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Two-stage stochastic optimal islanding operations under severe multiple contingencies in power grids

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ABSTRACT

Due to the catastrophic consequences of rolling blackouts, there is an increasing concern with the security and stability of modern power grids. Power grid islanding, as an emergency control operation method, can divide power grids into several self-sufficient islands and can then avoid wide-area blackouts. In this paper, we present a two-stage stochastic programming model to divide the power grids into self-sufficient islands before any multiple failures happen, and optimize islanding operations plan under severe multiple contingencies that lead to extreme situations where rolling blackouts may occur. Line switching and controlled load shedding are main tools for islanding, and the expected penalty for load shedding cost is minimized in consideration of contingencies with certain probabilities to happen. The presented model can give the system operator an efficient and optimal way to properly respond to outages. Several numerical experiments are performed on IEEE test cases to show the effectiveness of the proposed islanding operations method.

1. Introduction

Recent reports of large-scale blackouts in North America, Europe, South Asia, and other areas show that power systems are at times operating close to stability limits (see [1,2]). The power systems are thus very vulnerable to some unexpected events, such as hurricanes, earthquakes, extremely hot weather, system failures and outages, human errors, etc. As a result catastrophic failures or large-scale blackouts may happen. These blackouts have huge influences on the society. For example, the July 2012 Indian blackout affected over 620 million people (see [3]).

A power grid island is a self-sufficient subnetwork in a large-scale power system. To avoid wide-area blackout and minimize the losses, in case of multiple component failures in a power system (called contingencies), defensive islanding intentionally splits an interconnected power system into islands to prevent the further spreading of wide area blackouts. To respond to particular severe contingencies leading to extreme situations where rolling blackouts may occur, it may be desirable to isolate the impacted or failed area from the other parts, which remain operational with limited load shedding to help avoid catastrophic losses; Otherwise the traditional protection schemes will be triggered and used when normal contingencies occur. In other words, controlled islanding is the last line of defense in preventing large-scale blackouts in case of multiple severe contingencies. Compared with uncontrolled islanding, which may happen in a blackout, controlled islanding can help minimize the disturbance of power supply to a system as early as possible and facilitate the recovery process afterwards. Control islanding strategies have been extensively discussed in [4–9].

Power grid islanding has been studied in many papers. Some of them have studied the islanding problem without considering contingencies and in the others contingencies have been taken into account. As examples of the former category, in [10], a review of main aspects of power grid islanding has been presented outlining the islanding schemes according to graph partitioning, minimal cutset enumeration, and generator grouping. Graph partitioning is directly used to partition the vertex sets into several subsets in [11–15] by modeling the topology of the power grid by a graph, and also minimal cutsets are used for partitioning a network in [13,16]. Recently, Senroy, et al. [8] used the decision tree method for controlled islanding, and Pareto optimization has been used in [17] by Vittal and Heydt. Zhao et al. [18] used an ordered binary decision diagram based algorithm for network splitting and extended their work considering corrective actions to make the network more stable in [19]. Some other partitioning methods based on matrices were used to partition the power grid, for example, the spectral

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methods on power flow Jacobian matrix [11], and the spectral and k-means methods on real power flow matrix [20].

Approaches for simultaneously obtaining more than two islands are proposed in [12,14,15] by graph partitioning. Some optimization approaches [11,13,16,17] to power grid islanding relied on heuristic and approximation methods. In the recent work [15], an exact optimization approach for power grid islanding considering load shedding and connectivity constraints, which are crucial for the reliability of islands, was used for identifying multiple islands simultaneously. However, this model is for intentional islanding without considering any failures that lead to cascading blackout. Intentional islanding has also been addressed in [21–24] by several approaches including optimization approaches considering static stability and minimizing load shedding in power grids. Islanding has been proposed in [25] as a protection method in power networks with renewable distributed generators. In [26], optimization approaches based on a constrained programming formulation and heuristic methods have been used for minimizing the load shedding in the region where the failures start and in the topological complement of the region. In [27,28], given an area of uncertainty in the network, a mathematical formulation for the islanding based on mixed integer linear programming has been used to isolate unhealthy components of the network. However, [27,28] considered islanding of power grids under contingencies by bus splitting rather than line switching. On the other hand, line switching has been proved as an effective method for power grid operations to reduce the operational costs as well as to improve the reliability (see [29,30]). In order to trigger line switching some protection devices such as R-Rdot out-of-step relays discussed in [5,31] can be used. Most recently, [32] gave an overview of controlled islanding approaches, notably those using mixed-integer programming and suggested a two-stage stochastic program to tackle the problem of finding robust islanding that hedges against possible uncertainties. Their model is computationally intractable as the number of scenarios in the second stage grows exponentially in the number of uncertain pieces of the grid, and also it decides load shedding and line switching before instead of after any failures happen. Additionally, [33] proposed and thoroughly investigated three load-shedding strategies to prevent cascading failures in the power grids without considering the possibility for islanding.

