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Optimal allocation of stochastically dependent renewable energy based distributed generators in unbalanced distribution networks

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ABSTRACT

This paper proposes an algorithm for modeling stochastically dependent renewable energy based distributed generators for the purpose of proper planning of unbalanced distribution networks. The proposed algorithm integrate the diagonal band Copula and sequential Monte Carlo method in order to accurately consider the multivariate stochastic dependence between wind power, photovoltaic power and the system demand. Secondly, an efficient algorithm based on modification of the traditional Big Bang-Big crunch method is proposed for optimal placement of renewable energy based distributed generators in the presence of dispatchable distributed generation. The proposed optimization algorithm aims to minimize the energy loss in unbalanced distribution systems by determining the optimal locations of non-dispatchable distributed generators and the optimal hourly power schedule of dispatchable distributed generators. The proposed algorithms are implemented in MATLAB environment and tested on the IEEE 37-node feeder. Several case studies are done and the subsequent discussions show the effectiveness of the proposed algorithms.

1. Introduction

The power system is in massive need of alternative generation other than conventional type to face the mounting demand. The renewable energy is the best choice as it is infinite and green source of energy. Within the renewable energy sector, wind power and solar power are by far the most growing technologies due to their availability, low operating cost and development of their industry. However, wind and photovoltaic (PV) power are by nature non-dispatchable because the primary source cannot be controlled. Instead, they follow a stochastic distribution pattern dependent on the primary source and the generation technology [1].

The wind and PV power are difficult to be accurately simulated because they are strongly correlated to the climate, ambient temperature, season, time and geography. Renewable energy sources (RES) could be deterministically or probabilistically modeled. Deterministic methods are not able to model the stochastic nature of the RES. On the other side, probabilistic methods based on analytical techniques or the Monte Carlo method are able to consider this stochastic nature.

Both Monte Carlo based techniques [2–6] and analytical methods [7,8] had been utilized in adequacy assessment of generation systems containing wind and photovoltaic power. In spite of their complexity and high computational time Monte Carlo based methods provide more accurate results compared to the analytical methods. Analytical methods are easy to implement and fast to execute. However, their results are only indicative, since they make simplified assumptions including the consideration of only one power system loading snapshot. In [2] analytical techniques and the Monte Carlo method were both applied to model photovoltaic-distributed generation and solve a probabilistic load flow in radial distribution networks. Authors in [3] combined Monte Carlo simulation (MCS) and market-based optimal power flow considering different combinations of wind generation and load demand models over a year to evaluate wind turbines integration into distribution systems. A stochastic mixed-integer scheduling model was applied to investigate the transmission planning model of advanced wind forecast techniques [4]. A sequential Monte Carlo simulation technique was used to model wind generation and pattern search-based optimization method was used in order to minimize the system cost and satisfy the reliability requirements [5]. In [6] a method based on the pseudo-sequential Monte Carlo simulation technique had been proposed to evaluate the reserve deployment and customers' nodal reliability with high PV power

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penetration. The authors in [7] proposed a photovoltaic probabilistic model considering the correlation among the input random variables using joint cumulants. A probabilistic-based model of different types of renewable distributed generation (DG) units (i.e., wind-based DG, solar DG, and biomass DG) was integrated with planning technique in order to minimize the annual energy losses in a distribution system without violating the system constraints [8].

Optimal allocation of renewable DG units plays a pivotal rule in gaining the maximum benefits from them; on the other side non-optimal placement may cause undesirable effects. Several studies were performed for achieving the aforementioned task [8–14]. In [11] a probabilistic approach was proposed for optimal allocation of wind-based distributed generators in distribution networks. A continuous stochastic optimal allocation of wind power considering load uncertainty was presented in [12]. A multi-period optimal power flow was solved using non-linear programming in [13] for optimal allocation of renewable distributed generation.

