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Influence Graphs for Modeling of Cascading Failures in Electric Distribution Networks

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ABSTRACT

Power Grids are one of the most intricate systems and greatly affect economic, political, and social aspects of contemporary life. A well-operated power system consists of many control devices and protection methods to prevent the interruption of power to consumers. However, such systems are highly vulnerable to severe events; for instance, natural disasters, cyber-attacks, mal-function of control devices, etc. The occurrence of these odd events may lead to cascading failures, which are prominent contributors to blackouts.

This paper focuses on the development of a cascade model in a distribution network using Newton-Raphson's power flow method to study the impact of random line failures on other lines in the system. The random line failures are initiated to mimic the occurrence of severe events. The objective of this study is to collect data which includes the probability of a line failing due to the failure of another line. This probability data set is used to identify lines in a system that are most vulnerable to a threat and to illustrate interconnectivity of the lines using influence-based graphs.

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INTRODUCTION

1.1 Background

Cascade Failures can have enormous economic, political, and social ramifications and lead to catastrophic power system failures. Severe events, such as natural disasters, cyber-attacks, and malfunction of control devices are few of the many events that may initiate the cascading failures. As mentioned in [10], five of the major blackouts that have occurred in the USA are a consequence of faults, whereas the remaining are a result of natural disasters.

Power grids are typically designed to meet N-1 contingency. N-1 Contingency is a criterion which indicates that a single component failure should not cause the failure of another. This means that it takes at least two concurrent faults to initiate a cascading sequence of failures [11]. Therefore, in this paper we developed a model to initiate multiple element failures to analyze cascading events.

1.2 Objectives

The Paper focuses on developing a cascading power failure model using Newton-Raphson's power flow method to identify critical components in a distribution network that are most vulnerable to severe events or attacks. Below is a list of further core objectives that are a result from the identification of the critical components in a power system:

- Creation of a probability matrix to analyze the probability of a line failure due to failing of randomly disconnected branches

- Capturing the interactions among the components using the cascade model

- Illustrating a logical network of interactions among the components using influence-based graphs

- Producing historical data to analyze failures in future power system models

METHODOLOGY

2.1 IEEE 30 Bus System

A power grid consists of nodes and branches and can be represented by a directed graph *G(N, L),* where *N* denotes the set of nodes and *L* denotes the set of lines or branches [1]. In this paper, we use the IEEE 30 Bus System as a benchmark to develop the cascade model. The model and graphs are generated using power system simulations in MATPOWER [5]. The figure below is an illustration of the system where each node is represented by a dot and each branch is represented by a line connecting the nodes.