In this paper, we propose a power grid islanding scheme, through line switching and controlled load shedding, by considering a set of severe contingencies with a probability distribution. Each contingency state, with a probability to happen, includes failures of multiple grid components (buses, transmission lines and/or generators), which can lead to rolling large-scale blackouts. Additionally, based on the fact that most blackouts are starting from failures in a small "geographic area" (see [32]), we assume failed components of a severe contingency can be isolated into a single island in a grid. First, we partition a grid into several self-sufficient subnetworks, each of which can run separately with an acceptable load shedding amount. It should be noted that before any failures in the system, no islanding operations are employed at a normal state. The subnetworks comprising the entire grid are just defined artificially so that once failures happen, islanding operations by line switching can be used to isolate the failed part, and the other operational parts can operate with controlled load shedding.

We present a two-stage programming model to divide the power grid into self-sufficient islands before any failures happen, and optimize islanding operations plan under multiple severe contingency scenarios. The expected penalty for load shedding cost is minimized in consideration of contingency states with certain probabilities to happen. The whole model will give the system operator an efficient and optimal way to properly respond to failures happening in a grid.

Table 1
Sets and indices.

Symbol	Description
V	Set of buses (indexed by i, j)
E	Set of transmission lines (indexed by e)
G	Set of generators (indexed by g)
$\mathcal{C}$	Set of contingencies (indexed by c)
i_e, j_e	From/to buses (bus number) of transmission line $e = (i_e, j_e)$

The rest of this paper is organized as follows. In Section 2, a two-stage stochastic programming model is formulated for the islanding operations for a set of contingency scenarios. Several aspects, including special cases and solution approaches are also discussed. Section 3 performs comprehensive numerical experiments of our proposed model. Finally, Section 4 concludes this paper.

2. Models for islanding operations

2.1. Nomenclature

The sets, indices, parameters, and decision variables used in the model are defined respectively in Tables 1–3.

2.2. Stochastic programming model for islanding operations under contingencies

For a power grid consisting of buses in V, transmission lines in E and generators in G, the islanding operations follow these steps: (1) K islands in this power grid are predetermined before any contingency happens. (2) Once a contingency happens with one or more failed components, an islanding operation is used to

Table 2
Parameters.

Symbol	Description
D_i	Load demand at bus $i \in V$
$\overline{P_g}$	Generation capacity of generator $g \in G$
F_e	Transmission capacity of line $e \in E$
B_e	Susceptance of line $e \in E$
C_i	Penalty cost for load shedding at $i \in V$
$Prob(c)$	Probability of contingency $c \in \mathcal{C}$ such that $\sum_{c \in \mathcal{C}} Prob(c) = 1$
$d^{(c)} \in \{0, 1\}^{\lvert V \rvert + \lvert E \rvert + \lvert G \rvert}$	A vector used to define the contingency c, 1 if the element is failed and 0 otherwise
K	Number of islands proposed in a grid (indexed by k)
ε	Threshold for load shedding amount in operational islands

Table 3
Decision variables.

Symbol	Description
$x_{ik} \in \{0, 1\}$	$x_{ik} = 1$ if bus i is in island k and 0 otherwise
x	Vector formed by x_{ik}'s for all i and k, which decides all islands of the grid
$y_e \in \{0, 1\}$	$y_e = 1$ if the end buses i_e and j_e are in the same islands and 0 if the end nodes are in different islands
$Q(x, c)$	Load shedding cost under islands formed by x in contingency c
$p_g^{(c)}$	Power generation level by generator g in contingency c
$f_e^{(c)}$	Power flow on line $(i, j) \in E$ in contingency c
$s_i^{(c)}$	Load shedding amount at bus $i \in V$ in contingency c
$\theta_i^{(c)}$	Phase angle of bus $i \in V$ in contingency c
$z_e^{(c)} \in \{0, 1\}$	$z_e^{(c)} = 1$ if line e is switched on in contingency c, and 0 otherwise
$u_k^{(c)} \in \{0, 1\}$	$u_k^{(c)} = 0$ if island k is operational in contingency c, and 1 otherwise