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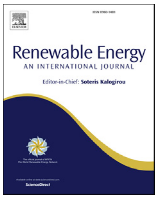

Probabilistic multi-objective optimal power flow considering correlated wind power and load uncertainties

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Increasing penetration of wind power in power systems causes difficulties in system planning due to the uncertainty and non dispatchability of the wind power. The important issue, in addition to uncertain nature of the wind speed, is that the wind speeds in neighbor locations are not independent and are in contrast, highly correlated. For accurate planning, it is necessary to consider this correlation in optimization planning of the power system. With respect to this point, this paper presents a probabilistic multi-objective optimal power flow (MO-OPF) considering the correlation in wind speed and the load. This paper utilizes a point estimate method (PEM) which uses Nataf transformation. In reality, the joint probability density function (PDF) of wind speed related to different places is not available but marginal PDF and the correlation matrix is available in most cases, which satisfy the service condition of Nataf transformation. In this paper biogeography based optimization (BBO) algorithm, which is a powerful optimization algorithm in solving problems including both continuous and discrete variables, is utilized in order to solve probabilistic MO-OPF problem. In order to demonstrate performance of the method, IEEE 30-bus standard test case with integration of two wind farms is examined. Then the obtained results are compared with the Monte Carlo simulation (MCS) results. The comparison indicates high accuracy of the proposed method.

1. Introduction

Energy security concerns, environmental issues and increasing demand have directed lots of attention to renewable energy sources. Among renewable energy sources, wind power has found high penetration in power systems throughout the world [1]. The integration of a significant amount of wind power which has uncertain nature has made important challenges in power system planing and operation [2]. The main issue is that the wind speed varies stochastically and output power of wind turbine has the same behavior. Many researchers have demonstrated that spatial and temporal correlation of renewable energy, i.e. wind power, which affect power system can be predicted and modeled using efficient methods [3,4]. Furthermore, in systems with high penetration of wind power, spatial and temporal correlation of wind power should be considered for extra accurate and reliable results [5,6].

Optimal power flow (OPF) is effective tool for analyzing economic behaviors of the power market and making compromise between power system economic and security [7]. This problem sometimes decomposed into two different problem called optimal active power dispatch and optimal reactive power dispatch (ORPD) problems [8,9]. Probabilistic OPF (POPF) has been widely used in planning and operation of power systems [10–12]. The methods of solving POPF can be classified into three main categories: analytical methods, simulation methods and approximation methods. Simulation methods refer to Monte Carlo simulation (MCS) method which is computationally expensive but popular for its simple implementation and high accuracy [13–15]. On the other hand, analytical methods are based on linearization and are less accurate [16–18]. An approach using an analytical method to solve the probabilistic load flow (PLF) considering load demand correlation based on the use of cumulants and Gram-Charlier expansion is proposed in Ref. [19].

Approximation methods like point estimate method (PEM), which is proposed to solve POPF in Refs. [7,20,21], have less computational burden and provides accurate results in the low number of uncertain variables but is impractical in large-scale problems. Unfortunately PEM methods are not able to handle problems with correlated Random Variables (RVs) and some modifications are necessary to make it capable. Two kinds of point

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estimate methods (2m and 2m + 1 scheme) are used in Ref. [22] to solve the POPF. The correlated samples of wind power injections and load points have been generated by Cholesky decomposition method, and the interior point method is used to solve the deterministic optimal power flow calculation.

A modified PEM is proposed in Ref. [23] to solve POPF, which considers correlation among wind power, solar energy and demand load. A review of the probabilistic techniques used for POPF studies and the application of unscented transformation (UT) method to generate correlated samples is presented in Ref. [24]. Zhaos point estimate method (PEM) combined with Nataf transformation applied into correlated PLF calculation is proposed in Ref. [25]. The proposed method can deal with correlated input RVs with normal or non-normal probability distributions and instead of PDFs of multivariate RVs requires raw moments of the marginal distribution function of each input RV and their correlation coefficients. In Ref. [26] traditional $2m + 1$ PEM extended by using a transformation to handle correlated RVs with arbitrary distributions in POPF problem. In [27], a method is proposed for incorporati$2m + 1$ ng the effects of spatially and temporally correlated input RVs within the point estimate method for POPF simulation. This method is used to solve multi-period POPF including correlation among time intervals of wind power generation.

