameters have on the optimum scheduled outputs for the generators. In this paper, the EED model is developed in the most general form. And various parameters can be set under different conditions. So the proposed EED model is of high universality and flexibility.

This paper is organized as follows: Section 2 develops an EED model that includes both conventional generators and wind-powered generators. Section 3 presents the WECS stochastic model and the transformation from the random variable of wind speed to the random variable of wind power. Section 4 presents a discussion of numerical results achieved with extensive sensitivity analysis. Finally, Section 5 concludes this paper with some policy recommendations.

2. Problem formulation

The EED problem which considers the economic and environmental issues comprehensively is referred to allocate the combination of load dispatch from all generators. It meets varieties of physical and operational constraints simultaneously. In general case, the system operator has certain conventional generators and certain wind-powered generators. Due to the uncertainties of available wind power at any given time, factors accounting for overestimation and underestimation of available wind power in both economic and environmental aspects should be included in real life.

In terms of the economic aspect, the reason for considering the factor of overestimation is that, if a certain amount of wind power is assumed but the available power is not sufficient at the given time, power shortage must be purchased from the other conventional energy or loads will be shed. As for the factor of underestimation, if the available wind power is actually more than the scheduled outputs, then the surplus power will be wasted. And the system operator has to pay a sum of money to the wind power producer for the waste of available capacity. In terms of the environmental aspect, the factor of overestimation should be considered according to the following reason, if a certain amount of wind power is assumed while the available power is not enough at the given time, power shortage must be compensated from the other conventional energy or loads will be shed. It will bring additional pollution caused by the overestimation of available wind power. As for the factor of underestimation, if the available wind power is actually more than the scheduled outputs, then the surplus power will be wasted. For the sake of meeting the total load demand of the power system, the conventional generators must afford the waste of available capacity that originally does not need to be undertaken. The underestimation of available wind power will also bring unnecessary pollution.

Based on the aforementioned discussions, the present formulation treats EED problem as a multi-objective stochastic programming problem which attempts to minimize both fuel cost and emission issues simultaneously, while considering the uncertainties of available wind power together with some equality and inequality constraints. The goal is to obtain an optimum allocation of conventional and wind-powered outputs among the available generators under the certain conditions.

2.1. Objectives

2.1.1. Cost

The cost function can be represented as follows:

$$f_{\mathrm{C}} = \sum_{i=1}^{M} C_i(T_i) + \sum_{i=1}^{N} C_{\mathrm{w},i}(W_i) + \sum_{i=1}^{N} C_{\mathrm{p},i}(W_{\mathrm{r},i} - W_i) + \sum_{i=1}^{N} C_{\mathrm{r},i}(W_i - W_{\mathrm{r},i}) \tag{1}$$

where M is the number of conventional power generators. N is the number of wind-powered generators. T_i is the scheduled power output for the ith conventional power generator. W_i is the scheduled power output for the ith wind-powered generator. $W_{\mathrm{r},i}$ is the available wind power from the ith wind-powered generator, it is a random variable varying with the given probability distribution. And its value range is $0 \le W_{\mathrm{r},i} \le W_{i,\mathrm{rated}}$, where $W_{i,\mathrm{rated}}$ is the rated wind power from the ith wind-powered generator. $C_i(\,)$ is the cost function of the ith conventional generator. $C_{\mathrm{w},i}()$ is the cost function of the ith wind-powered generator. This function will typically take the form of the payment to the wind farm operator for the wind power actually used. $C_{\mathrm{p},i}(\,)$ is the penalty cost function for not using all available power from the ith wind-powered generator, it is effectively the penalty associated with the underestimation of the available wind power. $C_{\mathrm{r},i}(\,)$ is the required reserve cost function from the ith wind-powered generator, associating with the uncertainties of wind power, it is effectively the penalty associated with the overestimation of the available wind power.

The fuel cost function of each conventional generator, considering the valve-point effect, is expressed as the sum of a quadratic and a sinusoidal function. The cost function can be further extended in the following forms:

$$C_i(T_i) = \frac{a_i}{2}T_i^2 + b_iT_i + d_i + \left|e_i \sin\left(f_i\left(T_{i,\min} - T_i\right)\right)\right| \tag{2}$$

where a_i, b_i, d_i, e_i and f_i are cost coefficients for the ith conventional generator; $T_{i,\min}$ is the minimum generation limit of the ith conventional generator.

A linear cost function which assumed for each wind-powered generator can be written as follows:

$$C_{w,i}(W_i) = g_iW_i \tag{3}$$

where g_i is the direct cost coefficient for the ith wind-powered generator.

Penalty cost function and required reserve cost function considering uncertainties of wind power can be formulated as follows:

$$C_{\mathrm{p},i}(W_{\mathrm{r},i} - W_i) = k_{\mathrm{p},i}E\left[(W_{\mathrm{r},i} - W_i)I(W_{\mathrm{r},i} \ge W_i)\right] = k_{\mathrm{p},i}\int_{W_i}^{W_{i,\mathrm{rated}}} (w - W_i)f_{\mathrm{W}}(w)\,\mathrm{d}w \tag{4}$$

$$C_{\mathrm{r},i}(W_i - W_{\mathrm{r},i}) = k_{\mathrm{r},i}E\left[(W_i - W_{\mathrm{r},i})I(W_{\mathrm{r},i} \le W_i)\right] = k_{\mathrm{r},i}\int_{0}^{W_i} (W_i - w)f_{\mathrm{W}}(w)\mathrm{d}w \tag{5}$$

where $k_{\mathrm{p},i}$ is the penalty cost (underestimation) coefficient for the ith wind-powered generator; $k_{\mathrm{r},i}$ is the reserve cost (overestimation) coefficient for the ith wind-powered generator; $f_{\mathrm{W}}(\,)$ is