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A parallel method for solving the DC security constrained optimal power flow with demand uncertainties

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ABSTRACT

The security constrained optimal power flow (SCOPF) is a fundamental tool to analyze the security and economy of a power system. To ensure the safe and economic operation of a system considering demand uncertainties and to acquire economic and reliable solutions, in this paper, a parallel method for solving the interval DC SCOPF with demand uncertainties is presented. By using the interval optimization method, the uncertain nodal load can be expressed as interval variables and integrated into the DC SCOPF model, which is then formed as a large scale nonlinear interval optimization formulation. According to the theory of interval matching and selection of the extreme value intervals, the interval DC SCOPF problem can be transformed into two deterministic nonlinear programming problems and solved by alternating direction method of multipliers (ADMM) to obtain the range information of interval formulation variables. Using ADMM, the above two deterministic problems, which are large in scale because of the large number of preconceived contingencies, all can be split into independent sub-problems corresponding to pre-contingency status and each individual post-contingency cases. These small-scale sub-problems can be solved in parallel to improve the computing speed. Compared with the Monte Carlo (MC) method, the simulation results of the IEEE 30-, 57- and 118-bus systems validate the effectiveness of the proposed method.

1. Introduction

The security constrained optimal power flow (SCOPF) [1,2], which is an extension of the conventional optimal power flow (OPF) [3], aims at determining an optimal operating point for control variables that minimizes a given objective function subject to physical constraints and control limits and takes into account both the normal state and contingency constraints. It can ensure the safe and economic operation of the power grid in theory.

1.1. Deterministic SCOPF

The traditional SCOPF, a large-scale optimal problem which might include nonlinear and non-convex items, discrete variables, etc., is computationally intensive because it considers a large number of contingencies [4]. Therefore, determining how to efficiently solve the deterministic SCOPF problem has become the research focus. The SCOPF problem has been widely classified into two classes: preventive security constrained optimal power flow (PSCOPF) [1], which assumes that the post-contingency conditions can be met without redispatching, and Corrective security constrained optimal power flow (CSCOPF) [2], which permits post-contingency control variables such as generators' active power and terminal voltage to be readjusted for removing any violations caused by the contingency.

In the SCOPF literature, many proven methodologies have been proposed in order to efficiently deal with this problem [4]. These methods can be divided into two categories. One category is solving the SCOPF directly [5,6]. However, this direct method for handling large-scale power systems with numerous contingencies in a centralized manner would result in a prohibitive memory and CPU times requirements [4]. The other category is reducing the size of the SCOPF problem [4,7]. Novel filtering techniques, relying on the comparison at an intermediate PSCOPF solution of post-contingency constraint violations among postulated contingencies, are proposed in [8] to accelerate the iterative solution of PSCOPF. In [7], the author used contingency filtering techniques to identify the binding contingency and limited the number of contingency. In addition, network compression method is used to reduce the size of each post-contingency model. Actually, all the

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methods belonging to the second category, including the above-mentioned methods, can be divided into four classes: iterative contingency selection schemes [8–10]; network compression [11]; hybrid methods which combine the two methods above [7]; decomposition methods [2,12–15]. The reader is referred to [4] for a detailed literature review on this topic. And, these methods are important because that the large-scale CSOPF problems should be reduced in size before to be solved, and the reduced problems can be used as the starting point for our approach in this paper.

Linear DC approximation of the (nonlinear, non-convex) AC power flow equation is frequently used in existing power systems [16]. DC-SCOPF is an approximation of AC-SCOPF for obtaining the optimal active power dispatch solution of the entire power system. In [17], the author improved the solution techniques for the AC SCOPF problem of active power dispatch by using the DC SCOPF approximation within the SCOPF algorithm. In this paper, we are interested in DC power flow constraints for the problem.

1.2. SCOPF under uncertainty

Modern power grids are characterized by increasing penetration of renewable energy sources and demand evolution, such as electric vehicles and energy storage [18,19]. This trend is expected to increase in the near future. Due to the privatization of the electricity market, the modern electricity market has changed. For example, some of the actions of the power participants are unpredictable [20].