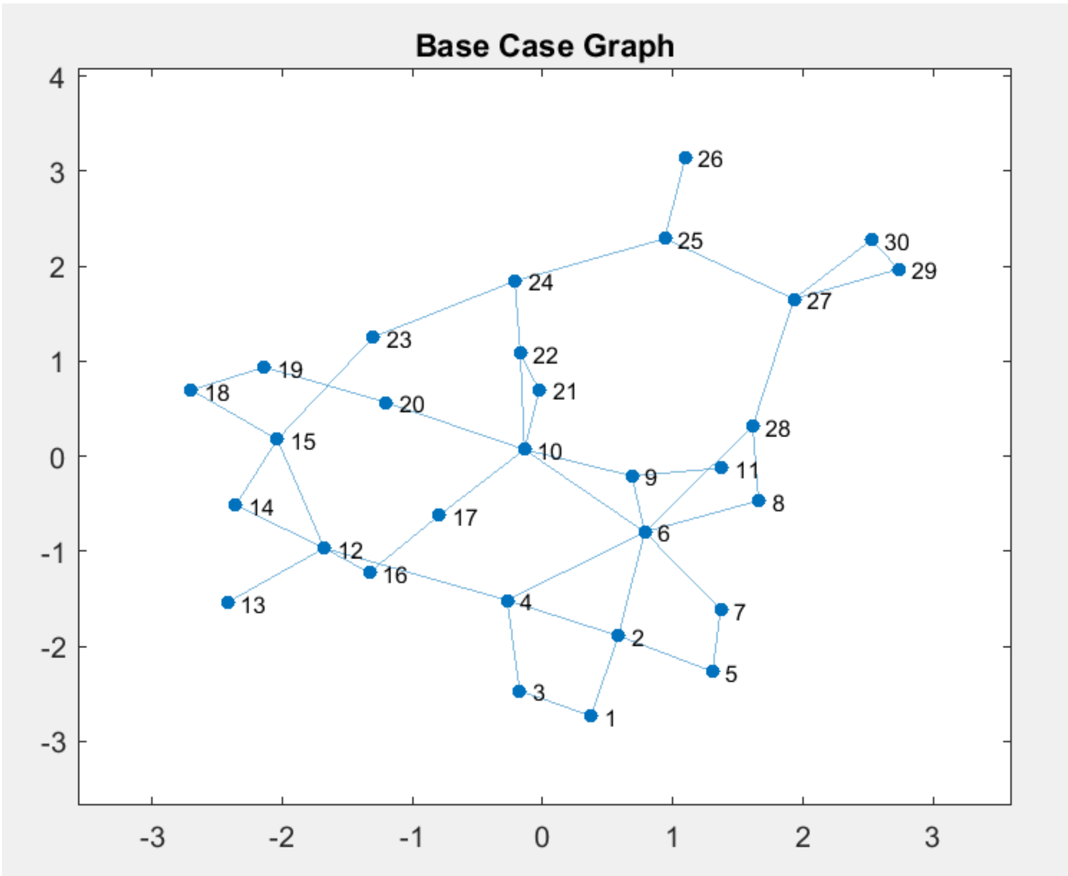

Figure 2-1: IEEE 30-Bus System

2.2 Cascade Failure Model

Every line in a system has an emergency rating value which dictates the power flow in a functioning system. In an event where the power flow exceeds the line's emergency rating, protective devices are initiated to remove the lines out of service to prevent overloading. The cascading failure algorithm is developed based on this deterministic rule. The power flow of the line is computed as follows, where f_l is the power flow, S_{ik} and S_{ki} are the apparent power flows from node *i* to *k* and from node *k* to *i* respectively [12]:

$$|f_l| = \frac{|S_{ik}|+|S_{ki}|}{2} \qquad (1)$$

To mimic the occurrence of a severe event or attack, we randomly disconnect two branches from the system to initiate the cascading process. As a result of these initial failures, the network topology of the power grid changes and may lead to a further division of the connected components, which we refer to as islands. After that, if the individual islands have supply and demand nodes, the island is considered alive provided that supply and demand are balanced. Following [7], the supply and demand rule used is shedding and curtailing: "the amount of power supply and demand are reduced at all nodes by a common factor. If the total active power supply is more than the active power demand in a connected component, the active power outputs of generators are curtailed. On the other hand, if the total active power supply is not sufficient to serve the total active power demand, load shedding is performed to balance the supply and demand within the connected component." Lastly, the deterministic rule is applied to find further line failures until the cascade process ends.

2.3 Pseudocode

(1) Generate two random numbers d1 & d2, such that 1<[d1,d2]<=num_links, where num_links is the total number of branches

(2) Disconnect the two links corresponding to d1 and d2

(3) Run PF

(4) Compute apparent power(S_branch), loading(Branch_loading), and voltages in each branch

(5) lineThreat = (1:num_links)'

lineThreat = lineThreat(S_branch >= capacity) where capacity is the emergency rating (RATE_A) defined in the casedata

(6) for e = length(lineThreat)
    Disconnect lines that are considered lineThreat

(7) Find the effect of the attack on the topology
  (a) Disconnect overloaded lines
  (b) Find Islands
  (c) Calculate the total load and generation in Islands
  (d) If P_load > 0 and P_gen > 0
      Island_cont = 1; % Island continues if there is both load and generation
  (e) Check if the Islands have a slack bus; If it does not have a slack bus, assign a slack bus, where the slack bus will be the node with maximum output power
  (f) If Island continues, do generation demand balancing

Stage 1 of Cascading

(8) For Islands that continue, Run PF

(9) If load flow does not converge, perform load shedding

(10) If there is no load left to shed, Mark Island as dead

(11) Clear the dead Island from current islands

(12) Compute and store apparent power, loading, and voltages for all Islands that continued

Prepare Next Stage

(13) For Islands that continue;

if there are overloaded links, repeat 7-11

elseif there are no more overloaded links

cascading failure stops for the island and Island is considered alive

end

3. RESULTS AND DISCUSSIONS

3.1 Cascading Stage Probabilities

When a pair of lines are disconnected from the system, the effect varies in the propagation of failures. To accurately identify the most vulnerable lines in the IEEE 30 bus system, approximately all possible pair of combinations were used as the random removal process. The system which consists of 41 branches roughly accounted for 817 different pair of combinations. Below are multiple tables that show the probabilities and number of occurrences of line failures per cascading stages after the removal of all possible pair of branch combinations. It is to be noted that there are only four tables because the maximum number of cascading stages that occurred were only four.

