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Optimal wind turbines placement within a distribution market environment

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ABSTRACT

This paper proposes a hybrid optimization method for optimal allocation of wind turbines (WTs) that combines genetic algorithm (GA) and market-based optimal power flow (OPF). The method jointly maximizes net present value (NPV) related to WTs investment made by WTs' developers and social welfare (SW) considering different combinations of wind generation and load demand over a year. The GA is used to choose the optimal size while the market-based OPF to determine the optimal number of WTs at each candidate bus. The stochastic nature of both load demand and wind power generation is modeled by hourly time series analysis. The effectiveness of the method is demonstrated with an 84-bus 11.4 kV radial distribution system.

1. Introduction

1.1. Motivation

Wind turbines (WTs) placement in a distribution network affects several parameters such as voltage profile, line losses, short circuit current and system reliability and these parameters should be assessed before installing the WTs in a distribution network.

Different factors can be considered in the determination of candidate buses for WTs placement: spacing and turbulence, visual impact, noise concerns, environmental considerations, location and distance to people.

When WTs are placed too close to one another, they can create turbulence. Eventually, the turbulence created by the close WTs placement can reduce efficiency by affecting the amount of energy created. WTs are extremely visible, especially when grouped together in a wind farm. Due to the nature of WTs, they must be placed in open areas exposed to wind, which serves to increase their visibility. A solution to the visual impact is to reduce the number of WTs in one location. Early models of WTs were loud. Scientists have recently developed updated models that reduce the noise created by the WT. Placement of WTs in an area where the impact of the noise is minimum can help reducing negative perceptions of WTs. Ideal locations for WTs include coastal areas, open fields, tops of rounded hills or gaps mountain ranges. A consistent and reliable wind source is required to turn the WTs and create the power source. Locating power plants at long distances from people is generally not convenient as in order to keep a high-efficiency link with the rest of the power grid, an expensive array of inverters and transformers is required [1].

Therefore, proper allocation of WTs plays a key role for the improvement of system performance in a distribution system [2]. Furthermore, the optimal placement of WTs is one of the most important aspects for power system planning. WTs allocation at non optimal places may cause an increase in the network losses and in the generation investment. Therefore, selecting the best places for siting and sizing of WTs in large networks represent a complex optimization problem [3,4].

1.2. Aim and approach

In this paper, a novel method for optimal placement of WTs in distribution networks is proposed. The method combines the genetic algorithm (GA) and the market-based optimal power flow (OPF) to jointly maximize the net present value (NPV) related to the investment made by WTs' developers and the social welfare (SW) over a year in distribution network operator (DNO) acquisition market. The GA is used to choose the optimal size while the market-based OPF to determine the optimal number of WTs.

The DNO is defined as the market operator of the DNO acquisition market, which determines the price estimation and the optimization process for the hourly acquisition of active power.

The uncertainty in wind power generation and load demand is modeled through hourly time-series model of load demand and wind generation. The interrelationships between demand and

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generation potential are preserved with their joint probability defining the number of coincident hours over the year.

The proposed method can help WTs' developers to better allocate WTs by considering cost reduction and consumers' benefits; moreover, it is consistent with the topology of the considered distribution system since it considers network constraints and distribution locational marginal prices (D-LMPs).

By following this approach it is expected that WTs will be allocated at buses where they are more advantageous that is near higher loads or in parts of the networks where the loads have maximum value and the consumers' benefit is higher. The method is applied to an 84-bus 11.4 kV distribution network.

