ECOLOGICAL UNIQUENESS FOR UNDERSTANDING COMPONENT IMPORTANCE IN POWER GRIDS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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August 2021

Major Subject: Energy

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ABSTRACT

The identification of critical components in electric power grids is an important challenge power engineers face. Similarly, many ecologists face the challenge of identifying important species in food web networks. Drawing similarities between power grid networks and food web networks, this study utilizes proposed methods from ecology literature to identify critical components in electric power grids. The ecological methods used in this study include the Sum of the Trophic Overlap (STO) and Weighted Trophic Overlap (WTO). This thesis also studied engineering methods proposed from power engineering literature to compare with the ecological methods. These engineering methods include the Normalized Line Outage Distribution Factor (NLODF) and the Topological and Impedance Element Ranking metric (TIER), for transmission line analysis, and the Controllability Index (CI) and centrality measures of betweenness centrality (BC), degree centrality (DC), and closeness centrality (CC), for non-line grid components analysis. The aim of this study is to determine if bio-inspiration provides a feasible tool to use in power grid analysis.

The results show that when analyzing transmission lines, NLODF is the most accurate method. The ecological methods are often not as accurate as NLODF, but they are comparable in some cases to NLODF and TIER. Additionally, the calculations for the ecological methods are faster than the engineering methods in small cases but become slower in larger grids, suggesting more usefulness in small grids such as microgrids. Studying non-line components, buses and generators, STO and WTO are very comparable to the engineering methods studied. However, their calculations are slower, again suggesting more usefulness in smaller grid sizes. While slower than engineering methods, STO and WTO having comparable accuracy to engineering methods in many cases suggests that ecological methods may be useful for power grid analysis.

This research suggests that ecological approaches to network analysis may be useful tools in power grid analysis and provides a starting point for future research utilizing ecological methods in power grid analysis. Other ecological methods exist that may be more computationally efficient than STO and WTO while maintaining similar or higher accuracy, so future research into these methods may provide useful results.

DEDICATION

I would like to dedicate this work to my parents Kellye and James Foster for their complete support in all of my endeavors.

And to my wife Rebekah Foster who continues to motivate me and provide immense encouragement at all times.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Astrid Layton, for her continuous support and guidance throughout the course of this research. I would also like to thank my committee members, Dr. Katherine Davis and Dr. Kirk Winemiller, for their insight and enthusiasm during this research.

Thank you to the CPMA team, especially Hao Huang and Rasoul Narimani, for their aid and advice while conducting this research.

Thanks also go to my friends and colleagues and the faculty and staff for making my time at Texas A&M University, and the Texas A&M Energy Institute, a great experience.

Finally, thank you to my family for continuing to support and encourage me throughout this process.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Texas A&M University professors Dr. Astrid Layton of the Department of Mechanical Engineering, Dr. Katherine Davis of the Department of Electrical Engineering, and Dr. Kirk Winemiller of the Department of Ecology and Conservation Biology.

The code for transmission line analysis by the NLODF method in Chapter 3 was provided by Hao Huang from the Department of Electrical Engineering at Texas A&M University. The code for transmission line analysis by the TIER method in Chapter 3 was provided by Professor Daniel Molzahn from the School of Electrical and Computer Engineering at the Georgia Institute of Technology.

The code for the Freeman centralization analysis in Chapter 5 was provided by Abheek Chatterjee from the Department of Mechanical Engineering at Texas A&M University.

Funding Sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

NOMENCLATURE

STO	Sum of the Trophic Overlap
WTO	Weighted Trophic Overlap
NLODF	New Line Outage Distribution Factor
CI	Controllability Index
BC	Betweenness Centrality
DC	Degree Centrality
CC	Closeness Centrality

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I INTRODUCTION*

Motivation

Critical components play a significant role in the function of power grids. Power lines and nodes can both be critical in the system and lead to blackouts if they are in fault [1]. The increased complexity of modern power grids exacerbates the negative impacts of these faults, increasing the need for critical component identification. In this paper, critical components are defined as components that have a large negative impact on the performance of the network when they are in fault. Other research may define criticality or importance based on different criteria, so it is important to define early what criticality and importance mean.

Power outages resulting from important component failures can be caused by weather events, cyberattacks, or equipment failures and can cost billions of dollars while having major impacts on daily life [2-4]. To prevent power outages, failure analyses that study *large* and *complex* grids quickly and accurately are needed to determine areas that require immediate attention. Current failure analyses in power grids utilize N-x contingency analyses, where N is the number of grid components (lines, buses, generators, etc.) and x is the number of components that fail. These contingency analyses determine the impact of various component outages on the overall grid [5].

The standard reliability measure used by the North American Electric Reliability Corporation (NERC) is N-1 which ensures that power grids can survive the failure of one component [6]. Contingency analysis of multiple elements (x>1) provides better analysis of grid failures which is more useful, but N-x becomes *infeasible* for large grids (for example, the Western Electricity Coordinating Council system with around 20,000 components) due to the exponential growth in

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Identifying critical grid components can help focus contingency analyses on the most important components, resulting in a dramatic reduction in the computational efforts needed. Identification can also improve grid resilience by focusing protection and redundancy on important components [8, 9]. However, identifying critical grid components is still a nontrivial task, with current methods being limited by intense computational requirements and a lack of grid physics (represented by the power flow equations) [10, 11]. Critical component identification will improve grid analysis and protection efforts, as well. For example, advanced security can be achieved by focusing security efforts on primarily critical components, and functional redundancy can improve resilience by reducing cost of unneeded redundancy.

There are many reasons power grid engineers aim to identify critical components to focus protection efforts [12]. However, traditional engineering methods for identifying critical power grid components can be computationally demanding and time consuming, providing the motivation for our research in bio-inspiration. Learning from ecological efforts may provide faster and more computationally tractable routes for identifying important power grid components. The methods proposed in this paper identify critical power grid components based on ecological methods used to identify critical species in ecological food webs.

Research Questions and Goals

The overall motivation of this thesis is to generate fundamental knowledge that builds towards the following main research goal by answering the following main research question.

Main research goal: Identify critical components in electric power grids in support of grid resilience efforts.

Main research question: How can ecological methods for identifying important ecosystem species offer novel routes to identify critical actors (lines, buses, generators) in electric power grids?

Secondary Research Questions

This thesis builds towards the achievement of this research goal/question via the following sub-research questions and their respective research goals.

RQ1: What methods are used in ecology to identify important species in food webs and how can those be translated to power grids?

Goal 1: Find, translate, and apply ecological methods for critical actor identification to electric power grids to improve the process of determining grid component importance.

RQ2: How do the accuracy and speed of the ecological methods for identifying critical transmission lines compare to the engineering methods for electric power grids?

Goal 2: Establish the viability of ecological critical actor determination methods for analyzing power grid transmission lines and benchmark them against traditional methods.

RQ3: How do the accuracy and speed of the ecological methods for identifying critical non-line components compare to the engineering methods for electric power grids?

Goal 3: Establish the viability of ecological critical actor determination methods for analyzing power grid buses and generators and benchmark them against traditional methods.

Contributions

This research focuses on the unique approach of implementing ecological food web analysis methods for determining critical network actors to electric power grid systems. The benefits are new methods not previously explored for identifying critical grid components that provide justification for the use of ecology inspired methods in power grid analysis. The impact of these findings may allow for further investigation into ecology inspired methods to increase safety and security of electric power grids. These findings may also allow for improved resilience of electric power grids by focusing resources and protection on the most critical components.

Primary Research Contributions

- **A novel approach for accurately identifying critical components in electric power grids.**

  Many engineering methods have been studied to identify critical components in electric power grids, but no single method has been identified as the best method for performing this task. This thesis shows how ecological methods can be used to accurately identify critical components in electric power grids. The ecological methods used to identify critical components in electric power grids are comparable in accuracy to certain engineering methods.

- **Improved resilience of electric power grids through allocation of resources.**

  Through identifying critical components, this research will help allocate resources for improving network resilience. Research has suggested that inspiration from the structure of ecological food webs can suggest design changes to improve the resilience of power grids [13]. An ecological preference for redundancy over efficiency [14-16] has been found to create bio-inspired networks with increased resilience when measured by *N*-*x* contingency analyses [13]. Understanding critical grid components will offer a route to focus added redundancy where it is most needed. Determining the validity of using ecological uniqueness to identify critical components in electric power grids will aid in identifying components best suited for redundancy.

Secondary Research Contributions

- **Mitigating computational effort required when performing failure analyses on electric power grids.**

  Determining the most critical grid components in a network can improve computational efficiency of power grid failure analyses by helping focus computation on primarily the most critical components.

- **More effective and efficient security systems in electric power grids.**

  Identifying critical components in electric power grids will allow power systems operators to better allocate security resources. Security will be focused on the most critical components while unnecessary security on less critical components will be removed.

Methodology

The proposed research questions and goals are answered in this research by performing the following tasks.

Research Goal 1: Find, translate, and apply ecological methods for critical actor identification to electric power grids to improve the process of determining grid component importance.

Research Task 1: Analyze ecological methods for identifying important species, especially those that may be computationally less intensive than current power grid methods and establish the required analogies with power grids to enable the translation of methods.

Outcome: Ecological metrics of *Sum of the Trophic Overlap* (STO) and *Weighted Trophic Overlap* (WTO) were found to have comparable accuracy to engineering methods when translated to power grids using an analogy of species vs grid components (lines, buses, generators). The application supports the use of quantitative ecological conservation methods for studying component importance in power grids, enabling a whole set of novel approaches for allocating resources in the achievement of grid resilience. The ecological approaches were found to originate from a similar graph theory background as a current power grid metric *New Line Outage Distribution Factor* (NLODF).

Research Goal 2: Establish the viability of ecological critical actor determination methods for analyzing power grid *transmission lines* and benchmark them against traditional methods.

<u>Research Task 2.1:</u> Validate the ecological and state of the art power grid methods for identifying critical transmission lines against the *true rank* as determined by each component's net impact on the grid when removed.

<u>Outcome:</u> Contingency analyses established a baseline "true" ranking of the criticality of the power grid lines. The *number* of violations in the grid when a component is removed was initially used to create the *true rank* of transmission lines in accordance with *N*-*x* standards in power grid analysis. However, due to the computationally taxing nature of *N*-*x* contingency analysis, the *magnitude* of the violations was then used in further studies to determine the true rank of transmission lines. The accuracies of the ecological and engineering methods were then determined for transmission lines and compared to the true rank of grid lines. In most grid cases, NLODF was the most accurate method for identifying critical transmission lines, but STO and WTO were comparable to both NLODF and TIER in many cases. The comparable accuracy of STO and WTO to the engineering methods suggest ecological methods can be a useful tool in power grid transmission line analysis.

Research Task 2.2: Validate the ecological and state of the art power grid methods for identifying critical components for only the *most* critical lines, as determined by each component's net impact on the grid when removed.

Outcome: Considering only the top 10, 20, and 30% of critical components for each grid case results in the accuracy of the different methods for identifying the *most* critical components. From the perspective of usability, calculating the rank of each component is infeasible for most real grid cases due to the large number of components. Focusing on only the top 10, 20, and 30% of components reduces the need for computationally demanding techniques. Studying transmission lines, NLODF and TIER were most accurate in most grid cases, but STO and WTO were comparable in many cases again.

Research Task 2.3: Validate the computational efficiency of the ecological and state of the art power grid methods for identifying critical grid lines.

Outcome: A comparison of computations times for the different ranking methods establishes a comparison of computational efficiency. The ecological methods are faster than or comparable to the engineering methods in smaller grid sizes but are slower in larger grid sizes. This suggests more usefulness from STO and WTO in smaller grids such as microgrids rather than larger power grid systems.

Research Goal 3: Establish the viability of ecological critical actor determination methods for analyzing power grid *buses and generators* and benchmark them against traditional methods.

Research Task 3.1: Determine the most critical grid buses and generators in the electric power grid case studies, using both the ecological and engineering methods as compared to the *true rank* of the components determined from contingency analyses.

Outcome: The “true” rank of buses and generators was determined through contingency analyses using the magnitude of violations for each component removal. The accuracies of the ecological and engineering methods were then determined for buses and generators and compared to the true rank of non-line grid components. In all grid cases, STO and WTO had comparable accuracies to the engineering methods. The comparable accuracy of STO and WTO to the engineering methods suggest ecological methods can be a useful tool in power grid non-line analysis.

