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Optimal intentional islanding to enhance the robustness of power grid networks

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HIGHLIGHTS

- We present intentional islanding as a mitigation strategy for cascading in power grid.
- An optimal islanding technique is presented.
- Since the optimization is not scalable two methods from network theory are proposed.
- All methods minimize load shedding in island and complement.

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ABSTRACT

Intentional islanding of a power system can be an emergency response for isolating failures that might propagate and lead to major disturbances. Some of the islanding techniques suggested previously do not consider the power flow model; others are designed to minimize load shedding only within the islands. Often these techniques are computationally expensive. We aim to find approaches to partition power grids into islands to minimize the load shedding not only in the region where the failures start, but also in the topological complement of the region. We propose a new constraint programming formulation for optimal islanding in power grid networks. This technique works efficiently for small networks but becomes expensive as size increases. To address the scalability problem, we propose two grid partitioning methods based on modularity, properly modified to take into account the power flow model. They are modifications of the Fast Greedy algorithm and the Bloom algorithm, and are polynomial in running time. We tested these methods on the available IEEE test systems. The Bloom type method is faster than the Fast Greedy type, and can potentially provide results in networks with thousands of nodes. Our methods provide solutions which retain at least 40–50% of the system load. Overall, our methods efficiently balance load shedding and scalability.

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1. Introduction

Power grids were designed for the purpose of transfer of electricity from the generators to the consumers, and were engineered keeping in mind the ever-increasing demand for electricity. However, in modern times the grid has reached a point where it has become very important to allow for its expansion in terms of technology and intelligence. Since the last few years, power grids have become increasingly interconnected. There are exchanges of large amounts of power over very

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long distances among different utilities to satisfy the increasing demand from the customers. The current setup is making the grid less stable and more vulnerable to intentional and unintentional failures. The system reliability and stability has been affected. As a matter of fact, there have been many occurrences of cascading failures in the recent past [1–3]. Defined by the North American Electric Reliability Corporation (NERC), a cascading failure is "the uncontrolled loss of any system facilities or load, whether because of thermal overload, voltage collapse, or loss of synchronism, except those occurring as a result of fault isolation" as mentioned in Ref. [4]. In simple words, when one failure leads to successive failure of other elements of the grid, leading to huge losses, the process is called a cascading failure. Some strategies such as reciprocal altruism [5], changing the dynamic equilibrium of the system to a point of self-organized criticality [6,7], and different load shedding schemes [8–11] have been suggested in the past for reducing the effects of cascading failures.

Intentional islanding of the power system is one such strategy. Intentional islanding can be defined as the intentional splitting of the grid into separate controllable parts or islands, each with its own independent generation. Intentional islanding may be accompanied by some load shedding in order to balance the generation and load in the sub-systems. Intentional islanding can be very helpful in isolating failures or localizing them within the region where they occurred and preventing them from spreading throughout the system. Several techniques have been proposed previously for islanding in power systems, such as those based on spectral analysis, slow coherency, ordered binary decision trees as well as optimization. An overview of these methods is described in Section 2.

In this paper, we propose a novel optimization formulation for optimal islanding of a power system. The formulation proposed here has been implemented using the CPLEX ILOG software by IBM [12], which transforms the logical constraints in the formulation to a mixed-integer program (MIP) internally. The formulation considers two parts of the system, the island (the region where the initial failure occurs) and the topological complement of the island. This technique aims at minimizing load shedding in both, the island and also its topological complement. Also, to limit the failure to a small portion of the system, the objective includes the minimization of the island size. However, the optimization problem is not scalable. The optimization takes a very long time to converge as the network size increases. This technique can be applied efficiently to small and medium sized systems such as the IEEE 14-node and 30-node networks [13] but it becomes computationally expensive for larger networks. For this reason, we propose two methods based on network partitioning and derived from the Fast Greedy algorithm [14] and the Bloom algorithm [15]. The original Fast Greedy and Bloom algorithms are based on the community detection metric, modularity [16–19]. Since the concept of islanding is similar to that of detecting communities, by integrating the power flow model, we can make these algorithms realistic for islanding in power grids. Both the methods have a polynomial running time, but the Bloom approach is faster. In general, these methods are an efficient balance between the amount of load shedding and the algorithm scalability. Both have been tested on the IEEE 57-, 118- and 247-node networks, besides the 14-node and the 30-node networks. The 247-node network is a modification of the IEEE 300-node network and has been obtained as discussed in Ref. [8].

The island boundaries can be computed offline for all the three techniques and known to the operators in advance. Whenever a failure occurs, the predetermined set of transmission lines in the region where the island is needed, can be disconnected. Hence, the strategies can be implemented in real time.

The main contributions of this paper are as follows:

- Proposing a novel optimization formulation for optimal islanding for minimizing load shedding in the island as well as the topological complement of the island.
- Proposing two polynomial time partitioning methods, based on modularity, and incorporating the power flow model to minimize load shedding in the islands and the island complement.

This paper is further organized as follows: Section 2 discusses the previous work that has been done in this field and the motivation for proposing the new techniques. The optimization formulation is discussed in detail in Section 3 and Appendix A. Section 4 discusses the two methods for islanding of the power grid. Numerical evaluation and comparison between the methods in terms of load shedding and the number of islands is described in Section 5. Section 6 discusses the conclusions and scope for future work in this area.

2. Related work

Since the past few years, the problem of intentional islanding is being studied as an important approach for isolating failures in the power grid [20–26]. It has been proposed by some researchers as an appropriate control action to protect the system when large disturbances take place. It is also considered to be an effective method to contain disturbances within a smaller area. Islanding leads to a faster restoration of the system to its initial state, as shown in Refs. [20,21]. Different methods have been suggested to define islanding based on slow coherency generator grouping combined with graph theory, ordered binary decision diagrams (OBDD), linear and non-linear optimization as well as spectral methods. While slow coherency methods are among the first few methods proposed for islanding, spectral methods are fairly new.

The slow coherency methods are based on grouping the generators according to slow coherency and then trying to find the minimum cut-set from the interface network between the generator groups using some search techniques [20,27,22,28,23,29]. The other category of methods deals with the ordered binary decision diagrams approach [24,30]. For large-scale power networks, islanding using OBDD is an NP-hard problem. Hence, different two and three phase variants of this strategy have been suggested.

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