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A topology analysis and genetic algorithm combined approach for power network intentional islanding

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ABSTRACT

Intentional islanding is to determine proper network splitting strategy while ensuring local power balance and transmission capacity constraints when islanding operation is unavoidable. The intentional islanding problem is very complicated in general because a combinatorial exploitation of strategy space is required. This paper apply a topology analysis and genetic algorithm combined approach for determining proper splitting strategies of large-scale power networks. Topology analysis is used to simplify the original power network into a simple equivalent network so that the splitting strategy space world be dramatically reduced; while the genetic algorithm incorporated with the breadth-first search (BFS) is employed to determine the final proper splitting strategy in the simplified power network. Two additional applications, mimicking weak connections between islands and obtaining specific pre-defined islands, of the proposed method are introduced. Simulation results on several test system show that the proposed approach can quickly provide proper splitting strategies and is effective for larger-scale power systems.

Introduction

In the last decade, several blackouts caused by cascading failures broke out around the world [1–3]. To alleviate the problem of cascading failures, preventive and corrective measures, such as UVLS (Under-voltage Load Shedding), UFLS (Under-frequency Load Shedding), generator triggering, and generator excitation controls have been mainly exploited to ameliorate the effects of severe disturbances [4–8]. However, in the situation of the power network being operated closer to limits, together with increased uncertainties from loads and distributed generations, these measures may fail.

To be brief, intentional islanding in this paper means splitting of large power network to mitigate the spread of failures because islanded sub-networks are not prone to aggravate existing conditions, but capable of local power balance. Usually, power balancing measures such as load shedding has to be involved in some sub-networks to guarantee security. Intentional islanding is thus promising as an alternative measure to prevent cascading failures. In fact, many blackouts happened could have been avoided if appropriate intentional (active) islanding operations had been performed following the local incident in time [9,10]. Therefore, intentional islanding of self-contained sub-networks and splitting of large power network is attractive to researchers and has created an increasing amount of attention.

Implementation of Intentional islanding is related to many aspects of security and control of power systems. Generally, an intentional islanding scheme would include the following three approaches: (1) identify the instant at which intentional splitting is inevitable (otherwise, there is a high possibility of blackout). It has to be assisted with possible measures of power system security online assessment [11]; (2) determine a proper strategy for intentional islanding and obtain the Minimal Cutset (MC) of transmission lines to be disconnected considering the constraints of power balance, operational constraints, transient stability, and synchronization constraints [12,13]; and (3) implement the strategy: this associates with the sequence of disconnecting selected lines [11].

In this paper, we try to solve the second problem of optimization assuming all dynamic constraints are satisfied [14–17]. This optimization problem is identified as to find the MC for splitting power network into islands that power balance can be most possibly met, and steady-state operating points within line limits can be ensured. To solve this optimization problem, many methods have

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been proposed in the literature. A review of main approaches for islanding schemes, such as graph partitioning, the MC numeration, and generator grouping is given in Ref. [18]. The most popular approach to this problem is ordered binary decision diagrams (OBDDs) [9]: the original power network is reduced into a simple network by graph theory at first; then a method based on OBDDs is used to find possible splitting strategies satisfying "load-generation balance" constraints; in the third phase, possible splitting strategies obtained are examined by power-flow calculations to select final splitting strategy with certain primary objective defined. Similarly, a two phase method has been used to find proper islanding strategies in Ref. [19]: the strategy space is narrowed down by highly efficient OBDD-based algorithm in the first phase, then the final proper splitting strategy is found by power-flow analysis in the reduced strategy space.

Employing OBDDs to search and define final MC strategy is a challenging task, both because the search space of line cutsets grows exponentially with network size, and that the complexity of problem is exacerbated by operating constraints. The high-dimensional OBDDs problem is computationally impractical to be tackled simultaneously considering all these constraints within a single step of optimization. Therefore, these search algorithms is only applicable to a significantly simplified network model. For example in Ref. [9], the network model must be simplified to approximately less than 40 nodes when using the OBDD-based method. However, consequently, solutions from simplified networks may miss superior solutions from the original network.