Research Task 3.2: Validate the ecological and state of the art power grid methods for identifying critical components for only the *most* critical buses and generators, as determined by each component’s net impact on the grid when removed.

Outcome: Considering only the top 10, 20, and 30% of critical components for each grid case results in the accuracy of the different methods for identifying the *most* critical components. Focusing on only the top 10, 20, and 30% of buses and generators, STO and WTO were more accurate than the engineering methods in most of the grids studied. This suggests these ecological methods to be useful in power grid non-line analysis.

Research Task 2.3: Validate the computational efficiency of the ecological and state of the art power grid methods for identifying critical grid non-line components.

Outcome: A comparison of computations times for the different ranking methods establishes a comparison of computational efficiency. The ecological methods are slower than the engineering methods in all grid sizes studied but are more comparable in smaller grid sizes. This suggests more usefulness from STO and WTO in smaller grids such as microgrids rather than larger power grid systems.

Assumptions

Certain assumptions are necessary to model ecological methods in electric power grids. Additional assumptions are needed to simplify analysis of the power systems as well. The following assumptions were made in this research.

1. **Electric power grid components, such as buses and lines, are analogous to species in food webs.** Ecological food web methods analyze the predator-prey interactions between species in food webs, following the energy transfer from one species to another via predation. An analogy is drawn between species in food webs and grid components such as buses, generators, and lines. These components also process and exchange energy throughout the grid, creating a network of grid actors analogous to the food web network of species. Some features of food webs (such as population response and seasonality) may not be analogous to power grids, but many aspects remain similar that allow for the analogy to be made. Furthermore, this analogy has been tested in prior work (Panyam et al. Applied Energy, 2019), but it is furthered here with the inclusion of lines as grid components. This analogy allows for the ecological methods to be translated to electric power grids.
2. **Transmission lines are treated as nodes.** In food webs, energy transfer is direct through predation, but electric power grids require transmission lines to transfer energy between buses and generators. However, transmission lines are still important components in power systems, so they are modeled as nodes in order to utilize the ecological methods.
3. **DC power flow is used.** This assumption allows for simplified electric power grid analysis. DC (as opposed to AC) power flow, while an approximation, is reliable and

accurate, and is also often used in contingency screening, the main focus of this research [17].

4. **No power loss occurs through transmission lines.** Assuming DC power flow allows for a secondary assumption that there are no power losses through the transmission lines. This simplifies analyses and calculations by removing the variable of power loss.
5. **The number of critical components must be integer values, requiring rounding up.** When analyzing the most critical components in the grids, the top 10, 20, and 30% of components were considered. Using a percentage meant a possibility of a non-integer value. Since the number of components must be an integer the value must be rounded. The top percent of components can be less than one, so the value found from the percent calculation was rounded up. This ensures a minimum of one line in a given top percent.

Thesis Layout

This thesis covers a range of topics regarding the analysis of electric power grids. Following the introduction, a thorough literature review covers the state-of-the-art engineering methods and ecological methods studied in this research. The literature review also discusses the analogies drawn between food webs and electric power grids. The literature review shows that some analogies have been drawn between food webs and electric power grids, but there is no prior research using ecological methods to aid in failure analysis of electric power grids. This shows a great potential for the use of ecological research in the analysis of electric power grids.

Chapters 3 and 4 focus on utilizing ecological methods in identifying both critical transmission lines and non-line grid components. Chapter 3 discusses the study and outcomes of the transmission line analyses, comparing the ecological and engineering methods. Chapter 4 discusses the study and outcomes of the non-line grid component analyses. The results showed that STO and WTO are comparable in accuracy to the engineering methods suggesting usefulness in power grid analysis. However, the results also showed lower computational efficiency, suggesting more usefulness of STO and WTO in smaller grid sizes. With comparable accuracy but lower efficiency, this study provides support to continue studying ecological methods for power grid analysis with aims to improve computational efficiency.

Finally, this thesis concludes with a summary of the work done and potential future works following this thesis research.

CHAPTER II LITERATURE REVIEW*

Research Question to be Addressed

What methods are used in ecology to identify important species in food webs and how can those be translated to power grids? Answering this question requires a study of ecological literature to understand how ecological networks are analyzed. Answering this question also requires knowledge of electric power grids and the methods that are currently used in power engineering for identifying important components. Understanding of both ecology and power engineering allows for analogies to be drawn between the two, allowing for some methodologies to be translated across disciplines.

Electric Power Grids

Critical actors in electric power grids are important to identify because failures of these components can lead to cascading failures and blackouts [18, 19]. Blackouts like the 1965 and 2003 blackouts of the Northeast United States, which were caused by failures of critical lines leading to cascading failures, could have been prevented by a better understanding of criticality in electric power grids [20, 21]. The cascading nature of these blackouts, and blackouts like these, suggest a need for better failure analysis and grid resilience. Power engineers have studied both how to improve electric power grid failure analysis [12, 22], and how to make electric power grids more resilient [4, 13] to reduce the impact of the failures of critical components. However, failure analyses still face challenges such as computational efficiency and accuracy [11] and resiliency improvement efforts face challenges of network complexity [4]. Identifying critical actors in electric power grids helps with these challenges. Failure analysis becomes more efficient by

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Engineering Methods for Identifying Critical Components

Many methods have been studied to identify critical grid components, but no method has been shown to be completely accurate. Methods studying grid topology as well as physical principles like power flow and operating point have been studied extensively with varying results [22, 25-27]. Some methods focus on identifying critical grid lines [18, 28, 29], while others study the importance of other components like buses and generators (which are considered nodes in the network) [23, 24, 30-33]. Of the methods pertaining to grid lines, in this chapter I studied the methods proposed by *Narimani et al* and *Schwarting et al*.

Narimani et al [22] proposes a *Normalized Line Outage Distribution Factor* (NLODF) to analyze and rank grid lines in order of importance, based on the lines' impact on grid performance. This method is part of emerging research focused on identifying critical grid components, but it uses a common traditional power system sensitivity measure called the *Line Outage Distribution Factor* (LODF). This LODF measure has been used for its ability to find the importance of grid lines and accounts for power flow through the network. LODF is a useful but approximate sensitivity-based method that computes line criticality based on power flow impacts resulting from transmission line outages. NLODF uses the computation of LODF to determine line importance, predicting the effect of the removal of one line on the distribution of power through the rest of the grid.

Another approach to identify important transmission lines is proposed by *Schwarting et al* [25] with the *Topological and Impedance Element Ranking* (TIER) method. This method utilizes generation shift factors which allow for an approximation between changes in generator dispatch and changes in transmission line flow. These shift factors can then be used to calculate TIER values that rank the line elements in the grid. Higher shift factors (or greater redispatch of power) result in higher TIER values, which relate to more important lines.

This method is useful for identifying critical lines, but it does have some drawbacks. First, two lines can be equally as important if their TIER values are the same, meaning distinct line ranking can't always be determined. Second, this method lacks a rigorous verification method, relying primarily on intuition. Third, importance in this method is based on economic impact of line outages rather than the impact on grid performance (as we define importance). However, we studied this method both to provide verification and to determine its effectiveness is identifying critical components as we define them.

In addition to identifying important lines, other grid components, such as buses and generators, are also important to identify for grid analysis. These components act as nodes in the network, and many efforts have been made to accurately identify the most critical nodes in power grids.

One such method proposed by *Li et al* [26] utilizes *structural controllability* to identify critical nodes in power grids. This method defines criticality in the same way that we do in this paper, so it provides a good metric to compare our methods to. The term "controllability" refers to the ability of engineers to fully control the power grid. *Driver nodes* are a set of nodes that, through their control, the rest of the system to be controlled. The set of driver nodes can change when different nodes are removed from the system because the topology of the network changes. The method proposed by *Li et al* determines the *Controllability Index*, which calculates change in driver nodes when a given node is removed. Nodes that cause a greater change in driver nodes are considered more important because their removal requires a larger set of driver nodes and therefore more nodes to control.

Other methods for identifying critical nodes in power grids originate in graph theory. The use of centrality measures from graph theory have been used in many studies to quantify how critical a given node is (based on various centrality criteria). *Wang et al* [27] studies the use of *betweenness centrality, degree centrality,* and *closeness centrality* in power grids to rank nodes in order of importance. *Betweenness Centrality* measures how often a node lies on the shortest path between any two others, a higher value relating to more central nodes. *Degree Centrality* calculates the number of connections a given node has, a higher value meaning more direct connections to other nodes. *Closeness Centrality* quantifies the average farness (inverse of distance) a given node has from all other nodes, a higher closeness value meaning a shorter distance from other nodes.

Ecology in Power Grids

Power grid networks and ecological food web networks can be considered analogous in many ways, and research has been performed studying these similarities [13, 16, 34, 35]. *Layton et al* and *Panyam et al* study analogies between food webs and power grids to design more robust and resilient power grids with promising results. *Dunne et al* studies cascading species extinctions in food web networks, which further highlights the functional similarity between species in food webs and components in power grids. Removal of various species in a food web can result in cascading extinctions, similar to cascading failures in power grids when various grid components fail [36]. To prevent these cascading extinctions or failures, ecologists and power grid engineers take similar approaches. Ecologists often aim to identify important species in food webs to allocate resources effectively to protect and conserve ecosystems [37-39].

Ecological Methods to Identify Critical Species

Identifying critical species in food webs is important to ecologists because it allows for more focused efforts in conservation of species and ecosystems. This motivation is one shared by power grid engineers who aim to protect power grid systems and conserve their functionality. Protection efforts in both ecology and power engineering require the identification of critical components to implement protection plans. Although, much like power engineering, no single method has been found to be best at determining important species [40]. Many methods, including centrality measures like the ones described previously, have been used in ecological network analysis to identify importance within the network [41, 42]. The use of centrality measures further supports the reasoning that ecological food webs and power grids can be analyzed in similar ways. However, there is not a well-established standard for what determines a species' importance [43], and some ecologists look to measures other than centrality to determine importance.

One such measure is the measure of uniqueness. Uniqueness is an important consideration when determining importance because a more unique species is less easily replaced if it is removed from the network. Uniqueness has been used in other ecological system analysis [44, 45], but it was first used to analyze specific species through the use of trophic field overlap [46]. In ecology, *trophic* refers to a species' feeding or nutritional relationships. Trophic levels in a food web are determined by the way species produce or consume biomass, nutrients and energy (e.g. producers, primary consumers, secondary consumers, etc.) [47]. Species in the same trophic level gain material and energy from sources at the same trophic levels. Species with similar trophic interactions have greater trophic overlap, whereas species that do not share many of the same interactions have less trophic overlap [46]. Simply put, species in the same trophic level will have a lot of *trophic overlap* because they share many food web interactions.

Jordán et al. [46] studied trophic field overlap as the interaction between species through predation. This method determines the functional similarity between a given pair of species. Species with more trophic overlap perform similar functional roles in the system (acting as prey or predator to the same species), so they are less unique and therefore less important in the system. This method has since been further developed by *Lai et al.* and *Xiao et al.* in [48] and [49], respectively.

Lai et al. proposed a structural analysis of trophic overlap called the *Sum of the Trophic Overlap*, or STO. This method uses the interaction between species without considering how much of a species is consumed. *Xiao et al.* proposes a modification to *Lai et al.* that does consider how much of a species is consumed. This method is called the *Weighted Trophic Overlap*, or WTO, and considers the structure *and magnitude* of flow through the food web.

STO and WTO measure the *uniqueness* of an actor by how dissimilar its trophic interactions are as compared to other species in the food web. Uniqueness is slightly different from the *importance* of a species to the food web, but it is considered because unique species are not as easily replaced in the system [48, 49]. Higher STO and WTO values indicate that a component is *less* unique, meaning it has more in common with other components in the network. These less unique components are considered less important because they are more easily replaced by other similar components.

