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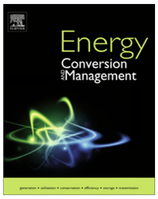

Optimal wind energy penetration in power systems: An approach based on spatial distribution of wind speed

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ABSTRACT

Contributing in power system expansions, the present study establishes an efficient scheme for optimal integration of wind energy resources. The proposed approach highly concerns the spatial distribution of wind speed at different points of a wind farm. In mathematical statements, a suitable probability distribution function (PDF) is well-designed for representing such uncertainties. In such conditions, it is likely to have dissimilar output powers for individual and identical wind turbines. Thus, the overall aggregated PDF of a wind farm remarkably influences the critical parameters including the expected power and energy, capacity factor, and the reliability metrics such as loss of load expectation (*LOLE*) and expected energy not supplied (*EENS*). Furthermore, the proposed approach is deployed for optimal allocation of wind energy in bulk power systems. Hence, two typical test systems are numerically analyzed to interrogate the performance of the proposed approach. The conducted survey discloses an over/underestimation of harvestable wind energy in the case of overlooking spatial distributions. Thus, inaccurate amounts of wind farm's capacity factor, output power, energy and reliability indices might be estimated. Meanwhile, the number of wind turbines may be misjudged to be installed. However, the proposed approach yields in a fair judgment regarding the overall performance of the wind farm. Consequently, a reliable penetration level of wind energy to the power system is assured. Extra discussions are provided to deeply assess the promising merits of the founded approach.

1. Introduction

In electrification process of modern power systems, the wind energy is recognized as a promising resource. In this triumph, moreover than the environmental issues, some of the key factors could be named as reduced installation costs along with supportive subsidies activated for further extensions. Although revealing a number of appealing features; however, the intermittent nature of wind speed is a real challenge against its reliable utilization [1].

Encountering such intrinsic snags, several research studies are carried out to capture the highest benefit of wind energy utilization. In a common sense among the researchers and practitioners, determination of optimal wind energy penetration is known as the initial task adopted for its successful integration. This, in turn, requires the development of efficient models for accurate estimation of harvestable energy through the wind farms including a number of wind turbines. Such issues are studied in small-scale isolated grids [2–5] and the large-scale power systems [6–8]. What is more, the inclusion of wind energy resources is also shown to manipulate the reliability considerations [9–11]. Thus, assuring secure operational plans puts another emphasis on devising efficient and accurate models for farm's integrations. Contributing to the outlined context, versatile methods have been addressed in the literature. More often, the wind speed profile is modeled based on deterministic and stochastic methods. The application of deterministic methods is faced with least computational burden; however, they neglect the uncertainties' presence [12–14]. Deploying the turbine's power curve is revealed as one of the common methods in this category [15–18]. To obtain more accurate results, appropriate forecasting schemes are deployed for representing the wind farm's output power [19–21]. A comprehensive review on such probabilistic mechanisms is given in [22]. Even though the investigated surveys have made benefit of uncertainty analysis, still, the spatial distribution of wind speed is not respected properly. Specifically speaking, the wind speed is treated with similar chronological behavior over a farm. This is while; a more recent study conducted on real-data profiles demonstrates that each piece

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Nomenclature

Indices and sets

i, S	index and set of scenarios for wind farm's output power
l	index of transmission lines
n, m	indices of buses
t, T	index and set of time intervals (hours)

Constants

$B_{nm,c}$	transmission line's susceptance between nth and mth buses at cth contingency
$flow_{l_{max}}$	maximum power transfer by lth transmission line (MW)
FP	fuel price (\$/MW h)
IC	investment cost for a single unit of wind turbine (\$)
L_n	load at nth bus (MW)
$P_{n_{max}}$	maximum capacity of generator at nth bus (MW)
$P_{n_{min}}$	minimum capacity of generator at nth bus (MW)
$VOLL$	value of lost load (\$/MW h)

