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MILP formulation for controlled islanding of power networks ☆

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ABSTRACT

This paper presents a flexible optimization approach to the problem of intentionally forming islands in a power network. A mixed integer linear programming (MILP) formulation is given for the problem of deciding simultaneously on the boundaries of the islands and adjustments to generators, so as to minimize the expected load shed while ensuring no system constraints are violated. The solution of this problem is, within each island, balanced in load and generation and satisfies steady-state DC power flow equations and operating limits. Numerical tests on test networks up to 300 buses show the method is computationally efficient. A subsequent AC optimal load shedding optimization on the islanded network model provides a solution that satisfies AC power flow. Time-domain simulations using second-order models of system dynamics show that if penalties were included in the MILP to discourage disconnecting lines and generators with large flows or outputs, the actions of network splitting and load shedding did not lead to a loss of stability.

1. Introduction

In recent years, there has been an increase in the occurrence of wide-area blackouts of power networks. In 2003, separate blackouts in Italy [1], Sweden/Denmark [2] and USA/Canada [3] affected millions of customers. The wide-area disturbance in 2006 to the European system caused the system to split in an uncontrollable way [4], forming three islands. More recently, the UK network experienced a system-wide disturbance caused by an unexpected loss of generation; blackout was avoided by local load shedding [5].

While the exact causes of wide-area blackouts differ from case to case, some common driving factors emerge. Modern power systems are being operated closer to limits: liberalization of the markets, and the subsequent increased commercial pressures and change in expenditure priorities, has led to a reduction in security margins [6–8]. A more recently occurring factor is increased penetration of variable distributed generation, notably from wind power, which brings significant challenges to secure system operation [9].

For several large disturbance events, e.g., [3], studies have shown that a wide-area blackout could have been prevented by intentionally splitting the system into islands [10]. By isolating the faulty part of the network, the total load disconnected in the event of a cascading failure is reduced. *Controlled islanding* or *system splitting* is therefore attracting an increasing amount of attention. The problem is how to split the network into islands that are as closely balanced as possible in load and generation, have stable steady-state operating points within voltage and line limits, and so that the action of splitting does not cause dynamic instability. This is a considerable challenge, since the search space of line cutsets grows exponentially with network size, and is exacerbated by the requirement for strategies that obey non-linear power flow equations and satisfy operating constraints.

It is not computationally practical to tackle all these aspects of the problem simultaneously within a single optimization, and approaches in the literature differ according to which aspect is treated as the primary objective. Additionally different search methods have been proposed for defining the island boundaries. An example where the primary objective is to produce load balanced islands is [11]. This proposes a three-phase ordered binary decision diagram (OBDD) to generate a set of islanding strategies. The approach uses a reduced graph-theoretical model of the network to minimize the search space for islanding; power flow analyses are subsequently executed on islands to exclude strategies that violate operating constraints, e.g., line limits.

In other approaches the primary objective is to split the network into electromechanically stable islands, commonly by splitting so that generators with coherent oscillatory modes are grouped. If the system can be split along boundaries of coherent generator groups while not causing excessive imbalance between load and generation, then the system is less likely to lose stability. Determining the required cutset of lines involves, as a secondary objective, considerations of load-generation balance and other

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constraints; algorithms include exhaustive search [12], minimal-flow minimal-cutset determination using breadth-/depth-first search [13], graph simplification and partitioning [14], and meta-heuristics [15,16]. The authors of [17] propose a framework that, iteratively, identifies the controlling group of machines and the contingencies that most severely impact system stability, and uses a heuristic method to search for a splitting strategy that maintains a desired stability margin. Wang et al. [18] employed a power flow tracing algorithm to first determine the domain of each generator, i.e., the set of load buses that 'belong' to each generator. Subsequently, the network is coarsely split along domain intersections before refinement of boundaries to minimize imbalances.

The current paper presents an optimization framework for controlled islanding. The method's primary objective is to minimize the expected amount of load that has to be disconnected while leaving the islanded network in a balanced steady state. The post-islanding dynamics are not modelled explicitly in the optimization, as this greatly increases the computational difficulty of the problem. Instead penalties are used to discourage large changes to power flows, and it is shown by simulation that this results in the islanding solutions being dynamically stable.

The proposed approach has two stages: first, a mixed-integer linear programming (MILP) islanding problem, which includes the linear DC flow equations and flow limits, is solved to determine a DC-feasible solution; secondly, an AC optimal load shedding optimization is solved to provide an AC-feasible steady-state post-islanding operating point. Integer programming has many applications in power systems, but its use in network splitting and blackout prevention is limited. Bienstock and Mattia [19] proposed an IP-based approach to the problem of designing networks that are robust to sets of cascading failures and thus avoid blackouts; whether to upgrade a line's capacity is a binary decision. Fisher et al. [20] and Khodaei and Shahidehpour [21] propose methods for optimal transmission switching for the problem of minimizing the cost of generation dispatch by selecting a network topology to suit a particular load. In common with the formulation presented here, binary variables represent switches that open or close each line and the DC power flow model is used, resulting in a MILP problem. However, in the current paper sectioning constraints are present, and the problem is to design balanced islands while minimizing load shed.