CHAPTER III DETERMINING TRANSMISSION LINE IMPORTANCE*

Research Question to be Addressed

<u>How do the accuracy and speed of the ecological methods for identifying critical transmission lines compare to the engineering methods for electric power grids?</u> Answering this question requires an analysis of various electric power grids using both ecological and engineering methods. Analyzing the accuracy and speed of each method allows for useful comparisons to be made. Methods with more accurate results will be more useful for grid analysis, but faster methods are also desirable. Comparing the different methods using these two metrics provides empirical data to determine which method is the best for analyzing electric power grids. Nine publicly available grid case studies are used in this research: 5-, 6-, 7-, 9-, 14-, 37-, 57-, 118-, and 200-Bus

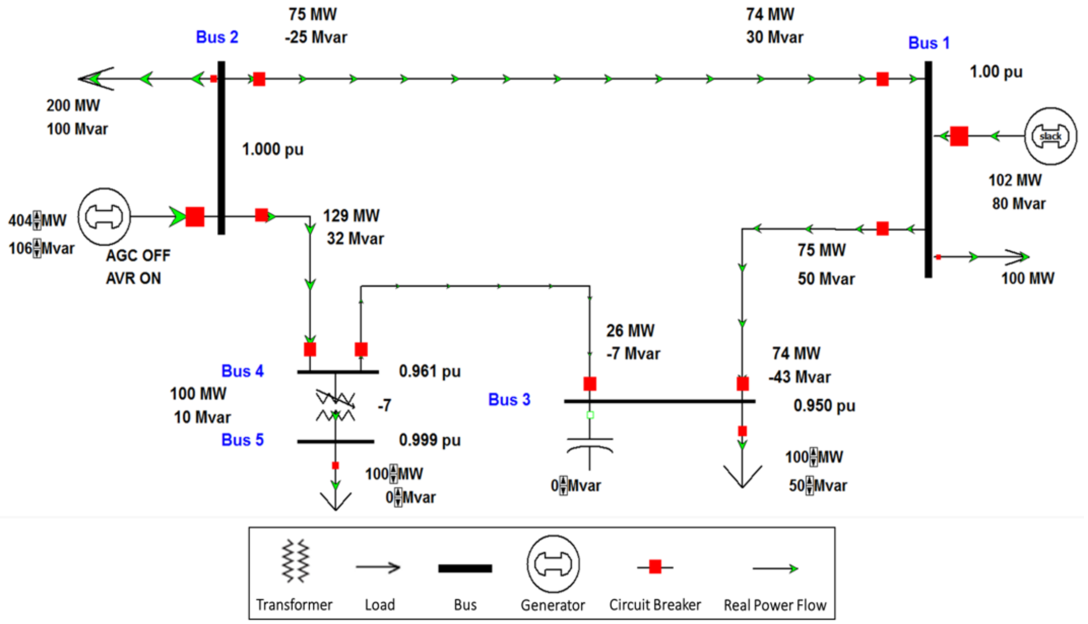

Figure 1. 5-Bus Grid (figure from PowerWorld). The lines, buses, and generators form the directional graph nodes.

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Methods

Engineering Methods

The first engineering method studied for transmission line analysis is that of NLODF, proposed by *Narimani et al*. The Normalized Line Outage Distribution Factor, NLODF, utilizes the metric of Line Outage Distribution Factor and normalizes it (hence the name) to rank each transmission line by importance. Eq. 1 shows the calculation for LODF of line *i* due to the outage of line *j* where Δf_i is the change in flow on line i and f_j is the initial flow on line j [51]. The change in flow is calculated by the power transfer distribution factor (PTDF) which tells how a line responds to a change in generation and load.

$$LODF_{i,j} = \frac{\Delta f_i}{f_j} \tag{1}$$

The LODF metric for each line is calculated for each line removal from the grid, resulting in a vector of distribution factors. NLODF takes this vector output and normalizes it to a scalar using the average and standard deviation. The calculation for NLODF is shown in Eq. 2. A higher NLODF value means that the associated line has a larger *negative* impact on the network when removed and is therefore more important.

$$NLODF(i) = \frac{mean(abs(LODFs))}{std(abs(LODFs))} \tag{2}$$

The second engineering method studied for transmission line analysis is the TIER method. The *Topological and Impedance Element Ranking* (TIER) method uses Lagrange multipliers and generation shift factors to determine transmission line importance based on changes in generator dispatch. Eq. 3 shows the calculation for TIER values from this method.

$$TIER_{line} = std\left(\frac{\lambda_{TIER}}{\mu_{line}}\right) \tag{3}$$

The standard deviation is denoted by *std*, the term λ_{TIER} is a Lagrange multiplier for dispatchable resources (generators) within the grid, and μ_{line} is a Lagrange multiplier for transmission lines. Higher TIER values relate to more important lines.

Ecology Methods

The methods of STO and WTO first require that the network be modeled as a directional graph (digraph). Digraphs in ecosystems select species as nodes and links as their caloric predator-prey exchanges (or mutually beneficial interactions in plant-pollinator networks). Energy transfer between species in food webs is direct, occurring through predation. The energy transfer between grid components, such as between buses, occur via transmission lines – also modeled as components here. Interactions between components can be identified from the digraph and quantified in a flow matrix (**M**), such as in Figure 2 for the 5-Bus grid, for further calculations.

$$\mathbf{M} = \begin{array}{c} \\ \mathrm{G1} \\ \mathrm{G2} \\ \mathrm{B1} \\ \mathrm{B2} \\ \mathrm{B3} \\ \mathrm{B4} \\ \mathrm{B5} \\ \mathrm{g1b1} \\ \mathrm{g2b2} \\ \mathrm{b1b3} \\ \mathrm{b2b1} \\ \mathrm{b2b4} \\ \mathrm{b4b3} \\ \mathrm{b4b5} \end{array} \begin{array}{cccccccccccccc} \mathrm{G1} & \mathrm{G2} & \mathrm{B1} & \mathrm{B2} & \mathrm{B3} & \mathrm{B4} & \mathrm{B5} & \mathrm{g1b1} & \mathrm{g2b2} & \mathrm{b1b3} & \mathrm{b2b1} & \mathrm{b2b4} & \mathrm{b4b3} & \mathrm{b4b5} \\ \left(\begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} \right. & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 96 \\ 0 \\ 0 \\ 78 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 404 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 74 \\ 0 \\ 0 \\ 26 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 126 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 100 \end{array} & \begin{array}{c} 96 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 404 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 74 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 78 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 126 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 26 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} & \left. \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 100 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} \right) \end{array}$$

Figure 2. Intercompartmental Flow Matrix (**M**) with Transmission Lines for the 5-Bus network of Figure 1.

This flow matrix **M** is intercompartmental, meaning it doesn't consider flows that cross the system boundaries). The **M** matrices from each grid are used to calculate the uniqueness values of the different ecological methods studied in this research. The matrix elements are the flows between nodes (i.e., grid components, set as the buses, generators, and lines) in the directional graph (digraph). Note: prior work studying ecological methods in electric power grids did not model transmission lines as nodes [13, 34]. Modeling transmission lines as nodes allows them to be treated as if they are species in a food web allowing the ecological methods to be used in transmission line analysis. Only the lines between buses are of interest because the grid models assume direct connections between generators and buses (no transmission line).

The calculation of STO considers only the network *structure*, meaning it only considers if there is an interaction between components or not. WTO considers the network structure as well as the flow magnitude being transferred through the network. STO utilizes an undirected structure matrix (**US**, Figure 3a) which stems from the flow matrix **M**, converting the non-zero values from **M** to ones values and converting to an unidirectional matrix. Values of one in matrix **US** signify an interaction from actor *i* to *j* while zero values signify no interaction. The weighted matrix (**WF**, Figure 3b) is used for WTO calculations. This matrix contains a flow percentage to represent flow magnitude in place of the ones values in matrix **US**. Other than this difference in starting matrices, the calculations for STO and WTO mirror each other. Note: the matrices in Figure 3 are used for transmission line analysis. Lines are not modeled as nodes in non-line analysis, so lines aren’t included in the matrices for non-line analysis.

$$\mathbf{US} = \begin{array}{c|cccccccccccccc|}
 & G1 & G2 & B1 & B2 & B3 & B4 & B5 & g1b1 & g2b2 & b1b3 & b2b1 & b2b4 & b4b3 & b4b5 \\
G1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
G2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
B1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\
B2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 \\
B3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
B4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
B5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
g1b1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
g2b2 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b1b3 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b2b1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b2b4 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b4b3 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b4b5 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}$$

(a)

$$\mathbf{WF} = \begin{array}{c|cccccccccccccc|}
 & G1 & G2 & B1 & B2 & B3 & B4 & B5 & g1b1 & g2b2 & b1b3 & b2b1 & b2b4 & b4b3 & b4b5 \\
G1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
G2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
B1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
B2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
B3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
B4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
B5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
g1b1 & 1 & 0 & 0.55 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
g2b2 & 0 & 1 & 0 & 0.74 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b1b3 & 0 & 0 & 0 & 0 & 0.74 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b2b1 & 0 & 0 & 0.45 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b2b4 & 0 & 0 & 0 & 0.26 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b4b3 & 0 & 0 & 0 & 0 & 0.26 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
b4b5 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}$$

(b)

Figure 3. Matrices for Transmission Line Calculations. (a) Undirected Structure Matrix (**US**). (b) Undirected Weighted Flow Matrix (**WF**) based on Figure 2.

Eq. 4-7 show the calculations for STO. D_j is the degree of species *j* or its total number of interactions. **DUS** is the degree normalized matrix, found by dividing each element in **US** by the degree of the various grid components. **IM** in Eq. 6 is the interaction matrix, where *n* is the maximum shortest path in the network plus 1. Note: adding 1 to the maximum shortest path allows for all components in the network to be considered in the analysis.

Once matrix **IM** is found, the strengths of the interactions can be determined using various threshold values ranging from zero to one. It is important to note the step size used in analysis, as it can affect the results. A step size of 0.001 is used here to define the threshold values. This is the largest step size that results in consistent ranking of lines. Smaller step sizes do not result in different ranks, so the larger step size is used for faster computation. Any step size larger than 0.001 would lead to lines being ranked differently. If an element in **IM** is greater than the predetermined threshold value, that interaction is considered strong. If the element is less than the threshold value, the interaction is weak. A matrix, **AM**, contains these strong and weak identifiers. There is a different **AM** matrix for each threshold value. Looking at a single **AM** matrix, if species k and m both have strong interactions with species q (determined by comparing AM_{kq} and AM_{mq} to the threshold value), species k and m experience some amount of trophic overlap. The trophic overlaps for all species/actors in the network are summarized in a matrix **TO** using the interaction strengths from the **AM** matrices. Each **AM** matrix has a corresponding **TO** matrix, which are used to calculate STO in Eq. 7. STO is calculated for each species in the network using the set of **TO** matrices.

$$D_j = \sum_{i=1}^{k} \boldsymbol{US}_{ij} \tag{4}$$

$$\boldsymbol{DUS}_j = \frac{\boldsymbol{US}_j}{D_i} \tag{5}$$

$$\boldsymbol{IM} = \frac{1}{n}(\boldsymbol{DUS} + \boldsymbol{DUS}^2 + \cdots + \boldsymbol{DUS}^n) \tag{6}$$

$$STO_j = \sum_{T=0}^{1} \boldsymbol{TO}(T)_j \tag{7}$$

WTO calculations are very similar to STO calculations. WTO calculates a weighted degree (WD_j) in place of D_j in Eq. 4, found by summing the rows and columns of **WF**. WTO then uses Eq. 5-7 with a matrix **DWF** (degree normalized weighted flow matrix) in place of **DUS** and *WTO* in place of *STO*. More details behind the derivation of STO and WTO, as well as some worked examples, can be found in Lai *et al.* and Xiao *et al.*, respectively [48, 49].

Analysis Methods

Multiple approaches to analyzing the engineering and ecological methods were studied. Each approach centered around the forming of a *true rank* of transmission lines that each method could be compared to. This would allow for the accuracy of each method to be calculated and compared. The first approach to creating a true rank focused on the *number* of violations when a contingency is applied. In this approach, transmission lines that caused more violations with N-1 contingencies were determined to be more important. If two or more lines had the same number of violations after an N-1 analysis, an N-2 analysis was run for those lines, and whichever line associated with more violations was determined to be more important. This analysis would continue with *N-x* contingencies until each line had a distinct rank. This method, however, was very computationally demanding, especially for larger grids, so the second method was devised.

