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Application of a genetic algorithm to *n-K* power system security assessment

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ABSTRACT

This paper addresses the security assessment of power systems when the simultaneous loss of K components is considered. The problem is formulated as a bilevel program. The upper-level optimization identifies a set of simultaneous out-of-service components in the power system, whereas the lower-level optimization models the reaction of the system operator against the outages selected in the upper level. The system operator reacts by determining the optimal power system operation under contingency. Due to the inherent nonconvexity and nonlinearity of the resulting bilevel problem, efficient solution procedures are yet to be explored. A genetic algorithm is proposed in this paper to attain high-quality near-optimal solutions with moderate computational effort. The modeling flexibility provided by this evolution-inspired methodology makes it suitable for this kind of bilevel programming problems. Numerical results demonstrate the effectiveness of the proposed approach in the identification of critical power system components.

1. Introduction

Reliability and security are major factors in the operation and planning of power systems. Current reliability policy and associated security standards in power systems worldwide materialize in the well-known *n*-1 and *n*-2 security criteria, by which the system is capable to withstand the loss of a single component or a couple of components, respectively [1]. However, recent blackouts have uncovered the vulnerability of power systems [2]. Moreover, these catastrophic events have been caused by the coincidence in time of the loss of several independent system components. Therefore, these disruptions reveal the need for considering a larger number of simultaneous outages.

The extension of current *n*-1 and *n*-2 security criteria to an *n-K* criterion with K out-of-service components considerably increases the number of contingencies that should be examined. Therefore, new models and solution approaches are required to properly account for the extended contingency set. In the framework of power system vulnerability analysis, the primary task is the assessment of security under multiple contingencies [3], hereinafter denoted as *n-K* power system security assessment. This tool provides information on the compliance of the *n-K* security criterion. Moreover, this analysis includes the identification of the critical power system components, i.e., those assets whose outage would yield the maximum damage to the system. The solution to the *n-K* power system security assessment problem is relevant for the system planner and the system operator so that effective protective and corrective actions can be devised. Thus, several strategies can be implemented such as adding new assets for purposes of redundancy [4,5], and hardening the infrastructure or improving its active defenses so that the hardened or defended assets become invulnerable [6,7].

The analysis of the impact of multiple out-of-service components could be carried out using traditional security analysis approaches in which a pre-specified set of contingencies is simulated, one at a time [8–12]. Current computing capabilities may allow using such traditional simulation-based methods for the set of contingencies associated with *n*-1 and *n*-2 security criteria for practical power systems. However, the incorporation of tighter security levels, such as the *n-K* criterion analyzed in this paper, would lead to intractability due to the huge number of contingency states that should be considered. As a consequence, traditional simulation-based models only examine a limited set of credible contingencies, which is determined based on experience and engineering judgment. This simplification, however, may yield suboptimal or even infeasible solutions once contingencies occur.

Researchers have only recently begun to address *n-K* power system security assessment with the development of models based on bilevel programming [3,13–21]. The upper-level optimization identifies a set of simultaneous outages in the power system whereas the lower-level optimization models the reaction of the system operator against the outages obtained in the upper level. Unlike traditional security analysis, bilevel programming models embed all contingencies associated with the *n-K* security criterion

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Nomenclature

Indices

j	generator index
ℓ	transmission asset index
n	bus index

Sets

J	set of indices of generators
J_n	set of indices of generators connected to bus n
L	set of indices of transmission assets
N	set of indices of buses

Constants

$FR(\ell)$	sending bus of transmission asset ℓ
K	number of simultaneous out-of-service transmission assets
P_n^d	demand at bus n
$\overline{P}_\ell^f$	power flow capacity of transmission asset ℓ
$\overline{P}_j^g$	capacity of generator j
$TO(\ell)$	receiving bus of transmission asset ℓ
x_ℓ	reactance of transmission asset ℓ
$\bar{\delta}$	upper bound for the nodal phase angles
$\underline{\delta}$	lower bound for the nodal phase angles