Branches	Number of Occurrences	Probability
10	497	0.608323133
[10;22]	30	0.036719706
[10;22;29]	1	0.00122399
[10;22;30]	4	0.004895961
[10;22;30;31]	1	0.00122399
[10;22;32]	1	0.00122399
[10;24]	1	0.00122399
[10;28;32]	1	0.00122399
[10;29]	145	0.17747858
[10;29;30]	11	0.013463892
[10;29;31;32]	2	0.00244798
[10;29;32]	29	0.035495716
[10;30]	47	0.05752754
[10;30;35]	1	0.00122399
[10;32]	3	0.003671971
[10;34;35;37;38;39]	1	0.00122399
[22;40;41]	1	0.00122399
29	1	0.00122399
[29;32;40]	1	0.00122399
[29;40]	2	0.00244798
[29;40;41]	3	0.003671971
36x1 double	1	0.00122399
38x1 double	1	0.00122399
[30;40;41]	2	0.00244798
[31;32;33;35;40]	1	0.00122399
40	4	0.004895961
[40;41]	25	0.030599755

Table 3-1: Probability Matrix Cascading Stage 1

Branches	Number of Occurrences	Probability
[]	79	0.096695226
[17;20;32;40]	1	0.00122399
[21;22;23;30;31;40]	2	0.00244798
[21;22;30;31;40]	1	0.00122399
[21;26;29;31;40;41]	1	0.00122399
[21;30;31;40]	2	0.00244798
[22;23;30;31;40]	2	0.00244798
[22;28;40]	1	0.00122399
[22;30;31;32;40]	1	0.00122399
[22;30;31;32;40;41]	1	0.00122399
[22;30;31;40]	19	0.023255814
[22;40]	1	0.00122399
[23;25;29;32;40;41]	1	0.00122399
[28;31;40;41]	1	0.00122399
[28;40]	20	0.024479804
[28;40;41]	9	0.011015912
29	1	0.00122399
[29;40]	5	0.006119951
[29;40;41]	12	0.014687882
[30;31]	1	0.00122399
[30;31;32]	1	0.00122399
[30;31;40]	3	0.003671971
[30;32;33;35;40]	1	0.00122399
[30;40]	2	0.00244798
[30;40;41]	3	0.003671971
[31;32;33;35;40]	17	0.020807834
[31;33;35;40]	9	0.011015912
[31;40]	3	0.003671971

Table 3-2: Probability Matrix Cascading Stage 2

Branches	Number of Occurrences	Probability
[]	778	0.952264382
12	2	0.00244798
[19;21;30;31;32]	2	0.00244798
21	1	0.00122399
[21;22;30;31]	1	0.00122399
[21;30;31]	2	0.00244798
[21;30;31;32]	2	0.00244798
[21;31]	1	0.00122399
[22;23;24;25;28]	1	0.00122399
[22;23;30;31]	2	0.00244798
[22;23;30;31;32]	2	0.00244798
[22;30;31]	2	0.00244798
[22;30;31;32]	3	0.003671971
28	4	0.004895961
31	4	0.004895961
[31;33;35]	8	0.009791922
32	1	0.00122399
35	1	0.00122399

Table 3-3: Probability Matrix Cascading Stage 3

Branches	Number of Occurrences	Probability
[]	813	0.995104039
12	2	0.00244798
21	2	0.00244798

Table 3-4: Probability Matrix Cascading Stage 4

After observing and analyzing the data, it is apparent that branch 10 is most vulnerable to be attacked following the random initial failures and branches 40 and 41 are most likely to fail in the event branch 10 fails. This data provides useful information because it allows us to take precautionary measures to prevent failures from occurring. Also, the data helps with future improvements in the power grids as in allocating energy storage devices are such highly susceptible locations.

3.2 Influence Graph

"Given a larger number of sequences, we can statistically describe how successive pairs of lines interact in the set of cascades by making a directed graph called the line interaction graph" [2]. In this graph, every line and the consecutively failed line is given a weight based on the probability matrix in the tables above. For instance, given that almost any random pair failures cause line 10 to be disconnected, the probability of line 10 failing given any single line failure is one. Similarly, all other links are given weights to generate a line interaction graph. Below is an illustration of the graph where each dot represents a branch and each line represents a link between the branches.