The second approach to creating a true rank also focused on contingency analysis but focused on the *magnitude* of failures rather than number. This method took inspiration from the violation index proposed by *Huang et al.* in [52]. Eq. 8 shows the calculation of this index, the Impact Factor (IF), where % Overflow is the amount of power overflow through a line and V_{below} and V_{above} are the amount of voltage at a bus below or above the bus's maximum voltage, respectively.

$$IF = (\%Overflow - 100\%) + (1 - V_{below}) + (V_{above} - 1) \tag{8}$$

Components with a higher impact factor are considered more important because they have a greater impact on the grid functionality. If two or more components were found to have the same impact factor (e.g., *IF*=0 if no violations), then *N-2* is used and so on until there are no more ties, giving a distinct rank to each component in the grid. This method was more computationally efficient than the first approach and was used in all nine grid cases to develop a true rank of transmission lines. Only in the 200-Bus grid was this method unable to completely rank all transmission lines due to computational demand, instead only ranking the top 25% of lines within the grid. This resulted in a slightly different analysis of this grid.

With the true rank of all transmission lines in the grids, the accuracy of each method could be calculated. Two methods for determining accuracy were used in this research. The first accuracy method, the *Overall Accuracy*, requires all of the transmission lines to be considered. In this method, the rank error for each method is calculated to determine how accurate they are. The rank error is defined as the distance in rank from the true rank, of each line. For example, as seen in Table 1, WTO ranks line b2b4 (the line from bus 2 to bus 4) as the fourth most important line in the 5-Bus grid, but the "true rank" (found from the impact factor calculation) has b2b4 ranked first. This yields an error of 3 for WTO when considering line b2b4.

Table 1. Line Ranks in 5-Bus Network

Line	True	WTO	STO	NLODF	TIER
b2b4	1	4	5	1	4
b1b3	2	1	3	3	4
b4b5	3	2	1	2	5
b4b3	4	3	3	5	4
b2b1	5	5	5	4	1

Table 1 also shows the other line rankings for each metric in the 5-Bus case study. From Table 1, WTO rank errors are: b2b4 with an error of 3, b1b3 with and error of 1, and b4b5, b4b3, and b1b2 with errors of 1, 2, and 0, respectively. This gives a total error of 7. When divided by the total number of lines the average overall error is 1.4. However, this average error is normalized only to the individual grid, making it difficult to compare to grids of other sizes. Larger grids have a greater likelihood of having a larger error. For example, when considering transmissions lines, the 5-Bus grid has a largest possible error of 4, but the 200-Bus grid's largest possible error is 276. To account for this, the average error is normalized by dividing by the largest possible rank error. In this example, WTO has a normalized average error of 0.28.

The second accuracy method, *Top Percent Accuracy*, focuses on only the most critical, or top ranked, transmission lines in the network. The accuracy of the top *X*% of lines (where *X* is either 10, 20, or 30%) is of interest because these are the most critical lines found by each method. The top 10, 20, and 30% of lines were chosen because the smaller networks, like the 5- and 6-Bus, consisted of only one or two lines when considering the top 10%. Grids larger than the ones studied in this research may only need the top 10% of lines to be considered because they account for more components.

In this top percent analysis, accuracy is calculated differently than in the *Overall Accuracy* approach. To determine accuracy, the top percent of the true rank is compared to the top percent of each method. The percent of components found in both the true rank and the studied method provides the accuracy of that method. For example, Table 1 shows that the top 30% of lines in the 5-Bus grid consists of two lines. The True Rank finds these lines to be b2b4 and b1b3 while WTO finds b1b3 and b4b5 to be the top 30% most critical. Both the True Rank and WTO consider b1b3 to be in the top 30% most critical lines, so WTO has one out of two lines accurately ranked, giving an accuracy of 50%.

With the accuracy methods established, another important consideration when calculating accuracy is the fact that the methods tested have the potential to rank various transmission lines the same. For example, the TIER method may calculate multiple transmission lines to have the same TIER value and rank them the same. STO and WTO *can* rank components the same, but this is less likely than the other methods tested in this research.

To account for rank ties when calculating accuracy, components that are tied are given the rank of their lowest possible tied rank. For example, Table 1 shows STO ranks b1b3 and b4b3 both as number 3. These lines would normally be considered tied for rank 2. However, the lower rank is used because it can't be determined with confidence which one is actually ranked second. Assigning a lower rank also leads to a lower *Overall Accuracy* and potentially a lower *Top Percent Accuracy*, meaning methods with more tied ranks are found to be less accurate. This is justified because methods with fewer tied ranks are more useful by giving distinct rankings of each component.

Overall Accuracy is calculated the same way for tied ranks, considering the lowest possible tied rank for components with the same rank. For example, STO has errors of: b2b4 with an error of 4, b1b3 with an error of 1, and b4b5, b4b3, and b1b2 with errors of 2, 1, and 0, respectively. The average and normalized errors are then calculated the same way by dividing by the number of lines in the grid.

Top Percent Accuracy analysis changes slightly when ties are considered. Considering Table 1 again, STO ranks line b4b5 as number 1, but there is no line ranked 2. This means STO only has b4b5 in the top 30% of lines because b1b3 and b4b3 (tied for rank 3) can't confidently be considered in the top 30%. This leads to STO having an accuracy of 50% when considering the top 30% of lines.

With these methods to determine the overall and top percent accuracy of each method, the engineering and ecological methods were used to rank transmission lines in each grid studied.

Results and Discussion

Accuracy

The aim of this study of transmission lines is to determine which method is best at identifying critical lines in power grids. Identifying these critical lines helps power engineers focus failure analysis calculations and allows for improved security and resilience efforts. Figure 4 - Figure 6 show the results of the study of transmission lines. These figures show the accuracies found for WTO, STO, NLODF and TIER metrics for each power grid network case study. The *normalized average rank error* in Figure 4 represents the overall inaccuracies of the four metrics. This illustrates *on average* how accurate a given metric is and easily compares the four metrics.

A shorter bar in this figure represents a more accurate method. Figure 4 shows that NLODF has the lowest average error among five of the eight power grid case studies and is tied for lowest with WTO in one. This means NLODF is the most accurate method overall when ranking lines. However, TIER was the most accurate in the 14-Bus grid while WTO was the most accurate in the 57-Bus grid, showing other methods are also useful in some cases. Additionally, Figure 4 shows STO and WTO performing comparably to the engineering methods, especially in larger grid sizes. With this data, it can be seen that STO and WTO are not necessarily more accurate, but they are comparable to the other methods which shows these ecological methods may be useful.

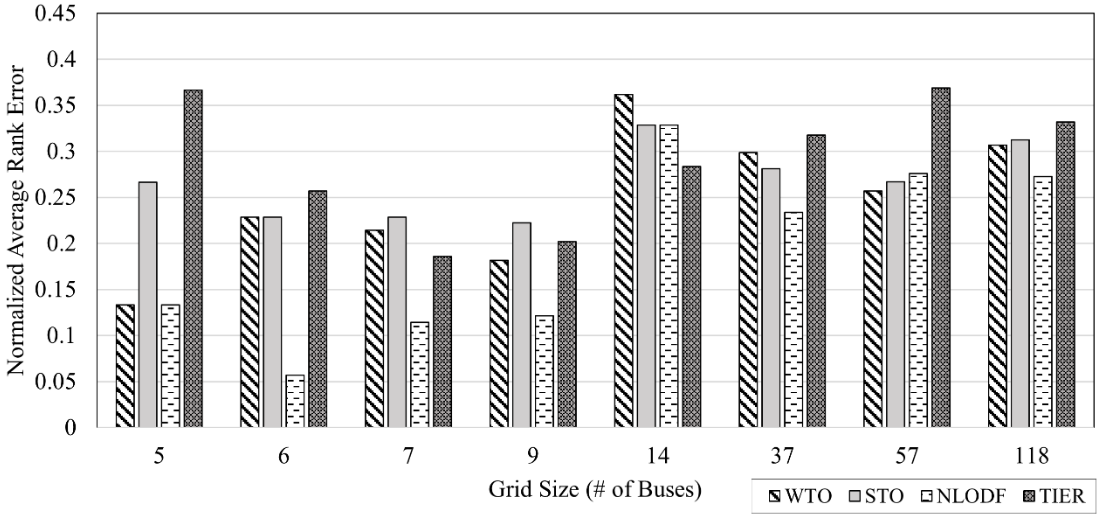

Figure 4. Transmission Line Overall Accuracy

To better visualize the results of Figure 4, Table 2 was created showing the number of grids each method was most accurate in along with the number of grid where each method tied for most accurate. Table 2 better illustrates that NLODF is the best method for ranking and identifying critical transmission lines while the other methods are not as accurate.

Table 2. Accuracy of Each Method (Transmission Line Overall Accuracy)

Method	Most Accurate (# of grids)	Tied (# of grids)
NLODF	5	1
TIER	1	-
STO	1	-
WTO	-	1

While total accuracy is important, it is not always feasible to consider all components in a grid, especially in larger networks like the 200-Bus case studied in this research. This is why Figure 4 only considers grid sizes up to 118 buses. Determining the true rank of all lines in the 200-Bus grid was too computationally intensive, so only a top percent analysis was done for this grid. Figure 5 shows the accuracy of each metric for the 10%, 20%, and 30% most important lines in the grid. This figure also only shows grid sizes up to 118 buses because the 200-Bus grid could only be analyzed studying the top 10%, 20%, and 25% of lines and was not included. Figure 6 shows the analysis of transmission lines in the 200-Bus grid.

The top percent are highlighted because these are the most critical lines as identified by the true rank. In Figure 5 and Figure 6, a higher bar means greater accuracy. As seen when comparing Figure 4 and Figure 5, the metric that was able to most accurately rank the top (i.e., most important) lines was not always the same metric that had the highest overall average. This shows that it is important to consider only the top percent of lines to determine the most accurate method for identifying critical lines. To determine which method is most accurate in each grid, first the top 10% of lines is considered. If it cannot be determined which method is most accurate when considering the top 10%, the top 20% is then considered. If it still cannot be determined which method is most accurate, the top 30% is considered.

Figure 5 shows that NLODF was the most accurate in three of the eight networks (5-, 9-, and 118-Bus cases) and tied for most accurate with WTO in the 37-Bus grid. TIER was most accurate in two of the 7- and 14-Bus grids, STO was most accurate in the 57-Bus grid, and WTO was most accurate in the 6-Bus grid (and tied with NLODF in 37-Bus). Figure 6 shows TIER to be the most accurate method in the 200-Bus case. These results give more evidence that NLODF is a relatively accurate method while STO and WTO are comparable to the engineering methods in some cases.

