Failure Localization in Power Systems via Tree Partitions

Extended Abstract

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ABSTRACT

Cascading failures in power systems propagate non-locally, making the control and mitigation of outages extremely hard. In this work, we use the emerging concept of the *tree partition* of transmission networks to provide an analytical characterization of line failure localizability in transmission systems. Our results rigorously formalize the well-known intuition that failures cannot cross bridges, and reveal a finer-grained concept that encodes more precise information on failure propagation within tree-partition regions. Specifically, when a non-bridge line is tripped, the impact of this failure only propagates within components of the tree partition defined by the bridges. In contrast, when a bridge line is tripped, the impact of this failure propagates globally across the network, affecting the power flow on all remaining lines. This characterization suggests that it is possible to improve the system robustness by temporarily switching off certain transmission lines, so as to create more, smaller components in the tree partition; thus spatially localizing line failures and making the grid less vulnerable to large outages.

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1 INTRODUCTION

Power system reliability is a crucial component in the development of sustainable modern power infrastructure. Recent blackouts, especially the 2003 and 2012 blackouts in Northwestern U.S. [1] and India [2], demonstrated the devastating economic impact a grid failure can cause.

Because of the intricate interactions among power system components, outages may cascade and propagate in a very complicated, non-local manner [7, 11], exhibiting very different patterns for different networks [14]. Such complexity originates from the interplay between network topology and power flow physics, and is aggravated by possible hidden failures [5] and human errors [4]. This complexity is the key challenge for research into the modeling, control, and mitigation of cascading failures in power systems.

There are mainly three traditional approaches for characterizing the behavior of cascades in the literature: (a) using simulation models that rely on Monte-Carlo approaches to account for the steady state power flow redistribution on DC [4] or AC [13, 15] models; (b) studying purely topological models that impose certain assumptions on the cascading dynamics (e.g., failures propagate to adjacent lines with high probability) and infer component failure propagation patterns from graph-theoretic properties [3, 12]; (c) investigating simplified or statistical cascading failure dynamics [6, 11]. In each of these approaches, it is typically challenging to make general inferences across different scenarios due to the lack of structural understanding of power redistribution after line failures.

A new approach has emerged in recent years, which seeks to use spectral properties of the network graph in order to derive precise structural properties of the power system dynamics, e.g., [8, 10]. The spectral view is powerful as it often reveals surprisingly simple characterizations of the complicated system behaviors. In the cascading failure context, a key result from this approach is about the *line outage distribution factor* [14]. Specifically, it is shown in [8] that the line outage distribution factor is closely related to transmission graph spanning forests. While this literature has yet to yield a precise characterization of cascades, it has suggested a new structural representation of the transmission network called the *tree partition*.

The main contributions of the present work are: (i) proving that the tree partition proposed in [8] can be used to provide an analytical characterization of line failure localizability, under a DC power flow model, and (ii) showing how to use this characterization to mitigate failure cascades by temporarily switching off a small number of transmission lines with minimal consequences on lines congestion.

2 MODEL DESCRIPTION

The power transmission network is described by means of the graph $\mathcal{G} = (\mathcal{N}, \mathcal{E})$, where the vertices $\mathcal{N} = \{1, \ldots, n\}$ represent buses and the edges in $\mathcal{E} \subset \mathcal{N} \times \mathcal{N}$ model transmission lines. We denote by $m = |\mathcal{E}|$ the total number of lines. The susceptance matrix is defined to be the diagonal matrix $B = \text{diag}(B_e : e \in \mathcal{E})$, where B_e denotes the susceptance of line e. We denote the branch flow on e as P_e and the power injection and phase angle at bus i as p_i and θ_i, respectively.

The DC power flow model is captured by the flow conservation constraint $p = CP$ and by Kirchhoff's law $P = BC^T\theta$, where C is the $n \times m$ vertex-edge incidence matrix of $\mathcal{G}$. The slack bus phase angle in θ is typically set to 0 as a reference to other buses. With this convention, there is a unique solution θ and P for each injection vector p such that $\sum_{j \in \mathcal{N}} p_j = 0$. According to this model, when a line e is tripped, the power flow redistributes on the newly formed graph $\mathcal{G}' = (\mathcal{N}, \mathcal{E} \setminus \{e\})$. If $\mathcal{G}'$ is still connected, then the branch flow change on a line $\hat{e}$ is given as $\Delta P_{\hat{e}} = P_e \times K_{e\hat{e}}$, where $K_{e\hat{e}}$ is the *line outage distribution factor* [14] from e to $\hat{e}$.

