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Cost savings and emission reduction capability of wind-integrated power systems

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ABSTRACT

In the face of energy crisis and environmental impacts of conventional energy sources, renewable energy sources have attracted tremendous interest. Among many resources, wind energy has proven to be a promising renewable energy option in recent times. The primary objective of utilizing renewable energy is its environmental sustainability and the idea of emission reduction constitutes a prominent part in it. The emission here refers to the CO_2, SO_2 and NO_x emissions from thermal power plants. However, recent research works suggest that there remains a considerable anomaly between the claims of emission reduction by wind energy developers and the actual emissions, particularly with the integration of wind power into the grid system. The estimation methodology involving tools like wind resource assessment and energy capture may not provide accurate estimates due to some power system generation and operational constraints. The objective of the present study is to analyse the impact of wind turbine ratings and economic emission dispatch (EED) on the generation cost and emissions in wind integrated power systems. In this regard, the study investigates the concept of emission factor and wind-integrated EED. Wind turbines available at different rated power and rated speeds are incorporated in four different test power systems and the actual cost and emissions over a selected period are evaluated. Finally, the impact of the wind power integration on the generation cost savings and emission reduction is investigated.

1. Introduction

Environmental sustainability is one of the major components of the United Nations Millennium Development Goals (MDG) [1] in which the contribution of sustainable energy sources is important. The Clean Development Mechanism (CDM) of the Kyoto Protocol incorporated the principles of sustainable development and identified emission reduction as one of the primary components of sustainable energy [2]. The core of the CDM process lies in calculation of emission reduction and additionality for any project which aspires to obtain funds from CDM. Additionality signifies that the project should lead to real, measurable and long term greenhouse gas (GHG) reduction which are to be measured with reference to a baseline. For demonstrating emission reduction, ACM0002 and AMS I.D. methodologies respectively can be used for large scale and small scale grid connected renewable energy projects [3]. Wind is one of the fastest growing sustainable energy sources which have been considered by policy makers for meeting emission reduction targets. To evaluate the sustainability of a wind energy project, the amount of emission reduction over the lifetime of a project must be estimated. In CDM wind energy projects, grid emission factors have been used to determine the amount of emission reduction for claiming emission reduction benefits [4]. However, the estimated value of emission reduction may be inaccurate and may differ considerably from the actual value after integration of wind energy system to the grid. The reason may be attributed to the operational constraints associated with power system operation [5]. There have been attempts at quantification of emission reduction from wind generation based on correlation factor between time evolution of marginal emissions and wind generation [6]. Instead of considering only emission aspect, policy makers may carry out a thorough analysis related to the impact of large scale wind integration on power system operation and emission targets thereof.

In recent years, the issue of emission control from thermal generators has been incorporated into economic dispatch model resulting in a multiobjective optimization problem referred to as economic emission dispatch (EED) [7–9]. The research efforts towards obtaining efficient and robust stochastic algorithms for EED are still continuing [10–14]. In one recent approach, exchange market algorithm is used and cost and emission are obtained for IEEE 30 bus system including operational aspects [15]. In addition, deterministic mathematical programming based approaches have also been attempted [16]. In [17], multi-objective EED (MOEED) is implemented over a 24 h dispatch

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period and fuel cost and emission are calculated with different DSM participation levels and it is concluded that emission reduction takes place with more participation of DSM. Imperialist competitive algorithm has been utilized in [18] to solve a profit based unit commitment (UC) problem where the objective is to maximize profits under emission constraints over a 24-h interval. In [19], the authors propose a method to include emission constraints in the EED model and utilizes the shadow pricing concept for optimal dispatch.