Another interesting observation from the top percent analyses is the consistency of metric performance in a network. When a metric is found to be most accurate in the top 10%, this metric will likely be as accurate or more accurate than the other metrics at 20% and 30%. This can be

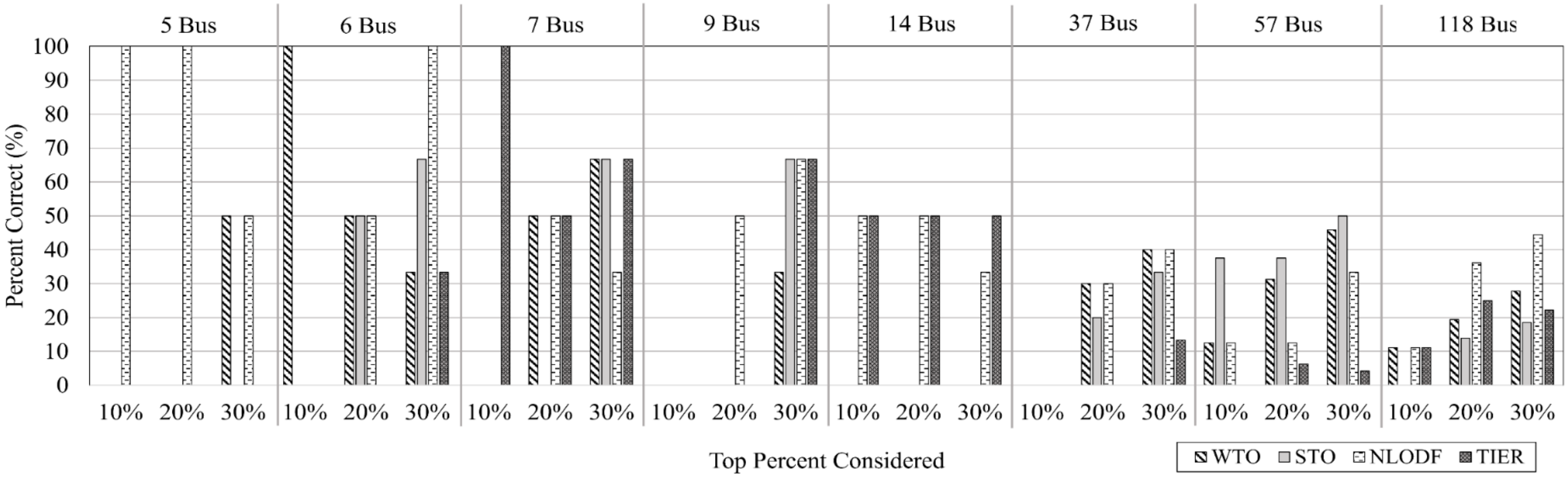

Figure 5. Transmission Line Top Percent Accuracy (5- to 118-Bus)

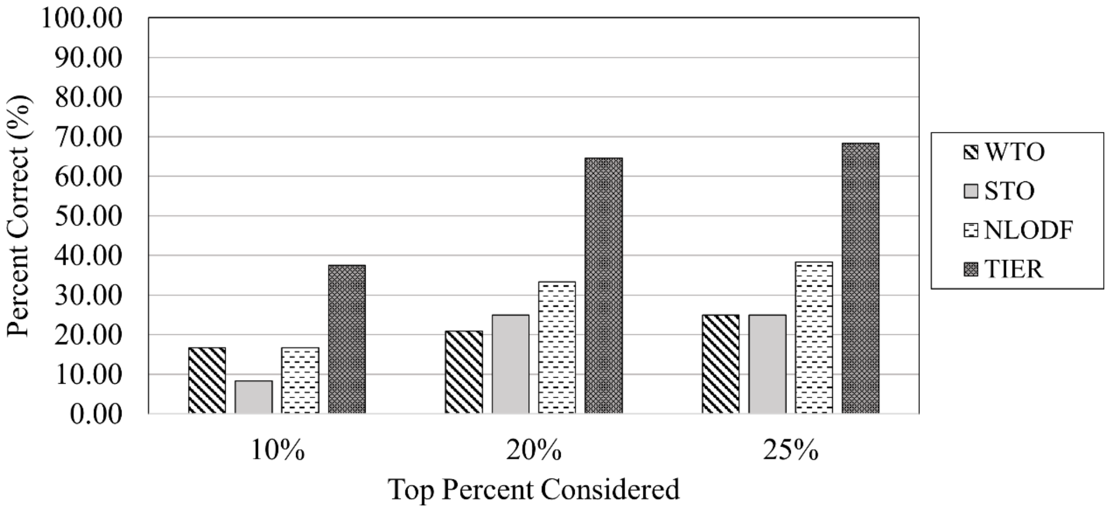

Figure 6. Transmission Line Top Percent Accuracy (200-Bus)

seen in the 7-Bus network where TIER is the most accurate at 10% and is just as accurate or better than the other metrics at both 20% and 30%. This is not true in the 6-Bus grid, but this is the only exception. The consistency in method performance may be useful for analyzing larger grids or greater numbers of lines. A power engineer that wants to determine the most critical top 30% of lines, an analysis at 10% would suggest which metric will be the most accurate at 30%. The engineer can then focus computation on that one method without needing to study the other methods.

To better visualize the results from Figure 5 and Figure 6, Table 3 was created. This table shows the number of grids each method is the most accurate in as well as the number of grids each method tied for most accurate in. This table clearly illustrates that NLODF is the most accurate method when identifying the most critical transmission lines while TIER is the next most accurate and STO and WTO are not very accurate comparatively.

Table 3. Accuracy of Each Method (Transmission Line Top Percent Accuracy)

Method	Most Accurate (# grids)	Tied (# grids)
NLODF	3	1
TIER	3	-
STO	1	-
WTO	1	1

Efficiency

Another important consideration in our analysis is the computational efficiency of each method. A major motivation of this research is finding computationally efficient methods for identifying critical components. Methods with faster computation have greater computational efficiency. These faster methods are more useful in larger grid sizes where more components must be considered. In some cases, it may be useful to sacrifice accuracy for faster calculations, giving preference to different methods based on different analyses. Table 4 shows the computation times of each method for ranking transmission lines. From this table, it can be seen that TIER is the fastest method in all grid sizes and NLODF is the slowest in eight of the nine (but very comparable to WTO in the 118-Bus grid). WTO and STO have comparable speeds to TIER and are significantly faster than NLODF in smaller grid sizes. However, in the 200-Bus grid, WTO and STO are much slower than NLODF and TIER. This may suggest STO and WTO may be more useful in smaller networks such as microgrids.

Table 4. Transmission Line Computation Time (seconds)

Grid Size	STO	WTO	NLODF	TIER
5-Bus	0.1769	0.1818	8.8235	0.1752
6-Bus	0.1935	0.1982	10.033	0.1781
7-Bus	0.2358	0.2387	12.566	0.1814
9-Bus	0.1952	0.2083	11.230	0.1802
14-Bus	0.4405	0.4561	18.373	0.1808
37-Bus	4.4639	4.3060	40.758	0.1829
57-Bus	13.066	12.478	53.800	0.1833
118-Bus	211.39	258.87	258.96	0.1952
200-Bus	745.64	827.54	359.32	0.1961

An interesting observation from this table is that the 7-Bus grid has longer computation times than the 9-Bus grid for all methods. This is because the 7-Bus grid has a larger number of transmission lines than the 9-Bus grid, leading to more components to analyze.

Summary

Two engineering and two ecological methods were used to rank and identify critical transmission lines in electric power grids. The two engineering methods studied were NLODF and TIER. NLODF uses the Line Outage Distribution Factor metric, a common metric to determine the impact of a given line's removal from the grid, to determine importance. NLODF considers an important transmission line to be one that creates a large change in power distribution throughout the grid. Similarly, TIER considers an important transmission line to be one that creates a large redistribution of power generation throughout the grid.

The ecological methods STO and WTO, however, determine importance in a different way. These ecological methods consider unique transmission lines to be more important because they are less easily replaced if removed. Unique transmission lines are those that have unique direct and indirect connections to other grid components. The strength of a line's connections to other components (magnitude of power flow across a line) can also impact its uniqueness, as in the use of WTO where flow magnitude is considered.

Using a true rank found by running contingency analyses, each method's accuracy was calculated to determine how effective it was at ranking all transmission lines in the grids studied. The accuracy of each method's top percent of lines was also calculated to determine how effective each method was at identifying only the most critical lines. The computational efficiency of each method was also found based on the time it takes each method to run an analysis.

The engineering method NLODF was found to be the most accurate method in both the overall and top percent accuracy methods. However, NLODF was also the least computationally efficient method with slower computation times in all grids. TIER was most accurate in fewer grids than NLODF but was significantly more computationally efficient that NLODF. STO and WTO were each the most accurate in only one grid, but they had comparable efficiency to TIER in smaller grid cases. However, STO and WTO are less computationally efficient than both NLODF and TIER in larger grid sizes, suggesting they may not be useful in real-world power grids. Additionally, in smaller grids where STO and WTO are more efficient than NLODF, TIER is slightly more efficient and also more accurate, suggesting TIER should be chosen over the ecological methods in smaller cases.

These results suggest that the ecological methods STO and WTO may not be better methods for identifying critical transmission lines than engineering methods that already exist. However, this study does show that the ecological methods are comparable to the engineering methods in many cases, suggesting that other ecological methods may have more potential for use in power grid analysis. Additionally, STO and WTO, while not particularly useful in real-world large-scale applications of transmission line analysis, may have some use in non-line analysis, as the next chapter studies.

CHAPTER IV DETERMINING BUS AND GENERATOR IMPORTANCE

Research Questions to be Addressed

How do the accuracy and speed of the ecological methods for identifying critical non-line components compare to the engineering methods for electric power grids? Similar to the previous chapter, answering this question requires an analysis of both the accuracy and efficiency of engineering and ecological methods. Comparing the different methods using these two metrics provides empirical data to determine which method is the best for analyzing electric power grids.

Methods

Engineering Methods

The engineering methods used in the analysis of power grid buses and generators are the Controllability Index, CI, and the centrality metrics of betweenness centrality, BC, degree centrality, DC, and closeness centrality, CC. These methods study the nodes within a network to determine which may be considered most important. Buses and generators are often modeled as nodes in power grids, similar to species in food webs. This gives justification for the use of these methods in this research for comparison to the ecological methods studied. Eq. 9 shows the calculation for the Controllability Index.

$$CI(i) = \left(N_i^D - N_{orig}^D\right) + \frac{\sum_{j \in \theta}\left(N_j^D - N_{orig}^D\right)}{K_i} \tag{9}$$

As discussed in the literature review, the Controllability Index is determined by the change in driver nodes within the system which allow for the system to be controlled, hence the name of the index. The minimum number of driver nodes in the original network is given by N_{orig}^D, the minimum number of driver nodes when node *i* is removed is given by N_i^D, and the degree of node *i* is given by K_i. The term N_j^D gives the minimum number of driver nodes when node *j*, from a set of adjacency nodes θ, is removed from the network. Adjacent nodes are considered in this calculation because a node's importance is not only related to itself. If a node *j* that is adjacent to node *i* is removed from the network, this could affect whether node *i* is a driver node, showing the need to consider adjacent nodes as well as the initial node itself.

Centrality measures are a common tool used in network analysis, used in both power grid and ecology studies. Due to the use in both areas, the centrality metrics studied in this research are the betweenness, degree, and closeness centrality measures. The equations for betweenness centrality, degree centrality, and closeness centrality are show in Eq. 10-12, respectively. The following equations are analyzing the centralities of a given node *i* in a network of *n* nodes.

$$BC(i) = \frac{\sum_{i \neq s \neq t} \sigma_{st}(i)/\sigma_{st}}{(n-1)(n-2)/2} \tag{10}$$

The number of shortest paths between node *s* and node *t* is denoted by σ_{st}, and the number of paths between node s and node *t* that node *i* lies on is denoted by $\sigma_{st}(i)$.

$$DC(i) = n_{adj}(i) \tag{11}$$

This is a very simple calculation because it only sums the number of adjacent nodes, n_{adj}, directly connected to node *i*.

$$CC(i) = \frac{n-1}{\sum_s d(s,i)} \tag{12}$$

The distance between node *s* and node *i* is denoted by *d(s,i)*. This distance is in the denominator because *Closeness Centrality* measures the closeness of nodes, the inverse of distance.

Ecology Methods

Non-line calculations of STO and WTO are mostly the same as the calculations for transmission lines. The only difference between the transmission lines analysis and the non-line analysis are the matrices that are used. In transmission line analysis, a flow matrix that includes the transmission lines as actors is used. In non-line analysis, the transmission lines do not need to be modeled as actors. This results in a matrix such as the one in Figure 7 that relates to the 5-Bus grid.

This matrix **M** is used to generate the undirected structure matrix **US** and weighted flow matrix **WF** used for STO and WTO calculations, respectively. These matrices are shown in Figure 8 and are used to complete the calculations using the same equations described in the previous section (Eq. 4-7).