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If the new graph $\mathcal{G}'$ is disconnected, then it is possible that the original injection p is no longer balanced in the connected components of $\mathcal{G}'$. Thus, to compute the new power flows, a certain power balance rule $\mathcal{B}$ needs to be applied. Several such rules have been proposed and evaluated in literature based on load shedding or generator response [14]. In this work, we do not specialize to any such rule and instead opt to identify the key properties of these rules that allow our results to hold. For further details see [9].

Given a vertex partition $\mathcal{P} = \{\mathcal{N}_1, \mathcal{N}_2, \cdots, \mathcal{N}_k\}$ of $\mathcal{G} = (\mathcal{N}, \mathcal{E})$, we can define a reduced multi-graph $\mathcal{G}_\mathcal{P}$ from $\mathcal{G}$ as follows. First, we reduce each subset $\mathcal{N}_i$ to a super node. The collection of all super nodes forms the node set for $\mathcal{G}_\mathcal{P}$. Second, we add an undirected edge connecting the super nodes $\mathcal{N}_i$ and $\mathcal{N}_j$ for each pair of $n_i, n_j \in \mathcal{N}$ with the property that $n_i \in \mathcal{N}_i$, $n_j \in \mathcal{N}_j$ and n_i and n_j are connected in $\mathcal{G}$. The partition $\mathcal{P}$ is said to be a *tree partition* if the reduced graph $\mathcal{G}_\mathcal{P}$ forms a tree. Given a tree partition $\mathcal{P} = \{\mathcal{N}_1, \mathcal{N}_2, \cdots, \mathcal{N}_k\}$, the sets $\mathcal{N}_i$ are called the *regions* of $\mathcal{P}$. An edge e with both endpoints inside $\mathcal{N}_i$ is said to be *within* $\mathcal{N}_i$. If e is not within $\mathcal{N}_i$ for any i, then we say e forms a *bridge*. In [9], we showed that each graph $\mathcal{G}$ has a unique irreducible tree partition and this particular partition can be computed in linear time. We will henceforth refer to the irreducible tree partition of $\mathcal{G}$ simply as tree partition of $\mathcal{G}$.

3 KEY RESULT AND DISCUSSION

Our main result applies in contexts where the power network is operating under *normal conditions*, which are mild conditions on the power injections and the power balance rules that are typically satisfied in practical settings. Furthermore, to avoid pathological cases, we assume that the line susceptances are perturbed according to a probability measure μ that is absolutely continuous with respect to the Lebesgue measure on $\mathbb{R}^m$. The interested readers can find all the details about these assumptions as well as the proof of our main result in our online report [9].

Theorem 1. *For a power network operating under normal conditions, $K_{e\hat{e}} \neq 0$ almost surely w.r.t. μ if and only if:*

(1) *$e, \hat{e}$ are within the same tree partition region and belong to the same cell; or*
(2) *e is a bridge.*

Theorem 1 states that, for a practical system, the tree partition encodes precise information on how the failure of a line propagates through the network. Indeed, this result shows that the impact of tripping a non-bridge line only propagates within well-defined components, which we refer to as cells (cf. [9]), inside the tree partition regions. In contrast, the failure of a bridge line, in normal operating conditions, propagates globally across the network and impacts the power flow on all transmission lines.

Theorem 1 yields many interesting insights for the planning and management of power systems and, further, suggests a new approach for mitigating the impact of cascading failures. To illustrate this, consider Figure 1, which shows how the tree partition is linked to the sparsity of the $K_{e\hat{e}}$ matrix through our result. Compared to a full mesh transmission network consisting of single region/cell, it can be beneficial to temporarily switch off certain lines so that more regions/cells are created and the impact of a line failure is localized within the cell in which the failure occurs, thus making the grid less vulnerable against line outages.

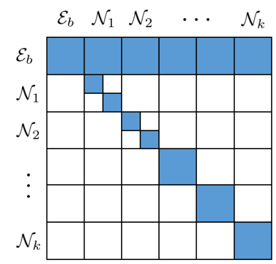

Figure 1: Non-zero entries of the $K_{e\hat{e}}$ matrix (as represented by the dark blocks) for a graph with tree partition $\{\mathcal{N}_1, \mathcal{N}_2, \cdots, \mathcal{N}_k\}$ and bridge set $\mathcal{E}_b$. The small blocks represent cells inside the regions.

However, it is reasonable to expect that such an action may increase the stress on the remaining lines and, in this way, worsen the network congestion. In fact, one may expect that improved system robustness obtained by switching off lines *always* comes at the price of increased congestion levels. In [9] we consider the realistic IEEE 118-bus test system as preliminary example and show that switching off only a negligible portion of transmission lines can lead to significantly better control of cascading failures without significant increases in line congestion across the network.

We believe that in general that if the lines to switch off are selected properly, it is possible to *improve the system robustness and reduce the congestion simultaneously.* Our future work focuses precisely on how to select these target lines optimally, as well as on understanding how to incorporate line capacities in our framework.

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