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A new method for solving preventive security-constrained optimal power flow based on linear network compression

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ABSTRACT

In a security-constrained optimal power flow (SCOPF) problem, control actions are so calculated that not only the objective function is minimized in base case (no contingency), but also the constraints are satisfied for post-contingency states. In a large-scale power system, if all contingency states are considered, the dimensions of optimization problem becomes so large that it may fail to converge to a solution. In this paper, to reduce the dimensions of problem, first for each contingency the network is partitioned into three regions of internal, external and boundary. The internal region is the one that its variables are more affected by the contingency. The rest of the network is called the external region. The boundary region consists of some buses at the external one connecting external region to internal one. After partitioning, the equations of external and boundary regions are linearized and some of external region variables and equations are omitted. This work reduces the network equations and consequently reduces the problem dimensions. In addition, two commonly used contingency filtering methods are described and compared. The simulations are done on the IEEE 39 and 118-bus test systems.

1. Introduction

The security-constrained optimal power flow (SCOPF) problem is a nonlinear, non-convex, static, large-scale optimization problem that contains both continuous and discrete variables [1]. The SCOPF can be formulated in the preventive (PSCOPF) or corrective (CSCOPF) mode. PSCOPF and CSCOPF lead to preventively and correctively secure systems, respectively [2]. In a preventive secure system, without any remedial action, none of the probable contingencies causes constraint violation. On the other hand, in a correctively secure system, any post-contingency constraint violation can be removed by suitable remedial actions. Corrective security causes a trade-off between operating saving and security margins. A power system (at least for some constraints) may be preventively secure in short-term operation and correctively secure in long-term one [2]. This paper focuses on the preventive mode. The size of problem increases with increase in the number of power system buses and contingencies. Therefore, the direct solution of the problem considering all contingencies and whole power system is impossible due to memory limitation and/or unacceptable computation times [1].

The main challenges to SCOPF have been reviewed in [3]. Several methods have been proposed to simplify the problem solution. One of these methods is contingency filtering that in which a limited number of contingencies are selected and only these contingencies are included in the SCOPF. The results of solving optimization problem using the selected contingencies are the same as when all contingencies are considered. The selected contingencies are called with different names such as "binding contingencies" [4–7], "umbrella contingencies" [8] and "key contingencies" [9]. The selected contingencies can be determined using post-contingency constraint violation [4–5]. Two methods of contingency filtering have been proposed in [4]. In the first method, one contingency dominates some other contingencies. But in the second method, two or more contingencies jointly dominate some contingencies. Both filtering methods are described in Section 5 and simulated in Section 6. The Lagrange multiplier vectors related to the post-contingency power flow equations of the SCOPF have been used to identify the selected contingencies. This is based on the fact that the sensitivity of the full SCOPF objective function to an infinitesimal perturbation in the right-hand side of the power flow equations related to each contingency is the same as the Lagrange multiplier vector [8]. In [7], a DC SCOPF approximation based on DC power flow equations has been used within the AC SCOPF algorithm. In preventive mode, the DC SCOPF is used to identify the selected contingencies and in corrective mode it is used for identifying both the selected contingencies and a limited number of corrective actions for each contingency. In [9] a method based on the maximum controllable rescheduling value in

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post-contingency state has been proposed to determine the selected contingencies. Also, a modified CSCOPF has been presented to remove conflicting contingencies, i.e. a set of contingencies that can not be considered together in the CSCOPF problem. Instead of determining a limited number of contingencies, some constraints can be selected as umbrella constraints. These are constraints that are necessary and sufficient to describe the feasible set of an SCOPF problem [10]. A linear optimization problem has been proposed in [10] to identify the umbrella constraints.

Network compression and reduction of problem equations and variables are other methods to simplify solving the SCOPF problem. The compression method presented in [11] identifies an active region for each contingency where the contingency has a notable effect on its voltages and power flows. The variables and equations of the active region are retained in their actual identity. The nodes and elements that are not owned by the active region are substituted by a REI-DIMO equivalent network [12].To identify the active region, sensitivity values are used that is not a good method. In [1] the combination of a contingency filtering method [4] and a network compression method [11] is used. Control variables in the external (inactive) region can not be considered in solving the SCOPF problem and the assessment of contingencies because they are replaced by the REI-DIMO equivalent. Presently, the SCOPF is handled for practical systems with thousands of buses; for example it is used in European transmission network and under the title "Pan European Grid Advanced Simulation and State Estimation" (PEGASE) project [13].

In [14] a simplified model is used instead of post-contingency power flow equations. Post-contingency voltages are expressed by a linear function of pre-contingency voltages using the compensation method. [15] presents a simplified and partly linearized SCOPF model to reduce the number of state variables instead of reducing the number of contingencies. Linearization is done for the inequality constraints in post-contingency states based on the sensitivities between the variables in pre and post-contingency states. So, the variables in post-contingency states are approximately expressed by the ones in pre-contingency state. Also, the equality constraints for post-contingency states are no longer needed.