Analysis Methods

The same methods to determine accuracy were applied to the non-line analysis as in the transmission line analysis. However, instead of attempting to use the *number* of failures from *N-x* analysis, only the magnitude was used to create the true rank of components due to it being more

$$\mathbf{M} = \begin{array}{c} \\ G1 \\ G2 \\ B1 \\ B2 \\ B3 \\ B4 \\ B5 \end{array} \begin{array}{c} \begin{array}{ccccccc} G1 & G2 & B1 & B2 & B3 & B4 & B5 \end{array} \\ \left[\begin{array}{ccccccc} 0 & 0 & 96 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 404 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 74 & 0 & 0 \\ 0 & 0 & 78 & 0 & 0 & 126 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 26 & 0 & 100 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right] \end{array}$$

Figure 7. Intercompartmental Flow Matrix (**M**) for the 5-Bus network.

$$\mathbf{US} = \begin{array}{c|ccccccc|} & G1 & G2 & B1 & B2 & B3 & B4 & B5 \\ G1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ G2 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ B1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ B2 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ B3 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ B4 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ B5 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{array}$$

(a)

$$\mathbf{WF} = \begin{array}{c|ccccccc|} & G1 & G2 & B1 & B2 & B3 & B4 & B5 \\ G1 & 0 & 0 & 0.39 & 0 & 0 & 0 & 0 \\ G2 & 0 & 0 & 0 & 0.66 & 0 & 0 & 0 \\ B1 & 1 & 0 & 0 & 0.13 & 0.74 & 0 & 0 \\ B2 & 0 & 1 & 0.31 & 0 & 0 & 0.5 & 0 \\ B3 & 0 & 0 & 0.30 & 0 & 0 & 0.1 & 0 \\ B4 & 0 & 0 & 0 & 0.21 & 0.26 & 0 & 1 \\ B5 & 0 & 0 & 0 & 0 & 0 & 0.4 & 0 \end{array}$$

(b)

Figure 8. Matrices for Non-Line Calculations. (a) Undirected Structure Matrix (US). (b) Undirected Weighted Flow Matrix (WF) based on Figure 2 matrix.

computationally tractable. With the true rank and ranks from the various engineering and ecological methods studied, the overall and top percent accuracy approaches were utilized again.

In addition to the accuracy approaches used in the transmission line analysis, another approach was studied to determine the accuracy of the various methods studied. While NLODF and TIER had the potential to rank some lines the same, the engineering methods for ranking nodes are more likely to have tied ranks. For this reason, Spearman’s rank correlation coefficient was studied for calculating method accuracy [53]. Spearman’s rank correlation coefficient is used in some statistical analyses to determine how similar two variables are. It is often used to compare rank lists of two different variables and determine if the similarity is statistically significant.

Spearman's rank correlation coefficient also account for rank ties, making it a potentially useful tool in the non-line analysis where the Controllability Index and various centrality measures often rank components the same. However, after initial studies using Spearman's rank correlation coefficient to determine method accuracy in the 5-Bus grid, the results did not give any useful information and this approach was not used further. The initial approaches of overall and top percent accuracy were used instead for non-line analysis.

Results and Discussion

Accuracy

Identifying critical buses and generators can allow power engineers to focus calculations on primarily those components in failure analyses. Identifying critical components can also provide information to allow for improved security and resiliency efforts. Figure 9 and Figure 10 show the overall and top percent accuracies of these methods. When considering non-line components, all components were able to be ranked by the true rank, allowing for overall and top percent analyses of all grids (5- to 200-Bus).

Looking at the overall accuracy of each method in Figure 9, CI is most accurate in two grids and tied with DC in one, STO, WTO, and BC are each the most accurate in two grids, and CC was not the most accurate in any grids. These results show that the ecological methods are very comparable to the traditional engineering methods studied and may be useful in identifying critical non-line grid components.

To better visualize the results from Figure 9, Table 5 was created. This table shows the number of grids each method is the most accurate in as well as the number of grids each method tied for most accurate in. This table clearly illustrates that CI, BC, STO, and WTO are comparable. CI is

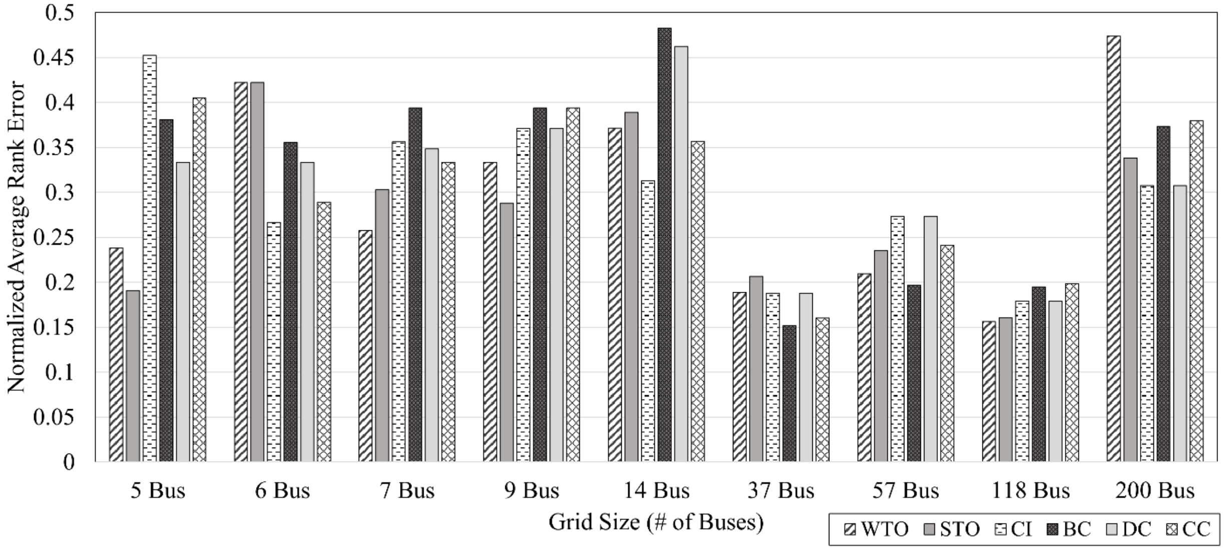

Figure 9. Non-Line Overall Accuracy

slightly more accurate than the other methods because it is tied in one more case than the other methods.

Table 5. Accuracy of Each Method (Non-Line Overall Accuracy)

Method	Most Accurate (# grids)	Tied (# grids)
CI	2	1
BC	2	-
DC	-	1
CC	-	-
STO	2	-
WTO	2	-

To further test the accuracies of each method, the top percent of non-line grid components were analyzed as well. **Figure 10**a shows the top percent accuracies for each method in the smaller five grids (5- to 14-Bus) while **Figure 10**b shows the larger five grids (37- to 200-Bus). This analysis shows many ties between methods and some methods performing accurately. Three grids did not have one method that was most accurate (5-, 6-, and 7-Bus). This makes sense because these grids are the three smallest that were studied meaning fewer components exist in the top percent, so less variation is likely. The larger grids experienced fewer methods tying, likely due to the larger number of components being considered.

The top percent study of non-line components also gave information about which methods were most accurate. The results show that STO is the most accurate in three grids (14-, 118-, and 200-Bus), BC is most accurate in two grids (37- and 57-Bus), WTO is most accurate in one grid (9-Bus), and CI, DC, and CC are not most accurate in any grids. These results show that the ecological methods are somewhat better at identifying critical non-line components than the other traditional engineering methods studied. However, even in grids where the ecological methods were not the most accurate, they were still comparable to the other methods. This shows promise for the ecological methods identifying critical non-line components in power grids because they are comparable to the other traditional methods.

To better visualize the results from Figure 10, Table 6 was created. This table shows the number of grids each method is the most accurate in as well as the number of grids each method tied for most accurate in. This table clearly illustrates that STO is the most accurate method when identifying the most critical non-line grid components, showing the usefulness ecological methods can have in power grid analysis.

Overall, the ecological methods perform better when ranking non-line components than when ranking transmission lines. This makes some sense, though, because transmission lines do not have a direct analogy in food

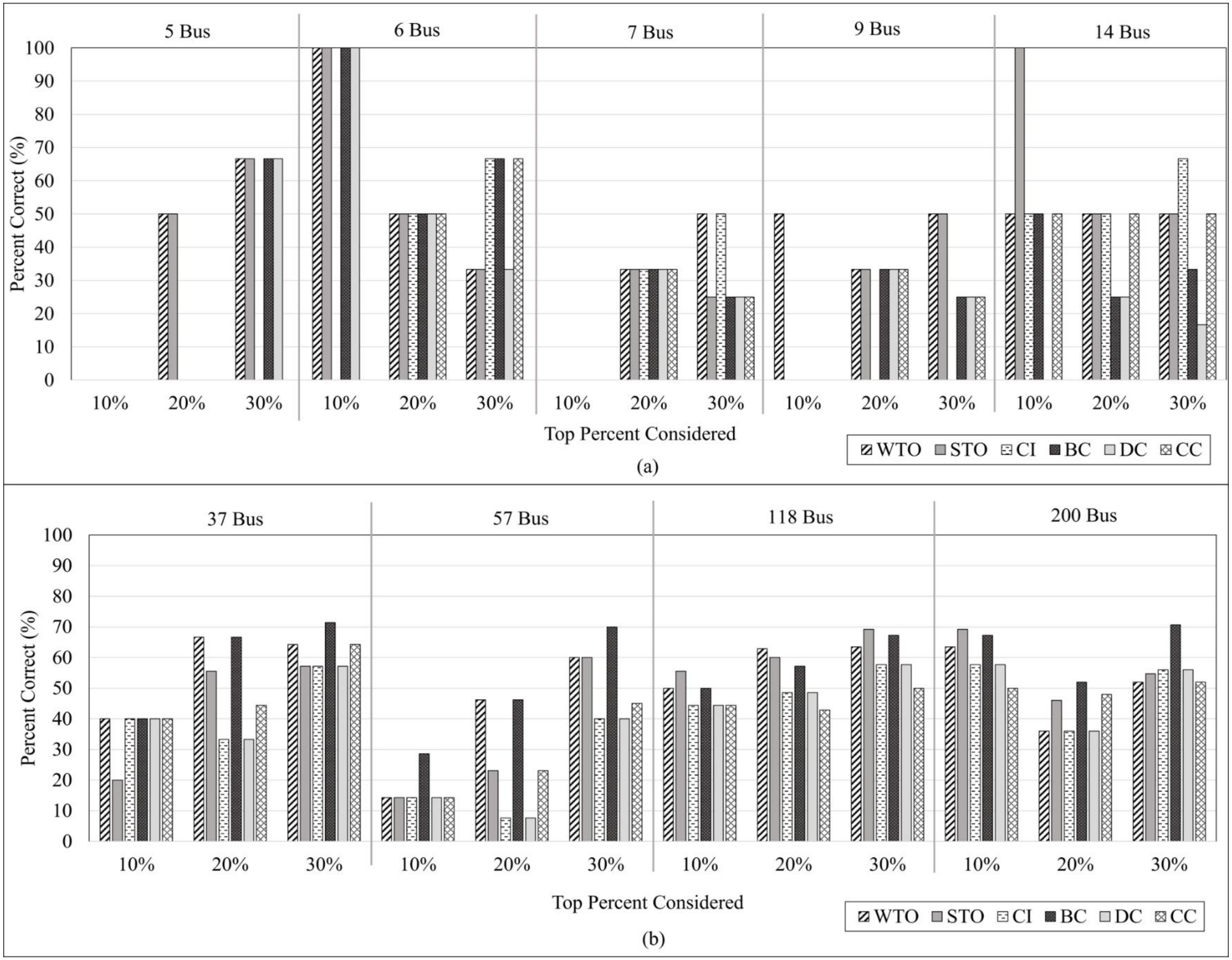

Figure 10. Non-Line Top Percent Accuracy. (a) Non-Line Top Percent Accuracy (5- to 14-Bus). (b) Non-Line Top Percent Accuracy (37- to 200-Bus).

Table 6. Accuracy of Each Method (Non-Line Top Percent Accuracy)

Method	Most Accurate (# grids)	Tied (# grids)
CI	-	2
BC	2	2
DC	-	1
CC	-	1
STO	3	1
WTO	1	2

web networks. WTO and STO find critical species in a food web, which are the nodes of the network. This required the grid transmission lines to be modeled as nodes, an assumption that does not appear to be useful.

