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Scalable corrective security-constrained economic dispatch considering conflicting contingencies

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ABSTRACT

Reliability is an overriding factor in power system operations. Corrective security-constrained economic dispatch (SCED) satisfying the "$N-1$" criterion is difficult because of a large number of contingencies and the strict time limits for real-time operations. The existence of conflicting contingencies further complicates the problem. To overcome these difficulties, this paper develops a new iterative contingency filtering approach to manage "$N-1$" transmission and generator contingencies via decomposition and coordination. Instead of always removing conflicting contingencies as in existing papers, we offer system operators an important option to keep them for increased reliability, enabled by identifying multiple conflicting contingencies simultaneously. To satisfy the strict time requirements in real-time operations, the computational performance of our approach is significantly enhanced by novel warm-start of subproblem models and by parallel computing. Numerical results demonstrate that our new approach is computationally efficient and scalable, and increases the system reliability. In particular, the Polish 2383-bus system with all transmission contingencies is solved within two minutes.

1. Introduction

Reliability is an overriding factor in power system operations. Power engineers make great efforts to "keep the lights on" under normal operation conditions and contingencies. A contingency is an unexpected outage of a component (a transmission line or a generator). To protect power systems against cascading failures and even blackouts, the North American Electric Reliability Corporation (NERC) set, among other reliability standards, the "$N-1$" criterion: in a system that has N components, no single contingency will lead to violations of other components [1]. In real-time wholesale electricity markets, this criterion is considered in economic dispatch (ED), a central operational process. ED is conducted every five minutes to decide how much MW of power each online generator (or unit) should produce to minimize the total generation cost. The version of ED considering the "$N-1$" criterion is known as "security-constrained economic dispatch" (SCED).

1.1. Motivations of corrective SCED

There are two categories of SCED models: preventive and corrective. Preventive SCED is currently practiced to manage transmission contingencies, and requires one set of ED decisions feasible against the base case (under which no contingency happens) and all "$N-1$" transmission contingencies [2]. Such a model restricts ED decisions to remain unchanged from the base-case values right after a contingency occurs. In corrective SCED [3], after a contingency happens, corrective actions can be taken to address the contingency. Corrective SCED models one set of base-case ED decisions and multiple sets of post-contingency ED decisions, one set per contingency. Post-contingency flows that are required to be within corresponding Long-Time Emergency (LTE) ratings in 15 min after a contingency [4,5]. It is ideal to include both preventive decisions to capture the system status right after a contingency happens, and corrective decisions to model the adjustment of post-contingency flows as improved corrective SCED [6]. Moreover, generator contingencies are currently managed by pre-defined reserve requirements based on capacities of particular generators [1]. Since these requirements do not explicitly consider each generator contingency, results may be conservative or infeasible for certain contingencies. In corrective SCED, the output of the tripped generator can be picked up by corrective actions of others. In addition, distributed battery energy storage is used to provide fast corrective actions to quickly alleviate short-term violations [7].

This paper focuses on corrective SCED considering "$N-1$" transmission and generator contingencies. Corrective SCED involves large numbers of post-contingency ED decisions and constraints, and has traditionally been very hard to solve within the timeframe of the real-

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Nomenclature

c (or c')	index of contingencies, $0 \le c \le L + K$. When $c = 0$, the system is under the base case; when $c = 1, \ldots, L$, the system is under a transmission contingency where line c is tripped; when $c = L + 1, \ldots, L + K$, the system is under a generator contingency where unit $(c - L)$ is tripped
i	index of buses, $1 \le i \le I$
k	index of online units, $1 \le k \le K$
l	index of lines, $1 \le l \le L$
$\alpha(l)$, $\beta(l)$	from and to buses of line l, respectively
$\Phi(i)$	set of units at bus i
$C_k(\cdot)$	increasing continuous piecewise linear generation cost function of unit k (\$)
D_i	demand at bus i (MW)
$f_{l,c}$	power flow along line l under contingency c (MW)
$f_{l,c}{}^{\max}$	rating of line l under contingency c (MW)
M	Penalty factor (\$)
$p_{k,c}$	dispatch decision of unit k under contingency c (MW)
p_k^{min}, p_k^{max}	minimum and maximum generation limits of unit k, respectively (MW)
R_k	Ramp rate of unit k (MW/minute)
$s_{k,c}{}^U$, $s_{k,c}{}^D$	slack variables to relax the ramp-up and ramp-down inequalities of redispatch constraints, respectively (MW)
t_c	time allowed for corrective actions under contingency c (minute)
X_l	reactance of line l (Ω)
y_c	penalty term of contingency c in the master SCED problem (\$)
$\Delta_{k,c}$	maximal allowed variation of unit k under contingency c (MW)
$\theta_{i,c}$	voltage phase angle at bus i under contingency c
ν_c	objective value of contingency subproblem c (\$)
S_A	set of (possibly) active contingencies that have been identified by the contingency filtering approach. Each active contingency has a positive optimal objective value of its corresponding contingency subproblem as formulated in Section 3.3 at the current or any previous iteration
S_C	set of candidate contingencies considered by the contingency filtering approach. It may start with either a predefined contingency set approved by the operator, or the set that contains all possible "$N-1$" contingencies. During the contingency filtering process, contingencies that are included in S_A, S_1 or S_2 are removed from S_C
S_1	set of Type 1 contingencies that have been identified by the contingency filtering approach
S_2	set of Type 2 contingencies that have been identified by the contingency filtering approach