To the best of the authors' knowledge, considering the stochastic dependence in the output power from renewable DG units among each other and with system demand was not presented nor had been in focus of recent publications. Hence, the problem regarding the optimal allocation of renewable energy DG units considering their stochastic dependence still requires attention. This paper presents a novel algorithm for modeling the renewable energy DGs and system demand based on diagonal Copula method and Monte Carlo method. Via the proposed model the dependence between wind turbines powers, wind power–photovoltaic power-system demand is considered. In addition, a supervised Big Bang-Big crunch (BB-BC) algorithm based on a modification of the traditional BB-BC method presented by Osman in [15] is proposed. The optimization algorithm utilizes the model results for solving energy loss minimization problem incorporating renewable energy based DGs and dispatchable DG. The optimization algorithm aims to precisely determine the optimal location of renewable DGs and the location and daily power schedule of dispatchable DG in order to minimize the annual energy losses in unbalanced distribution networks. The proposed algorithms are implemented in MATLAB environment and tested on the IEEE-37 nodes unbalanced feeder. The results and the consequent discussions prove the effectiveness of the proposed algorithms.

2. Role of stochastic dependence and diagonal band copula

The stochastic dependence of different random variables related to the operation of renewable based generators is evident. For instance, the wind speeds between different locations present a significant degree of correlation due to their mutual dependence on wind activity which is translated into correlation between the system wind powers in return. Not taking into account this correlation leads to a severe underestimation of the variability of the system power flows and consequently to an underestimation of the risks related to specific design decisions [16,17]. Moreover, the solar irradiance is correlated to the system demand. For example, at the late night the solar irradiance is almost zero, at the same time the system demand is at minimum daily value. In addition, the solar irradiance starts to increase after the sun set which is the same behavior of the system demand (i.e. the output power of the PV arrays is correlated to the system demand).

2.1. Measurement of stochastic dependence [18]

To measure the strength of dependence between random variables, the product moment correlation of ranks called rank correlation (ρ_r) is used. The **rank correlation** of random variables X, Y with cumulative distribution functions F_X and F_Y is

$$\rho_r(X, Y) = \rho(F_X(X), F_Y(Y)) \tag{1}$$

where $\rho(F_X(X), F_Y(Y))$ is the product moment correlation of two ranks (cumulative distribution functions or marginal distributions) and calculated using (2)

$$\rho(F_X(X), F_Y(Y)) = \frac{Cov(F_X, F_Y)}{\sigma(F_X)\sigma(F_Y)} \tag{2}$$

where Cov and σ are the covariance and standard deviation respectively. It is clear that there is a relationship between the product moment and the rank correlation. The rank correlation is a correlation of random variables transformed to uniform random variables. Hence we get immediately that rank correlation is symmetric and takes values from the interval $[-1, 1]$. Rank correlation equals one means that there is perfect dependence between random variables. While, rank correlation equal to zero means that the random variables are independent.

2.2. Diagonal band copula [18]

The notion of 'copula' was introduced to separate the effect of dependence from the effect of marginal distributions in a joint distribution. Copulas are family of functions that join or 'couple' multivariate distribution functions to their one-dimensional marginals. Alternatively, copulas are multivariate distribution functions whose one-dimensional marginals are uniform on the interval [0, 1]. Two random variables X and Y are joined by copula C if their joint distribution can be written as

$$F_{XY}(x, y) = C(F_X(x), F_Y(y)) \tag{3}$$

It can be written $F_X(x) = u$ and $F_Y(y) = v$, where u and v are realizations of the uniform random variables U and V respectively. In this case, the (3) will become

$$C_{V|U}(u, v) = F(x, y) = F(F_X^{-1}(u), F_y^{-1}(v)) \tag{4}$$

where $C_{V|U}$ is the conditional distribution of $V|U$ (copula of X, Y) and F^{-1} is the inverse of the standard univariate normal distribution function.

3. Modeling strategy

This section explains the proposed models of both renewable DGs and load considering their dependence. The proposed probabilistic models for the renewable DGs and system load are based on Monte Carlo method and diagonal band copula according to three years of historical meteorological and system demand data.

3.1. Historical data processing

Three years of historical data between the years 2001–2003 are used in this study. Six readings of the solar irradiance, ambient temperature, wind speeds were taken at two different locations at the same site at each hour during the three years. The available data is seasonally divided (i.e. each season data is separated). The data representing each season is further subdivided into 24-h segments (time segments), each referring to a particular hourly interval for the entire season. Thus, there are 96 time segments for the year (24 for each season). Considering a month to be 30 days, each time segment then has 1620 readings (3 years × 30 days per month × 3 month per season × 6 readings per hour). Moreover, system demand data for the same region where the metrological data were taken at the same three years are divided and used as aforementioned stated.