Variables

P_ℓ^f	power flow of transmission asset ℓ
P_j^g	power output of generator j
v_ℓ	binary variable that is equal to 0 if transmission asset ℓ is out of service, being 1 otherwise
w_ℓ	binary variable that is equal to 0 if transmission asset ℓ is disconnected by the system operator, being 1 otherwise
δ_n	phase angle at bus n
ΔP_n^d	load shed at bus n

without explicitly requiring their individual simulation. Bilevel programming [22,23] is a suitable framework for decision-making problems involving two optimization levels in which their respective objective functions are optimized over a jointly dependent set. Unfortunately, bilevel programs are strongly NP-hard [24] even in the simplest case with linear expressions and continuous variables. Therefore, devising exact methodologies to solve this kind of problems is a complex task.

Several solution techniques for bilevel-programming-based *n-K* power system security assessment have been proposed in the technical literature such as decomposition-based approaches [13,18,19,21], equivalent transformations to mixed-integer programs [14,15,17,3], and approximate methods [16,20]. However, all previous works share limitations from either the modeling or methodological perspectives. Thus, these models typically rely on a simplified representation of the system behavior leading to bilevel programs with convex lower-level problems. Furthermore, solution techniques (i) do not guarantee optimality, and (ii) are specifically tailored to such simplified models. Therefore, we still lack efficient tools addressing more realistic models.

This paper presents an alternative approach based on a genetic algorithm for a general bilevel programming framework for the *n-K* security assessment problem that allows considering the nonlinearities and nonconvexities associated with power system operation under contingency. Based on the idea of natural selection, a genetic algorithm [25] works by evolving or improving a constant-sized population of individuals over successive iterations called generations. Individuals represent samples of the search space and are typically referred to as chromosomes, which are encoded as strings of symbols. The position of a symbol and its value are respectively denoted as gene and allele. Each individual is evaluated in terms of its overall fitness with respect to the given application domain. High-performing individuals are selected to produce offspring that retain many of the features of their parents. The evolution process is carried out through a series of genetic operators [25–27]. Main genetic operators include (i) selection, which implements survival of the fittest or best solutions and determines the parents of the new generation; (ii) crossover, which randomly exchanges gene structures from two selected parents to produce new offspring; and (iii) mutation, which randomly changes one or more components of a selected individual, thus acting as a population perturbation operator.

Several factors have boosted the appeal of genetic algorithms as global optimization approaches:

- The need for more sophisticated models makes it difficult or even impossible the use of traditional optimization techniques. Although these models typically result in complex optimization problems with many local optima and little inherent structure to guide the search, the flexible modeling framework provided by genetic algorithms allows handling nonlinearities and nonconvexities.
- Genetic algorithms are generally quite effective for rapid global search of large solution spaces. As a result, near-optimal solutions are likely to be attained in reasonable computation times.
- Genetic algorithms operate on a pool of individuals, thus multiple solutions are suggested.
- The search mechanism is intrinsically parallel, thus lending itself to a parallel implementation with the potential reduction in the computational requirement.

As a result, genetic algorithms have been widely used in the field of power system operation and planning [28–30]. The practical relevance and timeliness of genetic algorithms in the context of power systems are both backed by recent contributions [31–34]. In addition, genetic algorithms have also been successfully applied to several instances of bilevel programming [35–40]. These previous works pave the way for the application of genetic algorithms to address the bilevel-programming-based *n-K* power system security assessment.

This paper reports experience with the application of a genetic algorithm to a particular instance of *n-K* power system security assessment. The problem addressed is a maximum disruption model [3] considering line switching, that was recently solved in [19] through a heuristic approach inspired by Benders decomposition. As a complicating factor, the set of corrective actions available to the system operator includes the modification of the network topology through the connection and disconnection of transmission assets, which requires the use of binary variables in the lower-level problem. It should be noted that the presence of binary lower-level decision variables has been typically neglected by available genetic-algorithm-based approaches for bilevel programming [35–37,39,40], thereby constituting a salient feature of our approach.

In the proposed genetic algorithm, an individual is defined as the vector of statuses of system components. The evaluation of each individual requires the solution of a mixed-integer nonlinear optimal power flow corresponding to the lower-level optimization. The application of genetic operators may yield infeasible