The stochastic programming theory, robust optimization [21], fuzzy set theory [22] and interval analysis [23] are frequently-used methods for dealing with uncertainty problems. So far, the first two methods has been used to describe uncertainty in SCOPF successfully [4]. In [24], a robust AC SCOPF algorithm with three-stage feasibility checking problem is proposed to deal with the day-ahead power systems security planning under uncertainties. [25] propose a robust DC SCOPF algorithm which uses the mixed integer bi-level program optimization to compute the worst patterns of uncertain variables associated to each contingency. A multi stage stochastic programming model is established in [26] based on the uncertainty of the node load. The proposed model and the planning method are flexible, but the integer variable of the model increases. A new robust optimization method considering both safety and economy was given in document [13]. Aiming at circuit risk and system risk, using Lagrangian relaxation and Benders decomposition technology to solve the corrective risk-based SCOPF problem was proposed in [27]. Taking into account the uncertainty of renewable energy production, load consumption, and load reserve capacities, in [28] the authors formulated a chance constrained OPF to achieve minimum cost. However, most of these methods require probability distribution functions for uncertain items [29]. And these functions are difficult to obtain in the actual situation. According to the theory of interval matching and selection of the extreme value intervals, the interval optimization problem was translated into two determinate nonlinear programming problems and was solved to obtain the range information of the interval optimization problem [23,30]. The interval analysis model does not require the distribution parameters of uncertainty to be determined, as it requires only the upper and lower boundary information.

1.3. Paper contributions and organization

In this work, we propose a novel approach based on the interval optimization method to solve CSCOPF with demand uncertainties problem in parallel. Above all, according to the interval optimization algorithm, the uncertain load variables are expressed as interval variables and lead into the model of corrective security constrained optimal power flow. Thus, an interval optimization formulation was constructed for corrective security constrained optimal power flow with demand uncertainties. Next, based on the theory of direct interval matching and selection of extreme interval, the interval optimal problem was translated into determinate quadratic programming problem, and solved by alternating direction method of multipliers (ADMM) to obtain the range information of interval formulation variables in parallel. Finally, the interval corrective security constrained optimal power flow results on the IEEE 30-, 57- and 118-bus systems are shown and the impact of the key parameters for the ADMM algorithm are described.

The major contributions of this paper are summarized as follows: (1) By using interval mathematics, the uncertain parameters can be expressed as interval form, and be integrated into SCOPF model which then formed as a more concise nonlinear interval optimization formulation; (2) According to the theory of interval matching and selection of the extreme value intervals, the interval SCOPF problem can be transformed into two deterministic nonlinear programming problems for determining the range information of interval formulation variables; (3) The resulted problems are solved in parallel by using ADMM. The simulation results show that the proposed method is computationally efficient and reliable, and it is effective for the SCOPF problem with multiple interval variables.

The remainder of this paper is organized as follows. Section 2 provides the formulations of the interval CSCOPF (ICSCOPF) problem. Section 3 presents method for solving the ICSCOPF problem based on ADMM. Section 4 contains numerical experiments, and Section 5 concludes the paper.

2. CSCOPF formulation

2.1. The OPF problem descriptions

The standard AC-OPF determines the least-cost operation of power systems by dispatching generation resources to supply systems loads, while satisfying prevailing system-level and physical constraints. In practice, AC-OPF problems are typically approximated by a more tractable "DC-OPF" problem that focuses exclusively on real power constraints in linearized form [31]; these linear real power constraints are also used in this paper.

Given that the operational costs of thermal units is commonly represented as a quadratic function of the generation level, the objective is $f_i(P_{G,i}) = (a_i + b_i P_{G,i} + c_i P_{G,i}^2)$, where a_i, b_i and c_i are the generation cost coefficients of the generator i. $P_{G,i}$ is the active output of the generator i.

The equality constraint of OPF formulation is the power flow equation of the system.

$$P_{G,i} - P_{D,i} - \sum_{j=1}^{N} (B_{ij}\theta_j) = 0,\ i = 1,\dots,N \tag{1}$$

where B_{ij} is the susceptance between the i-th and j-th buses. θ_j is the voltage angle at node j. $P_{D,i}$ is the real power demand at node i. N is the total number of nodes in the system.

The inequality constraints of the OPF model include the constraints of state variables and the limits of each physical quantity describing the power system, i.e.,

$$\underline{P}_{G,i} \leqslant P_{G,i} \leqslant \overline{P}_{G,i},\ i \in S_G \tag{2}$$

$$\underline{P}_{ij} \leqslant P_{ij} \leqslant \overline{P}_{ij} \tag{3}$$

where $\overline{P}_{G,i}$ and $\underline{P}_{G,i}$ are the maximum and minimum active power output of generator i respectively. S_G represents the set of generators in the grid. $\overline{P}_{ij}$ and $\underline{P}_{ij}$ are the maximum and minimum active power flow, respectively, on the line between node i and j respectively. $P_{ij} = B_{ij}(\theta_i - \theta_j)$ represents the active power flow on line between node i and j, in the direction from node i to node j. The constraint (2) is the upper and lower bound for the active power output of the generator i. The constraint is (3) power flow limit on each line.

For the sake of convenience, let x denote the vector of state