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An analytical and probabilistic method to determine wind distributed generators penetration for distribution networks based on time-dependent loads

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ABSTRACT

This paper proposes an analytical approach for optimal allocation of wind DG units in radial distribution networks. Using this analytical approach, size and location of wind DG units are determined at different optimal power factors of a wind DG ($OPF_w s$), while different types of time-dependent load models and probabilistic wind DG generation are considered. The proposed approach is based on the partial derivative of a multi-objective index (IMO) including four impact indices of real power loss (ILP), reactive power loss (ILQ), voltage profile (IVD) and voltage stability (IVS). IVS methods based on analytical expression are usually assumed separately (not in an IMO), to find only the optimum location. In this study, the IVS is defined for a new application as an index in the IMO so as to determine both optimal size and location of the wind DG units. Also, the impact of the wind DG penetration on system voltage stability is evaluated. The 33 and 69 bus systems are examined to show the validity of the proposed approach. From the results, the load models have a significant effect on the wind DG penetration in the network, and the match rate between wind DG output and demand curves for each load model is different.

1. Introduction

Nowadays the renewable distributed generations (DGs) has been grown in the power distribution networks. These units connect directly to distribution networks close to demand consumption. Therefore, they can supply renewable power for consumers at reasonable prices with higher security and reliability. Among renewable technologies, the global wind DG installations increased by 35,467 MW in 2013 and 51,447 MW in 2014 [1]. In 2015, the global growth rate of 17.2% was higher than in 2014 (16.4%). As of the end of 2015, the total wind capacity of the world reached 435 GW [2].

Proper allocation and placement of DG units into an existing distribution networks can play important role in the improvement of the network's performance. In the other hands, one of the main challenges in connecting some DGs, such as photovoltaic and wind is intermittent nature of their output.

For DG placement in distribution networks, various goals, such as power loss minimization [3], voltage profile improvement [4], voltage stability improvement [5], etc., in single or multi-objective function have been considered.

To solve the optimization problem, various optimization techniques such as non-linear programming [6], analytical approach [7], GA (genetic algorithm) [8,9], a Chaotic Artificial Bee Colony (CABC) algorithm [10], trade-off methodology [11], shuffled frog-leaping algorithm (SFLA) [12,13], and etc., have been used.

Non-linear programming and similar mathematical based methods are depending on iterative solution of the defined objective functions. This methods may have convergence problems depending on the problem nature. The GA, CABC and the SFLA are subsets of the meta-heuristic algorithms (MHAs). The MHAs solve the problem by considering a random solution sets and evolve these random solutions toward the global optimal point by iterations. To validate the obtained solution, multiple runs are required. By increasing control parameters of problem, initial population, iterations and number of runs will be increased for obtaining a reliable solution. This increases the computing time. In the trade-off methodology, in addition to decision making procedures, extra internal optimization methods are required for optimizing individual objective functions. Therefore, the performance of this method is depending on the selected optimization algorithm. But, analytical methods solve the problems based on sensitivity indices. Therefore, these methods do not suffer from mentioned drawbacks of the mathematical and MHA methods.

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In [7], an analytical method for siting and sizing DGs in a radial distribution network has been presented, where power losses is considered as only objective function. A method based on losses sensitivity to determine optimal size and location of DGs considering various time-dependent load models in distribution systems has been presented, in [14]. But, in this method, uncertainties and intermittency nature of the renewables are not considered.

In [15], an analytical method for placement and sizing of renewable DGs without considering the time-dependent combined generation-load model has been presented. Also, the optimal placement of dispatchable and nondispatchable DGs for minimizing power loss using analytical method has been presented, in [16]. In this method active and reactive power losses are considered as objective function. In [17,18], optimal analytical methods for allocation of DGs has been presented with only power loss as objective. In these papers, any attentions to other indices such as voltage profile or voltage stability have not been paid. Also, in [18], the influence of different time-dependent load models on DG penetration level in distribution systems has not been evaluated. In [19], an analytical method for allocation of photovoltaic (PV) units has been presented by a multi-objective function including indexes of voltage deviation, real and reactive losses. In [20], the authors have presented DG allocation using an analytical algorithm based on a voltage stability index. However, the voltage stability index has only been used to identify the critical buses in the distribution system which may face to voltage collapse, and has not been considered in a multi-objective function to determine size and location of DGs.

According to what was mentioned, it can be found that an analytical wind DG planning with considering system power loss, voltage profile and voltage stability as indices in a multi-objective function, the influences of time-dependent and combined generation-load models, probabilistic wind DG output and various optimal power factors of a wind DG on DG allocation in radial distribution systems simultaneously, has not been presented by any researchers in recent years. Also, in analytical papers, voltage stability indexes have always been proposed separately (not in a multi-objective function), to find only the best location for DG installation.

