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Stochastic optimal reactive power dispatch: Formulation and solution method

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ABSTRACT

Classical optimal reactive power dispatch (ORPD) is usually formulated as a deterministic optimization problem, such that the network structure and load power injections are known and fixed. Hence, the influences of load uncertainties and branch outages are not typically considered. This paper proposes a chance-constrained programming formulation for ORPD that considers uncertain nodal power injections and random branch outages. A solution method combining both probabilistic load flow and a genetic algorithm is proposed and demonstrated in order to solve the problem. Simulations on several test systems show that the proposed method can prevent under-compensation or over-compensation of reactive power and increase voltage security margins. These advantages are achieved with the acceptable expense of a small increase in active power loss when compared with the results of classical deterministic ORPD. Several techniques are presented in order to improve the efficiency of the proposed method and case studies demonstrate the effectiveness of the techniques.

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1. Introduction

In order to maintain desired levels of voltage and reactive power flow under various operating conditions and network configurations, power system operators may utilize a number of control tools such as switching VAr sources, changing generator voltages, and/or adjusting transformer tap-settings. By an optimal adjustment of these controls, the redistribution of the reactive power would minimize transmission losses. This forms the optimal reactive power dispatch (ORPD) problem and has a significant influence on secure and economic operation of power systems. Therefore, it has been widely researched and many research papers have been published on this field [1–6].

It should be noted that uncertainties always exists. It is impossible to predict the future system conditions precisely. Load forecasts have errors and lines may out of service randomly. Most of the published works on the ORPD problem assume deterministic nodal power injections and fixed network structure. In this paper we refer to this class of ORPD problem as the Deterministic ORPD (DORPD) problem. Although many global optimization algorithms have been developed for DORPD, the optimal solution obtained may not be "optimal" or even secure with regard to the real-time system. This is because the real-time system conditions always differ from what was forecast. In order to consider uncertain factors, ORPD can be formulated as an uncertain programming problem. Typical uncertain programming formulations are discussed in [7,8].

Ref. [9] presented an early idea to incorporate the effects of uncertain system parameters into optimal power dispatch. Different forms of linear stochastic optimal power flow (OPF) problems have been derived with different uncertainties in electric power systems in [10]. Although the computation issues were discussed, the implement of the solution methods was not presented in the paper. The objectives of stochastic OPF presented in [11,12] were to minimize the total cost of a base case operating state plus the expected cost of recovery from contingencies such as line or generator outages. Bender's decomposition method and constraint relaxation methods are proposed to solve the complex problem. Ref. [13] presented a cumulant method based solution for stochastic OPF. The objection was to find a set of control parameters that minimize the variance of the active power generation at the slack bus while maintaining a feasible power flow solution.

To model random factors, one of the approaches often considered is chance-constrained programming [14] in which (some or all) the constraints can be violated with a preassigned (usually very low) level of probability. This kind of approach has been applied to transmission system unit commitment [15] and expansion planning [16] considering random loads and/or generations. In this paper, a chance-constrained stochastic programming formulation for stochastic ORPD (SORPD) is proposed so that probabilistic load distributions and random branch outages can be considered. From the mathematical point of view, SORPD is a mixed-integer nonlinear

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stochastic programming problem. Therefore, it is very complex and virtually impossible to solve using standard mathematical programming methods. In recent years, artificial intelligence algorithms have often been used [7]. The constraints are usually converted into penalty functions and added to the objective function. Although sometimes a solution satisfying all the constraints may not be found, "near" feasible solutions can be obtained. However, when a chance-constrained stochastic programming formulation is adopted, a Monte Carlo simulation [17] should be run in order to check if the chance constraints are satisfied for every candidate solution. Therefore, the computational burden will be huge even for medium scale power systems.

In order to alleviate the computational burden, a solution procedure combining Probabilistic Load Flow (PLF) and a Genetic Algorithm (GA) is proposed. GA is widely used the power system optimizations [18,19] and especially suitable for solving reactive power optimization problem with discrete variables [3,4]. The fast analytic PLF method [20] is adopted to obtain the distributions of bus voltages and generator reactive power outputs. Several techniques have been proposed in order to accelerate the computational speed. The simulation results presented in this paper clearly demonstrate the efficiency of the proposed method.

2. Chance-constrained optimal reactive power dispatch formulation

The SORPD problem considering load uncertainties and random branch outages is formulated as the following chance-constrained programming problem:

$$\text{Min } f = aP_{\text{loss}}(\bar{\boldsymbol{V}},\bar{\theta},\bar{\boldsymbol{P}}_l,\bar{\boldsymbol{Q}}_l,\bar{\boldsymbol{Q}}_g,\boldsymbol{U}) + bS_{td}[\tilde{\mathbf{P}}_{loss}(\tilde{\mathbf{V}},\tilde{\theta},\tilde{\mathbf{P}}_l,\tilde{\mathbf{Q}}_l,\tilde{\mathbf{Q}}_g,\mathbf{U})] \quad (1)$$

$$\text{s.t.}\,\boldsymbol{g}(\bar{\boldsymbol{V}},\bar{\theta},\bar{\boldsymbol{P}}_l,\bar{\boldsymbol{Q}}_l,\bar{\boldsymbol{Q}}_g,\boldsymbol{U}) = 0 \quad (2)$$

$$\boldsymbol{V}_{\min} < \bar{\boldsymbol{V}} < \boldsymbol{V}_{\max} \quad (3)$$

$$\boldsymbol{Q}_{g,\min} < \bar{\boldsymbol{Q}}_g < \boldsymbol{Q}_{g,\max} \quad (4)$$