Most of the papers studying effect of the correlation of uncertain variables on POPF problem presented different methods to solve the problem but few of them have studied effect of variation of correlation on control and output variables. For instance, a new method is presented in Ref. [26] in order to observe effect of correlation on uncertain variables following different distributions but do not investigate how the variables will affect with variation of correlation. In other case, a new method for solving POPF with correlated variables is presented in Ref. [23] and effect of correlation on accuracy of the presented method is studied, but the impact of variation of the correlation on control variables was not studied. It should be noted that, OPF problem in accurate model, should consider many objectives simultaneously, as in reality is required [28]. So it is important to investigate effect of RVs and their correlation in multi objective POPF which is more closer to reality and can be more useful in planning of system to reach different targets, simultaneously.

In this paper, Biogeography Based Optimization algorithm with weighted sum method is used to solve probabilistic multi-objective optimal power flow problem and traditional PEM based Nataf transformation is utilized to handle correlation of wind sources and load demands. This paper studies the effect of correlation on control and output variables of MO-POPF problem. It is noteworthy that, the effect of correlation on the control and output variables of multi-objective POPF problem is studied for the first time in this paper. The standard IEEE 30-bus test system with two extended wind farms is used to examine the proposed method.

Contributions of the paper are as follows:

1. Using Hongs point estimate method and Nataf transformation to solve POPF problem with correlated input variables.
2. Solving probabilistic multi-objective optimal power flow considering wind power and load points correlation.
3. Using biogeography based optimization method as the optimization method.
4. Observing effect of correlation on the control variables and both objectives of the probabilistic multi-objective optimal power flow.

The rest of the paper is organized as follows: Section 2 formulates probabilistic MO-OPF and introduces PEM to solve it with uncorrelated RVs. Section 3 illustrates BBO algorithm for solving MO-OPF problem. Section 4 explains Nataf transformation and PEM based Nataf transformation to handle correlated RVs. Section 5 presents simulation results of examining proposed method on IEEE 30-bus test system and finally Section 6 concludes the remarks and results of the paper.

2. Uncorrelated PEM for probabilistic multi-objective OPF

2.1. Probabilistic multi-objective optimal power flow formulation

The multi-objective OPF problem with uncorrelated input variables can be formulated generally as below:

$$\begin{aligned}&Minimize \quad F(X,Y) = \{F_1(X,Y), F_2(X,Y)\}\\&S.t. \quad G(X,Y) \geq 0\\&H(X,Y) = 0\end{aligned} \tag{1}$$

where $F_1(X,Y)$ and $F_2(X,Y)$ are objectives of probabilistic optimal power flow problem (POPF). X is the vector of control variables and Y is the vector of uncertain input variables of POPF problem. $H(X,Y)$ and $G(X,Y)$ are representing the equality and inequality constraints of the multi-objective problem, respectively.

In this paper, fuel cost and total emission of the system are considered as objectives of multi-objective POPF problem, which can be formulated as follows [29]:

Fuel cost function:

$$F_1(X,Y) = \sum_{i=1}^{N_G} a_i + b_i P_{gi} + c_i P_{gi}^2 \tag{2}$$

Emission cost function:

$$F_2(X,Y) = \sum_{i=1}^{N_G} \left(\alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2 + \varepsilon_i exp\left(\lambda_i P_{gi}\right)\right) \tag{3}$$

Where $F_1(X,Y)$ is the total fuel cost of generation units in \$/h, N_G is total number of generation units, P_{gi} (MW) is active power output of the ith generation unit and a_i, b_i, c_i are the fuel cost coefficients of ith generation unit. $F_2(X,Y)$ is total emission released from ith generation unit (ton/h), $P_{gi}(pu)$ is active power output of ith generator and α_i, β_i, γ_i, ε_i and λ_i are their emission coefficients.

This paper uses weighted sum method to solve multi-objective optimal power flow:

$$F = k_1 \frac{F_1(X,Y)}{F_{1min}} + k_2 \frac{F_2(X,Y)}{F_{2min}} \tag{4}$$

where, k_1 and k_2 are the weighting coefficient of fuel cost and emission cost objectives, simultaneously, and F_{1min} and F_{2min} are minimum amount of them which can be obtained solving single objective OPF. In this approach, for balanced weighting of objective functions k_1 and k_2 are considered to be equal to 1.

Control variables:

$$X = \left[P_g, V_g, T, Q_c\right]_{1\times N} \tag{5}$$

$$P_g = \left[P_{g1}, P_{g2}, \ldots, P_{g(N_g-1)}\right]_{1\times(N_g-1)} \tag{6}$$

$$V_g = \left[V_{g1}, V_{g2}, \ldots, V_{gN_g}\right]_{1\times N_g} \tag{7}$$

$$T = \left[T_1, T_2, \ldots, T_{N_t}\right]_{1\times N_t} \tag{8}$$

$$Q_c = \left[Q_{c1}, Q_{c2}, \ldots, Q_{cN_c}\right]_{1\times N_c} \tag{9}$$