Variables

$EIFO$	expected income due to fuel offsets following the wind energy penetration (\$)
$EIRI$	expected income due to reliability enhancement by the wind energy penetration (MW h)
EUWE	expected and utilizable wind energy (MW h)
$flow_{l,c}$	power flow at lth transmission line and cth contingency (MW)
$IMTC$	investment and maintenance costs of wind farm (\$)
P_i	wind farm's output power at ith scenario (MW)
$P_{G_{n,c}}$	generated power at nth bus and cth contingency (MW)
PV	profit value of wind farm penetration to the power system (\$)
TEI	total expectation income of wind farm penetration to the power system (\$)
$WU\ F$	wind utilization factor
ω_i	probability value for wind farm's output at ith scenario
$\theta_{m,c}$	voltage angle at mth bus and cth contingency

of a farm is faced with unequal wind speed [23]. In mathematical statements, the authors have developed a Poisson distribution for representing such spatial distribution. Taking into account the power systems integrated with wind farms, this observation definitely influences all aspects of power systems including the expected output power, capacity factor, and the reliability indices.

Taking into account the farm's installations, this paper investigates the possible effects of wind speed's spatial distributions in technical performance of overall power systems. In this practice, the wind speed's spatial distribution is represented in the form of a suitable Poison probability distribution function (PDF). Subsequently, considering such distributions, the recorded changes in farm's parameters are explored in depth. The investigated parameters include the expected output power, energy, capacity factor, and the reliability indices. Then, the established approach is extended to determine the optimal penetration level of wind energy integrated to the power system. The conducted numerical analysis reveals an over/underestimation of harvestable wind energy in the case of overlooking spatial distributions. Thus, inaccurate amounts of farm's capacity factor, output power, energy, and reliability indices might be estimated. Meanwhile, the number of turbines may be misjudged to be installed. Specifically, such observations are recorded for the cases wherein the farm's capacity is smaller/greater than the system's peak load. The proposed approach is compared with the currently-deployed methods to clearly highlight the promising improvements. In this practice, a small isolated power system and also the IEEE 24-bus reliability test system (RTS) are tailored in depth. In brief, the main contributions of the proposed approach could be listed as follows:

- Incorporating the wind speed spatial distribution in assessing the performance of a farm.
- Devising an accurate estimation of expected power, energy, and capacity factor for farm's integrations.
- More accurate results in reliability evaluation of power systems including wind energy integrations.
- Determining the optimal penetration level of wind energy into the power system.

The remainder of this paper is organized as follows: Section 2 presents the proposed methodology on evaluating a power system including wind farm's integrations. Section 3 demonstrates the impact of spatial distribution of wind speed on wind farm's parameters. In Section 4, the trend of optimal wind energy penetration level and its applicability on power systems is accommodated thoroughly. Section 5 examines the performance of the proposed strategy based on extensive numerical analysis. Eventually, Section 6 provides the concluding remarks.

2. Evaluating the power system including wind farm

2.1. Scenario-based optimal power flow

Because of the inherent intermittent nature of wind, the output power of a wind turbine is uncertain. This uncertainty can be represented based on a suitable PDF. In a simple manner, this PDF is discretized to different scenarios with particular probabilities. To provide a fruitful understanding of this issue, assume the corresponding PDF of a wind farm's output power involves S scenarios. So, the occurrence probability of ith scenario is denoted as:

$$Prob\ (WP = P_i) = \omega_i; \quad i = 1, 2, \ldots, S, \tag{1}$$

where WP denotes the wind farm's power generation. It should be noticed that in Eq. (1), there are S discretized levels for the output power. Each of these levels is accompanied with the occurrence probability of $\omega_1, \omega_2 \ldots, \omega_S$, respectively. As the main purpose of the conducted study is to demonstrate the spatial distribution of the wind speed on its optimal allocation, thus, the optimal sitting aspects are not included herein. Consequently, only one wind farm is supposed to be included in the main power system. This inclusion does not mean the optimum location for that farm and only is a typical connection point. Afterwards, the effects of the proposed method are tailored for the connected farm to the grid. Assuming different hourly load levels for the power system, it is possible to reckon the expected values of power system's technical parameters at each time interval, considering distinct scenarios of wind farm's output power. These scenarios are extracted from farm's PDF which is a general one and can be deployed for any time interval. However, as the time intervals get shorter, then the specifications of the PDF only changes. Please note that the type of PDF remains constant. As an instance, in time interval T, the expected operation cost (EOC) of the power system can be obtained as:

$$EOC = \sum_{t=1}^{T}\sum_{i=1}^{S}(EOC_{i,t} \times \omega_i). \tag{2}$$