In addition to contingency filtering and network compression, there are some other methods that simplify the direct solution of the SCOPF problem. A new formulation of power flow is developed in [16] that directly includes bus voltage magnitudes and real and reactive line flows. This formulation is used to linear-programming-based solution of SCOPF. In [17] the non-convex parts of the SCOPF problem are first recreated by signomial functions based on Taylor series. After that, the signomial SCOPF formulation converts to convex using power transformation techniques. [18] and [19] solve the SCOPF problem using decomposition methods. The aim is to decompose the problem into subproblems related to each contingency. In these methods, after solving the optimal power flow (master problem), the obtained control variables are checked whether they make any violation for each credible contingency or not. If violation exists, the bender cut is provided by sending control variables to the contingency subproblems. [20] introduces a new type of the SCOPF problem named as preventive-corrective SCOPF (PCSCOPF). Contingencies are divided into two groups. One group is secured in the preventive mode and the other in the corrective mode.

This paper uses a linear network compression method to simplify solving the SCOPF problem. In this method, first for each contingency the network is partitioned into three regions of internal, external and boundary. Partitioning is done using Spectral Graph Partitioning method [20]. In the internal region, the variables are more affected by the contingency. The rest of the network is called the external region. The boundary region consists of some buses at the external one connecting external region to internal one. After partitioning, the equations of external and boundary regions are linearized and some of external region variables and equations are omitted. This work reduces the network equations and consequently reduces the problem dimensions.

2. Problem formulation

The PSCOPF problem can be formulated as follows [4]:

$$\min_{x_0,\cdots,x_c,u_0} f_0(x_0,u_0) \tag{1}$$

$$s.\ t.\ \ g_k(x_k,u_0) = 0 \quad k = 0,\cdots,c \tag{2}$$

$$h_k(x_k,u_0) \leqslant 0 \quad k = 0,\cdots,c \tag{3}$$

where f_0 is the objective function, g_k and h_k are, respectively, the set of equality and inequality constraints for kth contingency ($k = 0$ shows the base case (no contingency), while $k = 1,\cdots,c$ shows the kth contingency state, c is the number of contingencies). x_k is the vector of state variables (i.e., voltage phasors) for kth contingency state and u_0 shows the vector of base case control variables that in the preventive mode are not rescheduled in contingency states. Eq. (2) is base case and post-contingency power flow equations. Inequality constraint (3) contains physical and operational limits. A series of general issues related to statement and solution of the SCOPF problem have been presented in [2]. Some of them are as follows:

1- Models and their sensitivities can become discontinuous because of limits on power system elements and system operation.
2- SCOPF problems with different mathematical structures must be solved by suitable optimization algorithms such as linear, quadratic, non-linear or mixed-integer ones.
3- The eventual solution is usually path dependent because of non-smooth structures of realistic SCOPF problems.

3. Solving the PSCOPF problem

An iterative method is used to solve the PSCOPF problem. At each iteration, the PSCOPF problem is solved using the latest determined selected contingencies (denoted by c_b). Then with the obtained control variables, the post-contingency states are simulated for all contingencies including selected and unselected contingencies (used and not used in the PSCOPF problem) using the entire network without linearization and reduction. As for selected contingencies, the reduced network is used in the PSCOPF problem, only the constraints related to the internal region variables are satisfied. Therefore, the assessment of the external region variables using the entire network is also done for higher trustworthy. Of course, it is highly probable that with meeting internal region ones, there are not any violations for external region constraints. If all constraints in all contingencies are satisfied, the optimal solution has been obtained, and the computation finishes. Otherwise, some unselected contingencies from the ones leading to post-contingency violation are taken and added to the selected contingencies. If there are some violations for each of previously selected contingencies, that contingency must be considered in solving the PSCOPF problem using the entire network, i.e., without network compression. Other previously selected contingencies together with newly selected ones are included into the PSCOPF problem using the network compression. Then the PSCOPF problem is solved again. The stages of solution are as follows:

1- Put $c = 0$ (this converts the PSCOPF problem to an OPF problem), solve the PSCOPF problem. It is clear that in this stage $c_b = 0$. It is assumed that $P_{c_b}^*$ shows the optimal operating point.
2- Simulate all selected and unselected contingencies at $P_{c_b}^*$ using the entire network. If there are not any violations, $P_{c_b}^*$ is an optimal solution and the computation finishes. Otherwise, go to stage 3.
3- Select some unselected contingencies from the ones leading to post-contingency violation (in stage 2) and add to the selected