$$\boldsymbol{Pr}(\tilde{\boldsymbol{V}} \geqslant \boldsymbol{V}_{\min}) \geqslant \boldsymbol{p}_{V,\min} \quad (5)$$

$$\boldsymbol{Pr}(\tilde{\boldsymbol{V}} \leqslant \boldsymbol{V}_{\max}) \geqslant \boldsymbol{p}_{V,\max} \quad (6)$$

$$\boldsymbol{Pr}(\tilde{\boldsymbol{Q}}_g \geqslant \boldsymbol{Q}_{g,\min}) \geqslant \boldsymbol{p}_{\mathbf{Q}_{g,\min}} \quad (7)$$

$$\boldsymbol{Pr}(\tilde{\boldsymbol{Q}}_g \leqslant \boldsymbol{Q}_{g,\max}) \geqslant \boldsymbol{p}_{\mathbf{Q}_{g,\max}} \quad (8)$$

$$\boldsymbol{U}_{\min} \leqslant \boldsymbol{U} \leqslant \boldsymbol{U}_{\max} \quad (9)$$

where P_{loss}, and S_{td}, active power loss and its standard deviation; a and b, weighting coefficients; $\boldsymbol{g}(\cdot)$, load flow functions; $\boldsymbol{V}$ and θ, nodal voltage magnitude and angle; $\boldsymbol{P}_l$ and $\boldsymbol{Q}_l$, active and reactive powers of loads; $\boldsymbol{Q}_g$, reactive power outputs of generators; $\boldsymbol{U}$, control variables, includes voltage magnitudes of generator buses, reactive power injections of capacitors and reactors, tap positions; $Pr(\cdot)$, probability of the event in $(\cdot)$; $\boldsymbol{p}$, specified probability; superscripts $\sim$ and -, random variable and its expectation; subscripts max and min, upper and lower bounds.

The first term in the objective function represents the active power loss with regard to the forecasted system state (with expected loads and no outages), which is the equivalent to the DORPD problem. The second term in the objective function represents the standard deviation of the active power loss distribution. The minimization of this term reflects the objective of reducing the dispersion of active power losses. Constraints (2)–(4) are applied with regard to the forecasted system state. Inequalities (5)–(8) are the chance constraints applied to the probabilistic distributions of voltage magnitudes of the PQ buses and the reactive power outputs of the PV buses. Control variables $\boldsymbol{U}$ represent decision variables in this formulation. It should be noted that the constraints applied to state variables under branch outages are not explicitly shown. The influences of branch outages are implicitly reflected by the random variables $\tilde{\boldsymbol{V}}$, $\tilde{\theta}$ and $\tilde{\boldsymbol{Q}}_g$.

3. Solution method based on probabilistic load flow and genetic algorithm

The proposed formulation is a mixed-integer nonlinear chance-constrained programming problem. In order to solve this complex problem, GA has been employed in this research. In addition, an analytic PLF method is used to obtain the distributions of the desired random variables, so the chance constraints can be checked easily and quickly.

3.1. Probabilistic load flow

The PLF was proposed by Borkowska for evaluation of power flow considering uncertainties [21]. Given the distributions of input variables, such as real and reactive power injections, the distributions of the state variables and line flows can be obtained. So, the system uncertainties can be included and reflected in the results of PLF. The PLF can be performed by analytic or simulation method. Although usually simulation (such as Monte Carlo simulation) methods are able to provide more accurate results than analytic methods, the computation is more time consuming.

The analytical PLF method proposed in [20] is used to calculate state variable distributions under normally distributed load power injections and random branch outages with 0–1 distributions. The computational procedure that has been adopted for this paper can be summarized as follows (see Fig. 1):

(1) Calculate deterministic load flow (with loads equal to their expected values and no branch outage), obtaining $\bar{\boldsymbol{V}}$, $\bar{\boldsymbol{Q}}_g$ and the Jacobian matrix $\boldsymbol{J}$ of load flow Eq. (2). The sensitivity

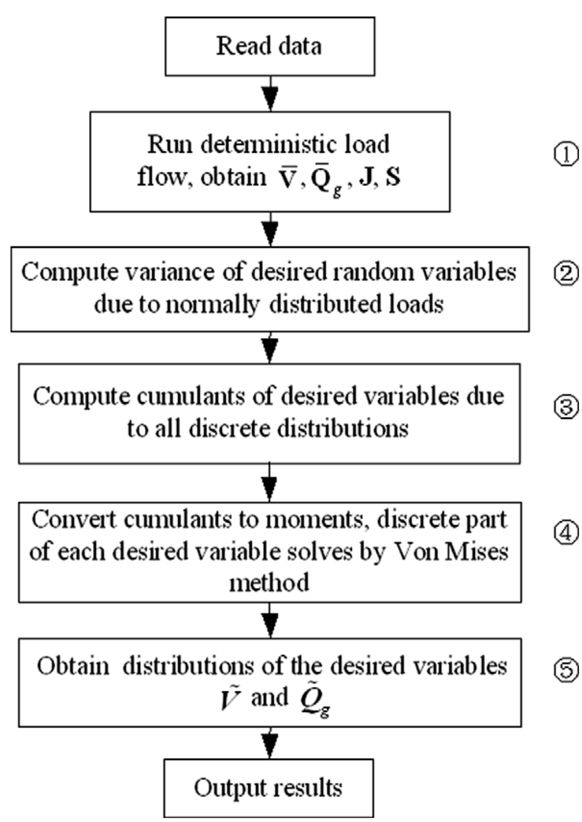

Fig. 1. Flowchart of the PLF algorithm.

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