The organization of the paper is as follows. The next section outlines the motivation and assumptions that underpin the approach. The DC MILP islanding formulation is developed in Section 3. The AC optimal load shedding problem is described in Section 4. In Section 5 computational results are presented. In Section 6, the dynamic stability of the networks in response to islanding is investigated. Finally, conclusions are drawn in Section 7.

2. Motivation

An application of islanding which has received little attention is islanding in response to particular contingencies so as to isolate vulnerable parts of the network. For example after some failure, part of the network may be vulnerable to further failure, or a suspected failure of monitoring equipment may have resulted in the exact state of part of the network being uncertain. In such a case an action that would prevent cascading failures throughout the network is to form an island surrounding the uncertain part of the network so isolating it from the rest. A method that does not take into account the location of the trouble when designing islands may leave the uncertain equipment within a large section of the network, all of which may become insecure as a result. Fig. 1a illustrates the situation: uncertain lines and buses are indicated by a "?". Fig. 1b shows a possible islanding solution for this network: all uncertain buses have been placed in Section 0 and all uncertain lines with at least one end in Section 1 are disconnected. The following distinction is made between *sections* and *islands*. The split network consists of two sections, an "unhealthy" Section 0 and a "healthy" Section 1 with no lines connecting the two sections, and all uncertain equipment in Section 0. However, neither section is required to be connected so may contain more than one island: in Fig. 1b, Section 1 comprises islands 1, 3 and 4, and Section 0 is a single island. The optimization will determine the boundaries of the sections, the number and boundaries of the islands, the generator adjustments, and the amount of each load that is planned to be shed.

A balance has to be found between the load that is planned to be shed and the residual load that is left in Section 0, which may be lost because that section is vulnerable. This can be achieved by taking as objective the sum of the value of the loads remaining in both sections after the planned load shedding minus a proportion of the value of the load remaining in Section 0 after the planned load is shed.

3. MILP islanding formulation

This section presents a MILP formulation for the problem of finding a steady state islanded solution in a stressed network, while minimizing the expected load lost.

Consider a network that comprises a set of buses $\mathcal{B} = \{1, 2, \ldots, n^{\mathrm{B}}\}$ and a set of lines $\mathcal{L}$. The two vectors F and T describe the connection topology of the network: a line $l \in \mathcal{L}$ connects bus F_l to bus T_l. There exists a set of generators $\mathcal{G}$ and a set of loads $\mathcal{D}$. A subset $\mathcal{G}_b$ of generators is attached to bus $b \in \mathcal{B}$; similarly, $\mathcal{D}_b$ contains the subset of loads present at bus $b \in \mathcal{B}$.

3.1. Sectioning constraints

Motivated by the previous section, the intention is to partition the buses and lines between Sections 0 and 1. It is suspected that some subset $\mathcal{B}^0 \subseteq \mathcal{B}$ of buses and some subset $\mathcal{L}^0 \subseteq \mathcal{L}$ of lines are faulty or at risk. No uncertain components are allowed in Section 1.

A binary variable γ_b is defined for each bus $b \in \mathcal{B}$; γ_b is set equal to 0 if b is placed in section 0 and $\gamma_b = 1$ otherwise. A binary variable ρ_l is defined for each $l \in \mathcal{L}$; $\rho_l = 0$ if line l is disconnected and $\rho_l = 1$ otherwise.

Constraints (1a) and (1b) apply to lines in $\mathcal{L} \setminus \mathcal{L}^0$. A line is cut if its two end buses are in different sections (i.e., $\gamma_{F_l} = 0$ and $\gamma_{T_l} = 1$, or $\gamma_{F_l} = 1$ and $\gamma_{T_l} = 0$). Otherwise, if the two end buses are in the same section then $\rho_l \leqslant 1$, and the line may or may not be disconnected. Thus, these constraints enforce the requirement that any certain line between sections 0 and 1 shall be disconnected.

$$\rho_l \leqslant 1 + \gamma_{F_l} - \gamma_{T_l}, \ \forall l \in \mathcal{L} \setminus \mathcal{L}^0, \tag{1a}$$

$$\rho_l \leqslant 1 - \gamma_{F_l} + \gamma_{T_l}, \ \forall l \in \mathcal{L} \setminus \mathcal{L}^0. \tag{1b}$$

Constraints (1c) and (1d) apply to lines assigned to $\mathcal{L}^0$. A line $l \in \mathcal{L}^0$ is disconnected if at least one of the ends is in Section 1. Thus, an uncertain line either (i) shall be disconnected if entirely in Section 1, (ii) shall be disconnected if between sections 0 and 1, or (iii) may remain connected if entirely in Section 0.

$$\rho_l \leqslant 1 - \gamma_{F_l}, \ \forall l \in \mathcal{L}^0, \tag{1c}$$

$$\rho_l \leqslant 1 - \gamma_{T_l}, \ \forall l \in \mathcal{L}^0. \tag{1d}$$