Efficiency

Table 7 shows the computation times of each method for ranking non-line grid components. The centrality measures were lumped into a single time because they used the same code and their computation time was so small. From this table, it can be seen that WTO and STO are the slowest methods. The Controllability Index, while slightly less accurate than STO and WTO, is much faster in larger grids. This, combined with CI being comparable to STO and WTO when ranking non-line components, may make it a more viable option for ranking non-line components, in large power grids especially. Similarly, the centrality measures studied are much faster than STO and WTO in larger grids while only being slightly less accurate. The engineering methods' greater efficiency is likely due to the fact that they use only the network structure to analyze components. STO also only considers network structure, but it performs more

Table 7. Non-Line Computation Time (seconds)

Grid Size	STO	WTO	CI	Centrality
5-Bus	0.0967	0.1494	0.0110	0.0047
6-Bus	0.1233	0.1586	0.0114	0.0040
7-Bus	0.1501	0.1498	0.0111	0.0034
9-Bus	0.1488	0.1518	0.0108	0.0030
14-Bus	0.1608	0.1627	0.0130	0.0040
37-Bus	0.5827	0.5286	0.0201	0.0041
57-Bus	1.3266	1.3244	0.0351	0.0047
118-Bus	21.088	23.513	0.4915	0.0068
200-Bus	77.417	81.151	1.7056	0.0075

calculations to identify uniqueness than the engineering methods require to quantity controllability and centrality. Additionally, WTO requires flow magnitude data, causing it to be less efficient than the structure-based methods.

While the ecological methods are much less efficient in large grids, they have comparable efficiencies to the engineering methods in smaller grid sizes. These results show that the ecological methods, while accurate at ranking and identifying critical non-line components in power grids may not be computationally efficient enough to be justifiable in larger grid sizes, but they may be useful for identifying critical components in smaller grids. While they are slightly less efficient than the engineering methods in smaller grids, STO and WTO are still very fast. This provides further evidence that the ecological methods of STO and WTO may be useful mainly in analyses of smaller network sizes such as microgrids.

Additionally, comparing the efficiency of STO and WTO when ranking transmission lines and non-line components shows greater efficiency for non-line components. This makes sense because the non-line analyses use smaller matrices for calculations. This further suggests that STO and WTO may be more useful in non-line grid studies than transmission line studies.

Summary

To study non-line analysis of power grid components, engineering methods for nodal analyses were used. Buses and generators are essentially nodes within the network of a power grid, so the methods of Controllability Index, betweenness centrality, degree centrality, and closeness centrality were used. The Controllability Index measures the impact the removal of a node has on the network based on how easily controlled the network is after the alteration. This allows for an understanding of which nodes allow for greater controllability and therefore greater importance. The centrality methods each measure how central, and therefore important, a node is within the network but in different ways. Betweenness centrality measures how often a given node lies on the shortest path between two other nodes, with more centralized nodes existing on a greater number of shortest paths. Degree centrality measures how many nodes a given node is directly connected to, with greater centralized nodes having more direct connections to other nodes. Finally, closeness centrality measures how close a given node is to all other nodes within the network, with more centralized nodes existing closer to other nodes.

Each of these methods utilizes the network structure to determine the importance of each node (with more central nodes being considered more important). Similarly, STO uses the network structure to identify node importance based on uniqueness. The measure of uniqueness is different from the measures of controllability and centrality that the engineering methods use, but it can still help identify important components in a network, with more unique nodes being more important. WTO also measures uniqueness but considers both the network structure and magnitude of flow through the network. This allows for a more detailed understanding of what makes a node more unique.

With each of these measures, grid buses and generators were able to be ranked in order of importance. Using the true rank of buses and generators found using failure magnitudes from *N*-*x* analyses, the accuracy of each method was calculated. STO and WTO were found to be slightly more accurate than the engineering methods studied in an analysis of the overall accuracy of each method. Additionally, STO and WTO were found to be the most accurate in most grids when studying the top percent of non-line grid components. This provided evidence that STO and WTO were effective at ranking *all* non-line components in the grid but also effective at identifying the *most critical* buses and generators in the power grids studied.

Following the accuracy analysis, a study of computational efficiency was performed. A major motivator for this research is identifying computationally efficient methods for identifying critical grid components, with more efficient methods being desirable. To determine computational efficiency, the computation time of each method was determined. Methods with faster computation are considered more computationally efficient. From this analysis, the ecological methods were found to be less efficient than the engineering methods studied but still fast. STO and WTO identified critical non-line components efficiently in smaller grids but less efficiently in larger grids. This further supports the use of these ecological methods in microgrid and other small grid analyses. Additionally, the ecological methods were found to be more efficient when ranking non-line components than when ranking transmission lines, further supporting the use of these methods in nodal analysis rather than line analysis.

Overall, these results also show how comparable ecological methods can be to existing engineering methods when identifying critical power grid components, supporting the further study of other ecological methods for identifying critical network actors.

CHAPTER V SUMMARY AND CONCLUSIONS

Summary

Identifying the most important components in electric power girds is critical for grid failure analyses and can aid in improving security and resiliency efforts to improve grid functionality. In improved failure analyses, instead of running *N-x* contingency analyses on all components in the grid, which can be computationally taxing and time consuming, computations can focus on only the most important components – saving time and money. Additionally, improved security can be implemented by focusing protection on the most critical grid components. Increased resiliency can also occur by applying strategic redundancy and support to critical grid components, making grid more robust and able to survive disturbances.

This work focuses on identifying critical grid components by studying the accuracy and efficiency of various engineering and ecological methods for determining grid component importance. Two main studies were performed: a study of transmission line importance, and a study of non-line component importance. Chapter 3 studied the identification of critical transmission lines by the engineering methods NLODF and TIER and the ecological methods STO and WTO. Results from this study showed the engineering method of NLODF to be the most accurate both when ranking all transmission lines and when identifying the most critical transmission lines. However, NLODF was the least efficient method in most of the grid cases studied. The *most* efficient method studied was the TIER method which was less accurate than NLODF but more accurate than the ecological methods. STO and WTO were the least accurate methods studied, being most accurate in only one grid case each. However, these methods had comparable accuracy to TIER in many cases, even if not the most accurate. Additionally, STO and WTO were not as efficient as TIER in larger cases but were comparable in smaller cases.

The results suggest that the ecological methods studied may not be feasible for use in real-world large power grid systems. However, the ecological methods may still be useful in identifying critical components in small grids like microgrids, especially non-line grid components like buses and generators. The results show how comparable ecological methods can be to existing engineering methods, supporting further studies into other ecological methods, some perhaps resulting in greater accuracy or computational efficiency. Ultimately, this study showed that STO and WTO may not be viable tools for transmission line analysis, but the results do suggest the potential for ecological methods in power grid analyses.

Chapter 4 studies the identification of critical non-line grid components, like buses and generators, by engineering and ecological methods. The engineering methods studied in this analysis were the Controllability Index and centrality measures of betweenness centrality, degree centrality, and closeness centrality. The ecological methods studied were STO and WTO again. The results show the accuracies of each method to be very comparable when ranking all components and when identifying the most critical components. However, STO and WTO were both slightly more accurate than the engineering methods when identifying the most critical grid components. Studying the efficiency of each method, STO and WTO were found to be the least efficient, only slightly less efficient than the engineering methods in smaller grids but much less efficient in larger grids.

These results suggest that STO and WTO are useful for identifying critical non-line grid components in smaller grid sizes but are less useful in larger grids. However, while STO and WTO are not as useful in larger grids due to their relative inefficiencies, their accuracies are still comparable to the engineering methods in these grids. This supports studies into other ecological methods for identifying critical network actors. STO and WTO having comparable accuracies to the existing engineering methods shows that ecological methods may be useful in power grid analysis. This supports the study of other ecological methods that may be more accurate or more efficient than STO and WTO and more traditional engineering methods.

With both studies resulting in STO and WTO being more useful in smaller grid sizes, the application of these methods is likely in microgrid analysis. Furthermore, STO and WTO are more comparable to engineering methods and more computationally efficient in non-line analysis, suggesting more use in analyzing bus and generator criticality. Identifying critical buses and generators in microgrids is one potential application of ecological methods in power grid analysis. Other applications and studies into bio-inspired power grid analysis are discussed in the following section.

Future Work

Further Studies into STO and WTO

In addition to STO and WTO being used in microgrid analysis, another potential application of these ecological methods could aid in improving grid resilience. Research has suggested that inspiration from the structure of ecological food webs can suggest design changes to improve the resilience of power grids [13]. An ecological preference for redundancy over efficiency [14-16] has been found to create bio-inspired networks with increased resilience when measured by *N-x* contingency analyses [13]. Future work may show that STO and WTO identify critical components where added redundancy is most needed. Determining the validity of using ecological uniqueness to focus redundancy within electric power grids can progress research into improving power grid resiliency.

Additional future research regarding STO and WTO may also aid in more general analyses of electric power grids. For instance, STO and WTO metrics may help identify vulnerability of electric power grids in terms of voltage instability [33] or provide efficient solutions for the optimal allocation of line capacity [36]. STO and WTO may also aid in the problem of intentional controlled islanding [54].

Freeman Centralization

STO and WTO may provide information that allows redundancy to be applied to power grids to make them more resilient. These redundancies will effectively decentralize the networks, so understanding the overall network centrality is an important step to improving grid resiliency. Inspired by research to design power grids through bio-inspiration, a preliminary study into overall network centrality has been conducted. This preliminary research studies the overall network centrality of power grids and food webs with the aim to identify other metrics that can be used to compare the two types of networks.

Freeman’s centralization method was used in this preliminary study to determine the overall centrality of various food web and power grid networks [55]. Freeman’s centralization method, with index FC for Freeman Centralization, can be used for any centrality measure. The centrality measures used in this preliminary research were betweenness, in degree, out degree, and out closeness. Figure 11 shows the overall network centrality of 59 different food webs obtained from the enaR package from R.

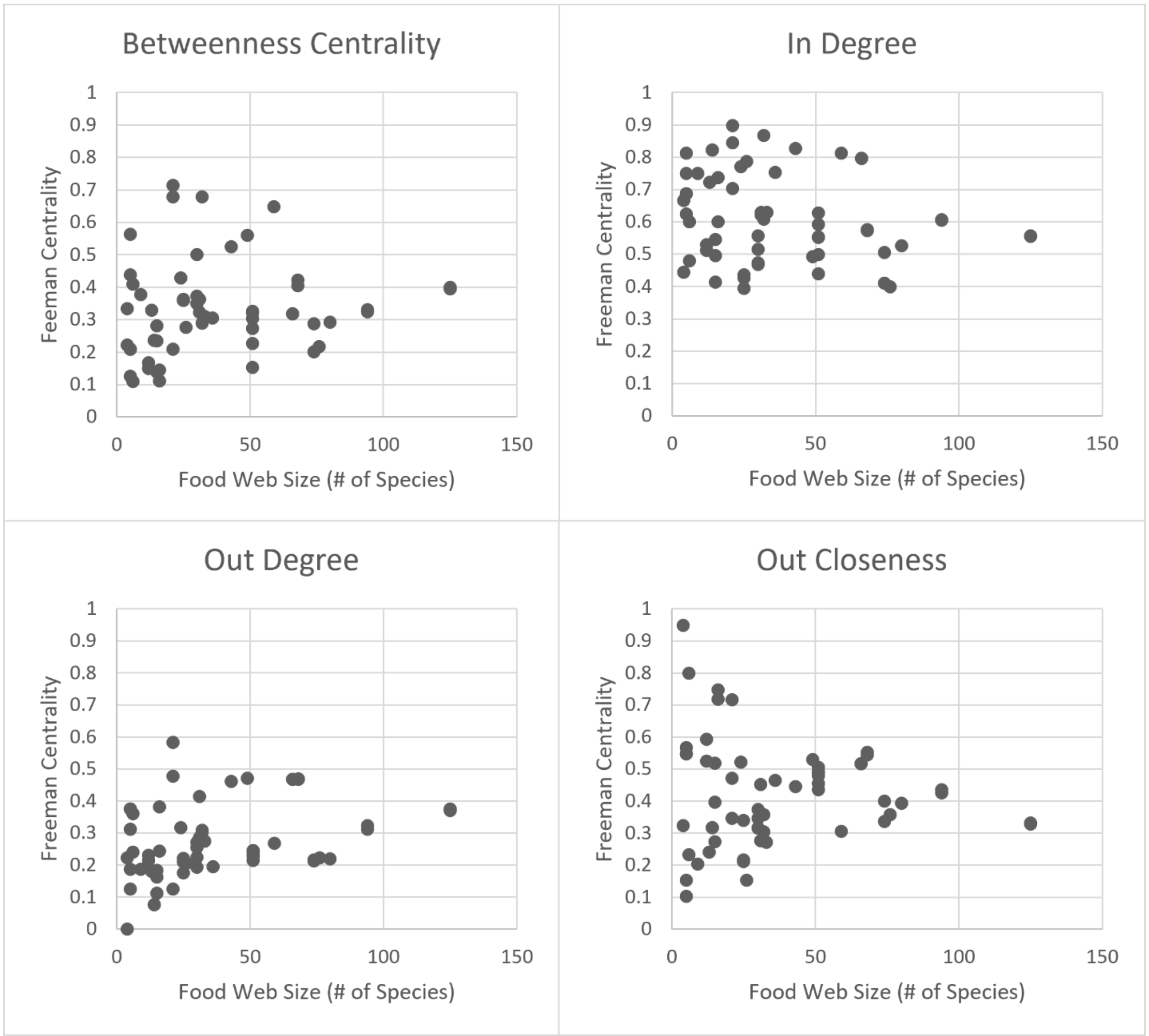

Figure 11. Freeman Centrality of Food Web Networks

These graphs show that no relationship or trend between network size and centrality exist, which is useful to know because this may be different for power grids. However, while there isn't a relationship between network size and Freeman Centrality, there may be a range of FC values that most food webs occur. Figure 12 shows box and whisker plots of this data illustrating the range of FC values food webs commonly have.