In this paper, a topology analysis and genetic algorithm combined approach (TAGACA) is proposed to solve the problem of intentional islanding in a power network. In real world power networks, the huge number of potential lines to be disconnected to form islands makes intentional islanding a high-dimensional problem. Topology analysis is firstly utilized to identify redundant edges, such as must-connect edge, radial-structure redundant edge, and multi-path redundant edge in power network islanding. The must-connect edge is to guarantee no isolated generator bus and load bus produced, and radial-structure redundant edge and multi-path redundant edge do not affect the search process of the set of power lines to form isolated islands. Vertices contraction can also be used to further reduce redundant edges, if necessary. In the 3rd section, a modified genetic algorithm incorporating breadth first search technique is proposed to search the optimal cutset in the simplified network. Techniques based on BFS are proposed to avoid infeasible initial population and to repair reproduced infeasible population. The operational constraints and existence of equilibrium for each sub-network are considered, while obtaining minimum cutset in the process of optimization. Also, the proposed combined approach is capable of mimicking weak connections and forming defined islands. Finally, simulation results are provided to examine performance of the proposed approach in the last section.

The main contributions of this paper can be summarized as two aspects:

(1) The paper has proposed an approach based on topology analysis for network simplification, mainly to reduce the search space of line cutsets in advance, while guarantee the solutions from the simplified network model is equivalent as from the original network model.
(2) The paper has also incorporated topology analysis techniques into genetic algorithm to deal with infeasible solutions produced during the genetic operations.

Accordingly, remaining parts of the paper are organized as follows: Section 'Topology analysis for islanding' conducts a topology analysis for power network islanding, as well as the definition and measures of MC, Redundant Edge and Vertices Contraction. In Section 'Proposed methodology for intentional islanding', the TAGACA and two examples of applications are provided. In Section 'Case studies', several medium-scale and a large-scale power networks are illustrated to validate the effectiveness, efficiency, and applicability of the proposed approach. Finally in Section 'Conclusions and future works', some conclusions are drawn.

Topology analysis for islanding

This section provides topology analysis for power network simplification before islanding. Definitions of power network, power network islanding and minimal cutset used in this paper are firstly provided. Then three types of Redundant Edge, namely Must-connect Edge, Radial-structure Redundant Edge, and Multi-path Redundant Edge are introduced. Moreover, in order to deal with a large-scale power network effectively, the concept and procedures of Vertices Contraction are presented.

Power network

From the view of topology, a power network is a connected node-weighted graph, G, including a set of vertices (buses), V, which are defined with weights, W, and are connected in pairs by edges (lines), E. The vertices with generations, loads, and with nothing are weighted with positive values, negative values, and zeroes respectively. Considering power balancing of a power network, island-able sub-networks must be with both generations and loads (vertices with both positive and negative weights).

Power network islanding

Power network islanding is to partition the connected graph into isolated sub-networks by disconnecting a set of edges.

Minimal cut-set

A cut-set of a connected graph, $G\ (V, E, W)$, is a potential set of edges, $E_1 \in E$. After removing E_1, the residual graph, $G_1\ (V_1, E{-}E_1, W_1)$, is no longer connected. For a given graph, $G\ (V, E, W)$, a cutset, E_1, is the MC if and only if removing all edges in E_1 would split G into two islands/disconnected sub-networks.

The MC is required in splitting power network. For example, in Fig. 1, both *Cutset* 1 and *Cutset* 2 split the graph into two sub-networks with the same vertices, whereas only *Cutset* 2 is the MC.

Redundant edge

This section defines three types of Redundant Edge: Must-connect Edge, Radial-structure Redundant Edge, and Multi-path Redundant Edge.

For a given graph, $G\ (V, E, W)$, with two sub-sets of vertex, *Group* 1 and *Group* 2, if there is not any positive-value or negative-value weighted vertex in *Group* 1, and all paths of connecting any vertex

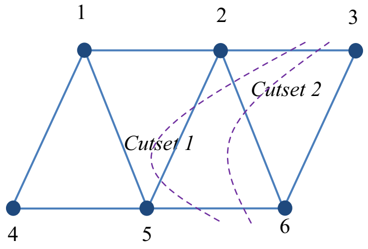

Fig. 1. Cutset and minimal cutset.