The contribution of this study is optimal allocation of wind DG units with considering various types of time and voltage dependent-load models. Here, a multi-objective index (IMO) based analytical expression as a combination of four indices, namely real power loss, reactive power loss, voltage profile and voltage stability is defined. The IMO is formulated to determine optimal location and size of wind DG units at different optimal power factors (OPF_w). The match rate between load demand patterns and probabilistic wind DG output curve is evaluated and discussed.

2. Load and wind DG modeling

2.1. Load modeling

It is assumed that the system demand curves can follow various load patterns (i.e. industrial, residential and commercial) in p.u. [21]. The system load factor (LF) is defined as the ratio of the area under the load curve in p.u. (the demand during each period is constant) to the total duration [22] as:

$$LF = \sum_{t=1}^{24} \frac{p.\,u.\,demand(t)}{24} \tag{1}$$

Dependence of the load on the bus voltage and time variations at period t (t is one hour) for a specific day is defined as follows [23]:

$$P_K(t) = \lambda \times P_{OK} \times V_K^{\alpha}(t),\; Q_K(t) = \lambda \times Q_{ok}(t) \times V_K^{\beta}(t) \tag{2}$$

where λ is load demand parameter (for base operation condition $\lambda = 1$), P_k is the real power and Q_k is the reactive power that inject at bus k, P_{ok} is real load, and Q_{ok} is the reactive load at rated voltage at bus k, V_k is the voltage at bus k, and α and β are respectively, the exponents of real and reactive load voltage given in [24].

2.2. Wind DG (wind turbine) modeling

2.2.1. Wind speed and generation profile modeling

The Rayleigh pdf can be a good formula for modeling the wind speed unpredictable (probabilistic) behavior for each hour of a day from [25]. This is based on historical data collected for year 20,151[1] at Dorood (a town in Lorestan province, Iran) as:

$$f_r(\upsilon) = \left(\frac{2\upsilon}{c^2}\right)\exp\left[-\left(\frac{\upsilon}{c}\right)^2\right],\; c \approx 1.128\upsilon_m \tag{3}$$

here, υ_m denotes the mean wind speed. From (4) the probability of wind speed of state υ at each specific period (1 h) can obtained as follows [26]:

$$\rho(\upsilon) = \int_{\upsilon 1}^{\upsilon 2} f_r(\upsilon).\, d\upsilon, \tag{4}$$

where υ_1, υ_2 are the limits of state υ. Now the wind speed pdf for 40 states (assumed in this study) with an interval of 1 m/s for each period (1 h), are generated using (3), (4). The unpredictable output power of the wind turbine-based DG at wind speed υ, $P_{w_o}(\upsilon)$ is expressed as [26]:

$$P_{w_o}(\upsilon) = \begin{cases} 0 & 0 \leqslant \upsilon \leqslant \upsilon_{cir} \\ P_{rated} \times \frac{(\upsilon - \upsilon_{ci})}{(\upsilon_r - \upsilon_{ci})} & \upsilon_{ci} \leqslant \upsilon \leqslant \upsilon \\ P_{rated} & \upsilon_r \leqslant \upsilon \leqslant \upsilon_{co} \\ 0 & \upsilon_{co} \leqslant \upsilon \end{cases} \tag{5}$$

where υ_{ci} is the cut-in speed, υ_{co} is the cut-off speed and υ_r is the rated speed of wind turbine. The characteristics of the considered wind turbine in this study (turbine 2) can be found in [26]. Finally, for each period t, the probabilistic output power of the wind turbine (PP_w) is defined as [26]:

$$PP_w(t) = \sum_{\upsilon=1}^{40} P_{w_o}(\upsilon)\rho(\upsilon) \tag{6}$$

Note that, the area under the curve of each hour is unity.

2.2.2. Calculating wind DG capacity factor

The capacity factor of the wind turbine is calculated as [26]:

$$CF_w = \frac{P_w^{output}}{P_w^{\max}}. \tag{7}$$

where $P_w^{\max}$ is the rated power or maximum output and P_w^{output} is the average output power of the wind turbine for a day calculated from (6).

2.2.3. Optimal power factor

To achieve possible minimum of the total system power losses, the power factor of the wind DG should be equal to power factor of the total system load (PF_D). Thus, the optimal power factor of the wind DG (OPF_w) is defined as follows [27]:

$$OPF_w = PF_D = \frac{P_D}{\sqrt{P_D^2 + Q_D^2}} \tag{8}$$

where P_D and Q_D are the total real and reactive load powers respectively.

2.2.4. Wind DG penetration level in the network

It is the ratio of the total output power of the wind DG and the system total load [28].

[1] [online]. Available: http://www.lorestanmet.ir/1