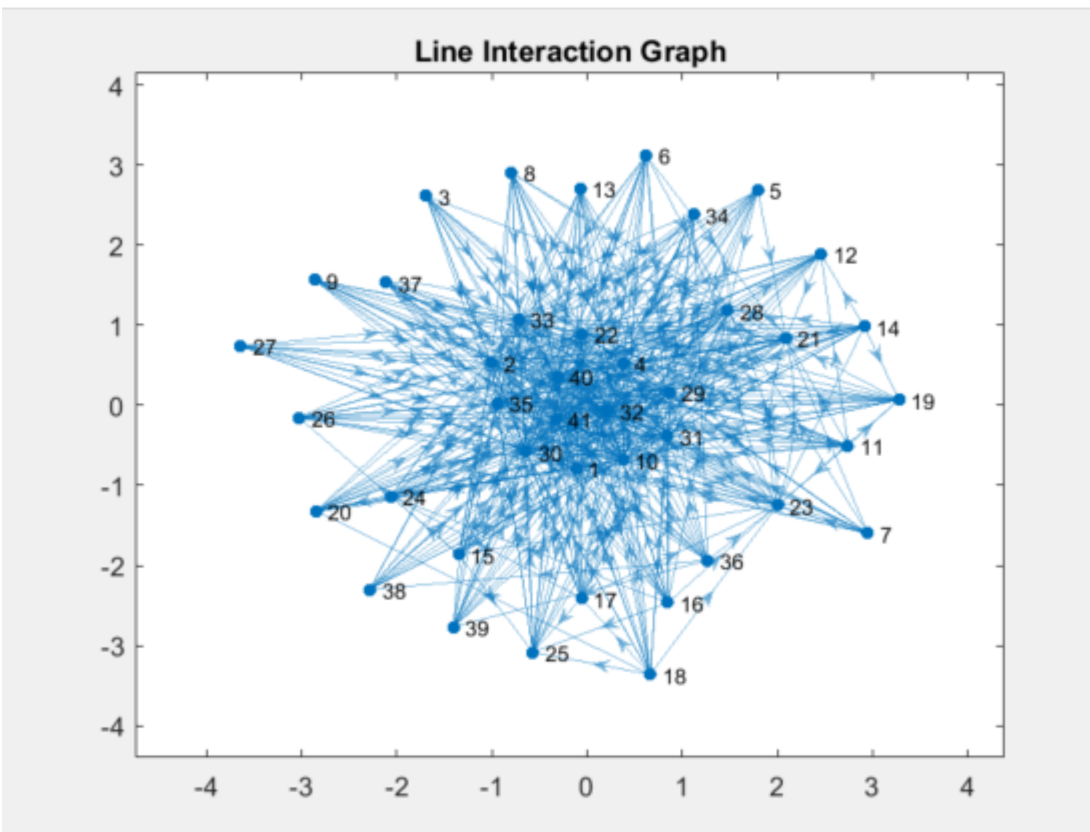

Figure 3-1: Line Interaction Graph

Analyzing the above graph, we can see that the links become darker as you center in. This shows that the more vulnerable lines are grouped in the center as there are more links and as you stretch out, there are less links; hence, the outer lines are less vulnerable.

4.0 CONCLUSION AND FUTURE WORK

A cascading model was developed using MATPOWER power simulation to identify vulnerable lines in the IEEE 30 bus system. The cascading algorithm used was based on the deterministic outage rule where an initial set of line failures causes other lines to fail due to overloading. Various initial failures impact the prorogation of cascading stages and determines subnetworks or islands before yielding a final result.

This model can be used effectively to analyze the strength of a power network to identify causes that may lead to damaging of the system. It also allows us to become more proactive because we can prevent catastrophic failures. Furthermore, it allows for further improvements in the grid as in installations of energy storage devices at vulnerable locations to at least mitigate the failure from spreading. This will allow us to save economic, political, and social uproar.

In future work, we will:

- Include into the model nodes with Distributed Energy Resources (DERs), Energy Storage Systems (ESS), and microgrids.
- Further develop the visualization and presentation of the Influence Graphs.
- Test and validate the proposed model on real distribution networks from the New York City area.

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