A number of formulations have been attempted to incorporate wind power in EED model [20–23]. In a widely used concept presented in [20], overestimation and underestimation costs are included in dispatch model for wind-thermal systems. In another approach explained in [21], the probabilistic characteristics of wind power are included in the model in the form of constraints. Alternatively, a wait-and-see approach incorporates the probabilistic characteristic of the problem in the probability density function (pdf) of the solution [22]. In the above three approaches thermal pollutant emissions are not considered. In another work [23], the effect of wind power on emission control is investigated, where incomplete gamma function for wind power model is used. However, the capability of wind integration on reducing emission has not been quantified in the above work. Among evolutionary approaches, the wind integrated EED is solved using evolutionary algorithm based on decomposition (MOEA/D) in [24]. Similarly, a gravitational acceleration enhanced particle swarm optimization (GA-PSO) is proposed in [25] for solution of EED problem with wind power. In the previous two works, in some scenarios used by the authors, emission have increased after wind integration although cost reduction is achieved. Further, a multi-period multi-objective optimal dispatch is utilized in [26], but no attempt is made to compare the cost and emission before and after wind integration. The concept of carbon savings as the difference between business-as-usual (BAU) emissions and emissions with renewable integration is used in [27], however, the work solely focuses on wind power modelling and optimization techniques. Two different PDFs represented in the form of available wind generation and dispatched wind generation are considered in [28] but no attempt is made to quantify the emission reduction capability of wind power. The authors in [29] perform scheduling for a system containing four hydro plants, ten wind power plants and three thermal power plants where the focus is on developing a new stochastic optimization algorithm for hydro-wind-thermal scheduling but emission reduction capability of wind integration in conventional power systems is not discussed. Thus, it is observed from the above mentioned literature that in most of the similar works by integrating wind farms into standard test systems, researchers have not given adequate focus to analyze the benefits of wind farm integration, particularly in terms of savings in cost and emission. In some of the cases the inclusion of wind units have only managed to reduce the cost but the solutions have resulted in increased emission. Also, no attempt has been made to quantify the cost savings and emission reduction after wind integration. Further, no previous research has incorporated the turbine performance index (TPI) [30] into the problem of EED, which may lead to a more realistic estimation of cost savings and emission reduction. Finally, this work is novel in comparing the estimated emission reduction with the actual emission reduction after wind integration.

In this context, the objective of the present work is to investigate the impact of wind turbine ratings and EED on cost savings (CS) and emission reduction (ER) in wind-integrated power systems. For this, a cluster of two wind farms are integrated in each of the three test power systems. EED is performed with power output of the wind farms at different rated power and TPI of the turbine. The contributions of the current work are stated as follows.

1. Unlike previous works, a comparison is made between cost and emissions before and after wind power is incorporated in the EED model, thereby quantifying the CS and ER capability of the wind power.
2. Emission factor of the test power systems is calculated which is then used to compare the estimated ER from wind power with actual ER which occurs when wind power is incorporated in the EED model.
3. For sensitivity analysis, the rated power and TPI of the wind turbines used in the wind farm are varied and their impact on CS and ER is analysed.

The rest of the paper is organized as follows. Section 2 presents the background of the methodology used for the work, where it essentially focuses on reviewing some fundamental concepts related to wind power generation and its integration. The exact problem set up and the characteristics of the problem are defined in Section 3. The solution methodology adopted in this work has been elaborated in Section 4. Section 5 elucidates several results obtained and draws inferences out of them. Finally, Section 6 concludes the paper and identifies future scopes in this work.

2. Background

In the current work, wind speed is modelled using Weibull distribution and linear power curve model of the turbine is used to calculate power output and energy capture. The impact of change in turbine characteristics i.e. rated power and TPI on cost and emission is investigated. The concept of emission factor is also used to evaluate the emission reduction as compared to estimated. The approach of this work is restricted to EED only and tools provided in *MATLAB* are used to obtain the same. The details are described below.

2.1. Wind speed simulation

The Weibull distribution described in (1) and (2) has been found to give a good representation of the variation in hourly mean wind speed over a year [31].

$$f(v) = k\frac{v^{k-1}}{c^k}\exp\left(-\left(\frac{v}{c}\right)^k\right) \tag{1}$$

$$F(v) = \exp\left(-\left(\frac{v}{c}\right)^k\right) \tag{2}$$

where $f(v)$ and $F(v)$ are respectively PDF and CDF of Weibull distribution, v is the wind speed, k is the shape parameter describing the shape of the distribution and c is the scale parameter, which is more important in energy calculations.

A number of methods have been suggested for estimating parameters of Weibull distribution. Some of the commonly used methods are graphical method, maximum likelihood method (MLE), modified MLE, moment method, equivalent energy method and wind energy pattern factor method [32]. Intelligent parameter estimation algorithms have also been utilized for Weibull parameter estimation [33]. Once the Weibull parameters are determined using the above methods, wind speed can be simulated using inverse transform method [34] following Weibull distribution as described in (3).

$$X = F^{-1}(U), \quad U \sim (0, 1) \tag{3}$$

where X is the random variable to be simulated i.e. wind speed and F is the CDF of the random variable i.e. (2).

Other distributions have also been used for describing wind speed variations such as gamma distribution, log-normal distribution, inverse Gaussian distribution and squared Normal distribution; wind speed can also be characterized and simulated without assuming any probability distribution [35]. However, the variable of significance for EED is not wind speed but wind power. The wind turbine power output depends on wind speed at turbine hub height which is significantly higher than the measurement heights of meteorological towers. Wind speed varies