time dispatch [8]. Furthermore, different types of infeasible contingencies, especially conflicting ones, often exist in practical systems and further complicate the solution process [9,10]. It is thus important to identify, differentiate, and manage them.

1.2. Literature review

To solve the corrective SCED problem, there are three typical approaches: the direct approach, contingency filtering, and Benders decomposition. The direct approach considers all possible contingencies and solves the corrective SCED problem as a large linear programming (LP) problem or a large nonlinear programming problem depending on whether the DC or AC power flow model is assumed. Since there are large numbers of decision variables and constraints corresponding to contingencies, the direct approach requires large computer memory and long solution time [11]. In addition, although a pre-screening step that solves the base-case problem together with each contingency sequentially can be used to identify some of the infeasible contingencies, that step can take considerable time and is blind to those contingencies that are conflicting with each other [10].

To reduce the problem size, contingency filtering methods (often considering AC power flow) start with solving the base-case model, and then iteratively add selected active contingencies to update the solution [9,12–14]. The base-case and selected active contingencies were solved in a master problem, while candidate contingencies were checked or ranked in subproblems. The active contingencies were selected by ranking all contingencies based on the severity index (the 2-norm of weighted constraint violations) [12], the rescheduling index (the minimum of the maximal controllable redispatch value) [9], or by using the non-dominated contingency technique (comparing constraint violations) [13]. The non-dominated contingency technique was used together with a network compression method in [14], where a general SCED formulation with both preventive and corrective actions were modeled. In addition, [14] managed discrete variables, including transformer ratios, phase shifter angles and the shunt reactive power, by a progressive round-off method.

Alternatively, Benders decomposition was used to divide the corrective SCED problem into a base-case master problem and multiple contingency subproblems [8,10,11,15,16]. For a given base-case ED solution, feasibility cuts were derived from subproblems and were added to the master problem to update the base-case ED solutions. In [8,11,15,16], AC power flow was considered, and the generalized Benders decomposition was used. In [15], a linear feasibility cut was shifted adaptively according to the constraint violation to alleviate the infeasibility caused by the nonconvexity. Moreover, [15] also investigated a global optimization method based on Lagrangian duality as well as the alternating direction method of multipliers. In [16], semidefinite programming (SDP) was used as convex relaxations of subproblems, and Benders cuts were developed on top of the relaxations. In a recent work [10], DC power flow was considered, and multi-stage redispatch was modeled for transmission contingencies.

Infeasible contingencies were first discussed in [9] where only transmission contingencies were considered. All islanding contingencies, identified in a primary contingency filtering step, were directly removed. Conflicting contingencies were identified and removed one at a time by relaxing the redispatch constraints with penalty terms. In [10], all infeasible contingencies were removed. Removing conflicting contingencies and all islanding ones may decrease system reliability as will be discussed in Section 2.2.

To further improve the performance, the authors of [9] developed a decomposed parallel interior point method to accelerate the solution process, and tested parallel computing by using from 3 to 8 processes. Performance enhancements in [10] included reducing the number of subproblems in iterations, solving subproblems by using the barrier method without crossover, including difficult contingencies within the master problem, and using parallel computing. The overall approach in [10] was able to solve the Polish 2383-bus system with all transmission contingencies within 10 min, using GAMS on a server that had two 3.46 G X5690 Xeon chips with 12 Cores, and 288 GB Memory. A faster approach is still desired to satisfy the strict time requirements in real-time operations.

1.3. Contributions and organization of this paper

This paper focuses on developing a novel contingency filtering approach to solve large-scale corrective SCED problems within the