1.3. Literature review

A lot of previous works have been carried out to seek the optimal capacities and locations of distributed generators (DGs). In [5], a Tabu search method to obtain the optimal sizes and locations of DGs has been proposed. In [6], the authors proposed a cost based model to allocate DGs in distribution networks in order to minimize DG investment and total operation costs of the network. The objective function is solved using an ant colony optimization (ACO) method. In [7], a novel method for optimal allocation of DGs in distribution systems to minimize the network losses and to guarantee the acceptable reliability level and voltage profile has been proposed. In [8] an optimization technique is suggested to establish the maximum wind power injected into the grid with fixed transmission capacity taking into account the network security. In [9], a numerical algorithm is proposed to estimate the maximum wind energy exploitation in independent electric island networks. In [10], the differences in the improvement patterns of offshore wind power in Europe and US are discussed. In [11] the authors provided an investigation for the wind power investment in Turkey inspiring the interest of wind investment and evaluating the wind generation costs in this country. In [12], a linear programming model is suggested to specify the optimal technology mix, taking into account wind power production as a negative load that influences the variability of the load profile and therefore the network operation. The metaheuristic methods such as GA, particle swarm optimization (PSO), and ACO are used to solve the generation expansion planning problem in [13,14]. Virtual mapping procedure (VMP) and penalty factor approach (PFA) are also used to improve the efficiency of the metaheuristic techniques. In [15], the authors proposed a novel method based on PSO to solve an OPF problem considering security constraints to minimize the total operating cost.

1.4. Contributions

To the best of our knowledge, no wind power investment method in distribution level from the point of view of WTs' developers in the market environment by using hybrid GA and market-based OPF has been reported in the literature. For this reason, the proposed method is innovative if compared with other methods reported in the literature.

One of the innovative aspects of the proposed method is that, according to the distribution network topology, it allows WTs' developers allocating WTs at more advantageous locations in terms of earned revenue. This is attained using D-LMPs, a natural extension from the transmission system, able to provide a real-time price to the customer. By using D-LMPs, supply offers and demand bids and the physical aspects of the distribution network, including distribution and other operational constraints are assessed in the proposed method.

Also, by using the proposed method, WTs' developers can evaluate WTs placement taking into account the D-LMPs' values that directly influence their profits.

Another novelty of the proposed method is the participation of WTs' developers in a distribution level market comprising both a day-ahead schedule of WTs and loads according to the market price and a real-time intraday optimization operation. The uncertainty in wind power generation and load demand is modeled through hourly time-series model of load demand and wind generation. The interrelationships between demand and generation potential are preserved with their joint probability defining the number of coincident hours over a year.

1.5. Paper organization

The rest of the paper is organized as follows. Section 2 explains the model features. Sections 3 and 4 describe GA implementation and DNO acquisition market formulation, respectively. Section 5 explains the 84-bus test system while Section 6 presents some numerical results. Discussions and conclusions are presented in Section 7.

2. Model features

2.1. Modeling of time-varying load demand and wind power generation

A future year for the expansion planning is considered and the optimal investment is established for that year. This analysis is known as static expansion planning, is used in this paper for the wind power investment. This static method comprises a proper tradeoff between modeling precision and computational tractability.

The wind generation and load demand are modeled through hourly time series analysis in a year as shown in Fig. 1. The method reduces hourly time-series data to a number of scenarios where the load demand and wind generation for every hour are assigned to a series of bins. Describing the number of coincident hours over the year preserves the interrelationships between potential of load demand and wind power generation with their joint probability [16].

In order to reduce the computational burden of a full time series analysis, wind generation and load demand are aggregated into a controllable number of scenarios on the basis of their joint probability of happening. The number of coincident hours is represented by the duration of each hour as shown in Fig. 1 (right). It splits the demand and generation into a series of bins. In order to show the procedure, ten ranges for demand (i.e. [0, 10%], (10%, 20%], ..., (90%, 100%]) and 11 ranges for wind generation (i.e. {0}, (0, 10%], (10%, 20%], ..., (90%, 100%]) are used. It is seen that with demand higher than 30%, 74 non-zero scenarios are considered in the analysis. Furthermore, low load demand, i.e. 40%, and high wind generation, i.e. 60–100%, present few coincident hours.

The uncertainty in wind power generation and load demand are represented via scenarios. Each demand level is characterized by eleven wind generation levels, i.e. 0–100%. There are seven load demand and eleven wind generation levels. Therefore, jointly considering the load demand and wind power generation levels results in 77 scenarios, i.e. seven load demand levels, with two blocks per level with different sizes and the same price, by eleven wind power generation levels with four blocks per level with the same size and the same price for all blocks.

2.2. The structure of the proposed method

The method combines GA and market-based OPF to maximize the NPV related to the investment made by WTs' developers over a year as shown in Fig. 2. The GA is used to find the optimal sites