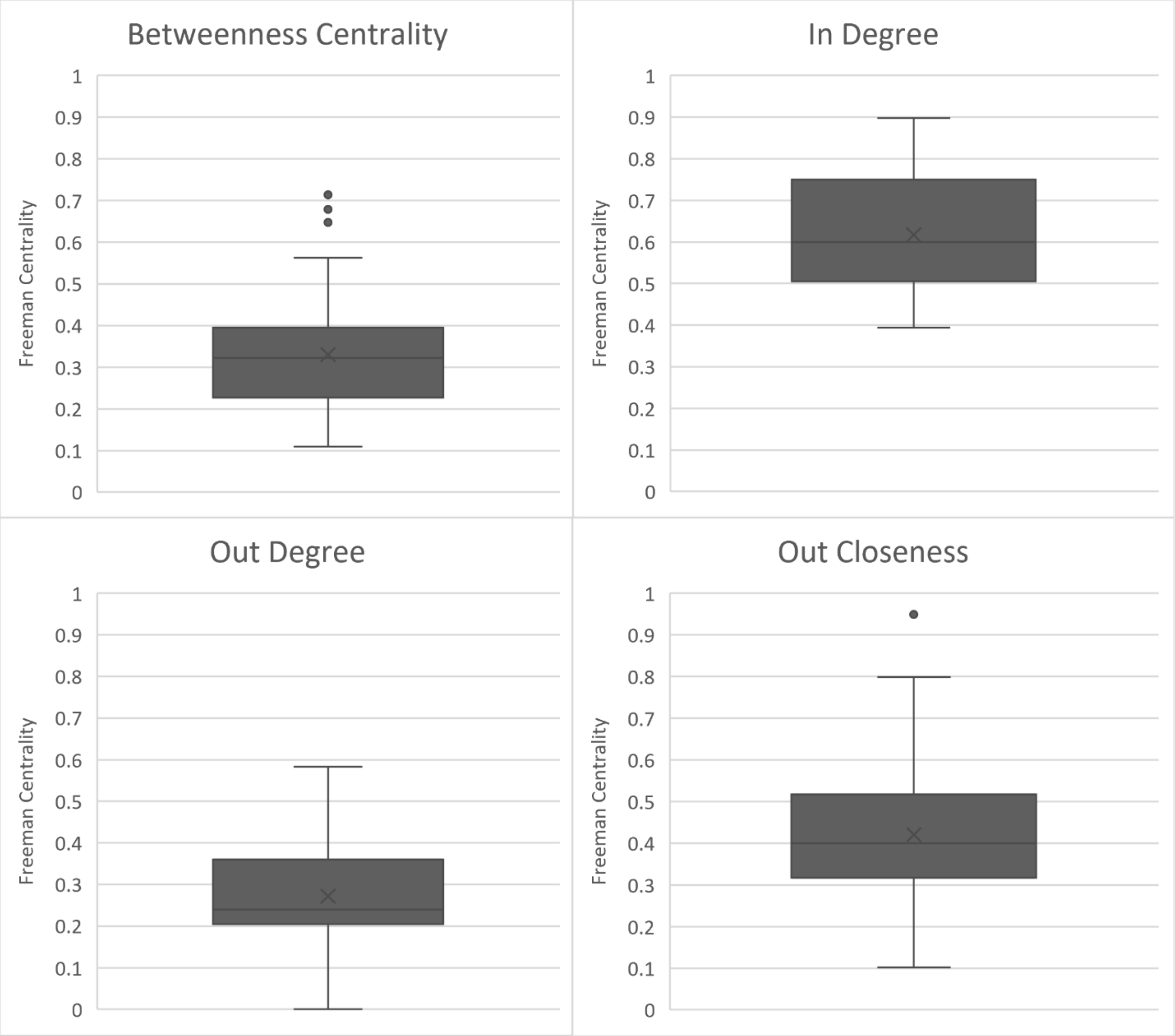

Figure 12. Freeman Centrality Box Plots of Food Web Networks

These graphs show the ranges of FC values for the various centrality measures studied. This data provides information about the overall network centrality of food webs which can be used as a goal for power grid networks. Power grids that emulate the centrality of food web networks may have similar robustness and resilience. This preliminary study analyzed the same power grids studied in this thesis research (5-Bus to 200-Bus grids). Figure 13 shows the FC values of these power grids.

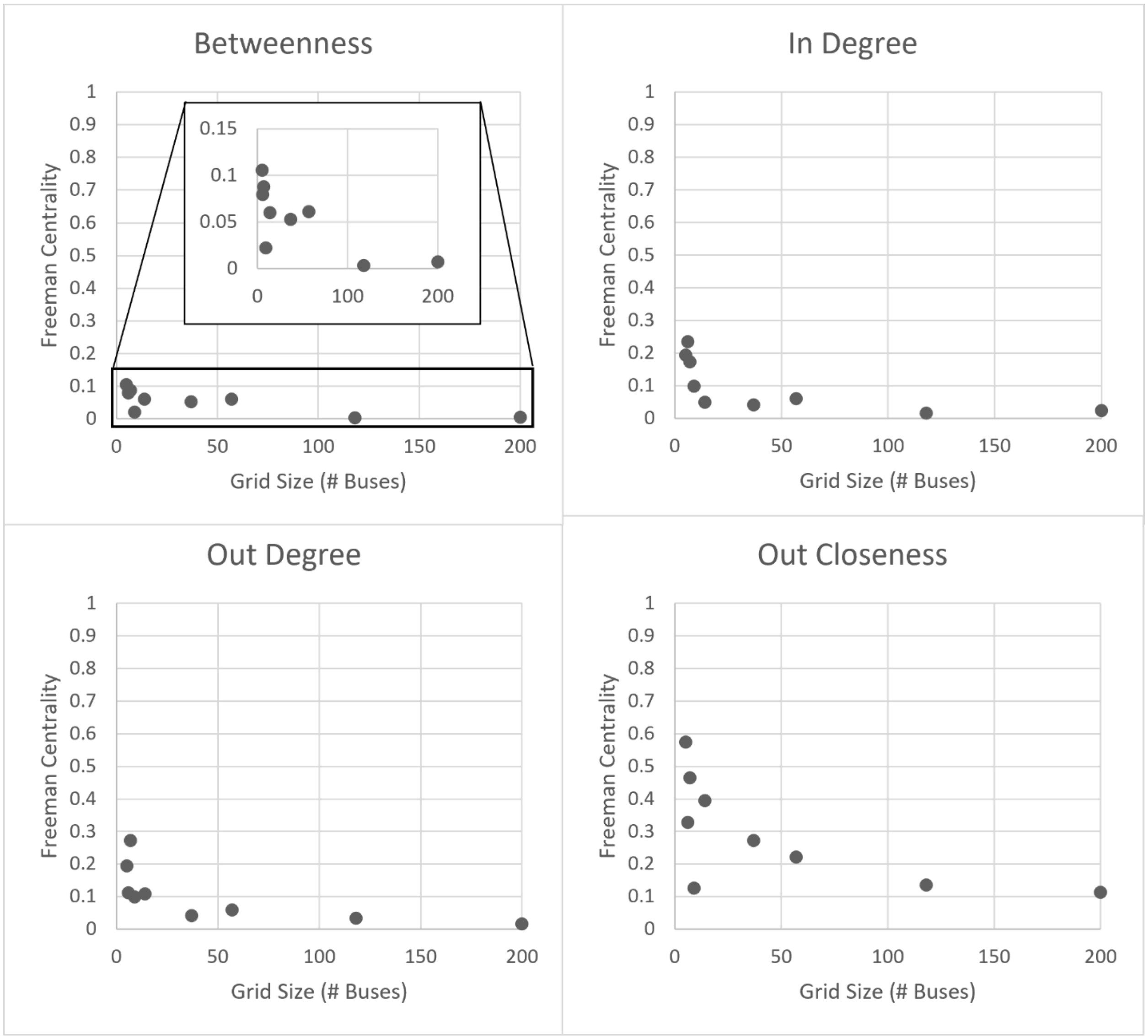

Figure 13. Freeman Centrality of Power Grid Networks

These plots show a clear trend between grid size and Freeman Centrality. As grid size gets larger, the overall network centrality decreases. This is likely due to the larger number of generators in the network because generators are only connected to one bus, meaning they have a low centrality value. With more generators, more components have lower centrality values and the overall centrality of the network goes down. Also from these plots, it can be seen that most power grids do not lie within the range of FC values that food webs occur. This means that the power grids studied have lower overall network centralities than the food web networks studied. Increasing power grid centrality to be similar to food web networks may prove useful in designing more resilient power grids. Ecological methods that identify critical species in food webs, like STO and WTO, may be useful in identifying components in power grids to apply redundancy to increase the centrality and improve resilience.

This is only a preliminary study, but further research can be conducted studying how STO and WTO can be used to increase power grid centrality and resilience. Other ecological methods also exist that may be useful in these analyses as well. One of these methods will be discussed in the following section.

Keystone Index

Other ecological methods exist in addition to STO and WTO that can also be explored to identify critical power grid components. One such metric is the Keystone Index proposed in [37] that aims to identify critical species in food webs, similar to STO and WTO. However, the Keystone Index does not measure uniqueness of a species, but rather utilizes directional networks to measure where a species lies in the hierarchy of the network. Studying this metric may provide another ecological method to identify critical components in power grids. This thesis has presented evidence that supports the research of other ecological methods, like the Keystone Index, for power grid analysis, and these other methods provide future avenues of research.

Conclusion

This research has shown that ecological methods may have potential in electric power grid analysis. This research focused on the identification of critical grid components by various engineering and ecological methods, analyzing the accuracy and efficiency of each method. The methods of STO and WTO were found to be comparable to the engineering methods studied in accuracy and efficiency in many cases. These ecological methods were more accurate and efficient when identifying non-line grid components such as buses and generators and less accurate and efficient when identifying critical transmission lines. STO and WTO were also found to be more efficient in smaller grid sizes rather than larger grid sizes, suggesting more usefulness in analyses of microgrids.

While STO and WTO were not necessarily the *best* methods to analyze power grids in all network sizes when considering accuracy and efficiency, they proved that ecological methods can be useful in some cases and comparable to engineering methods many grids. STO and WTO may have applications in microgrid analysis to identify critical buses and generators, but they may also have applications in identifying areas for strategic redundancy. Future studies into applications of STO and WTO may provide further evidence for the use of ecological methods in power grid analysis and design.

This study focused primarily on the ecological methods of STO and WTO, but there are other ecological methods that aim to identify critical species in food webs. Further studies into these methods may provide further evidence for the application of ecological methods in power grid analysis. These methods, such as the Keystone Index, may also prove to be more accurate or more efficient than STO and WTO, resulting in more uses of these methods.

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