Power Grid Network Bangladesh - A Complex Network Study

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ABSTRACT

This study presents the first comprehensive complex network analysis of Bangladesh's power transmission infrastructure, utilizing data from the Power Grid Company of Bangladesh (PGCB). The network, comprising 206 nodes and 312 weighted edges, exhibits a barely scale-free structure with a power law exponent of 2.05 and a low clustering coefficient of 0.055, indicating a hierarchical, tree-like topology. Centrality analysis identifies critical nodes highly vulnerable to targeted disruptions, particularly those with high betweenness centrality. Resilience testing confirms significant susceptibility to fragmentation under targeted attacks. To address these vulnerabilities, we propose and evaluate an algorithm that strategically adds edges between high-betweenness nodes, creating alternative paths. Implementation results demonstrate enhanced robustness against both random and targeted attacks. This research provides actionable insights for strengthening Bangladesh's power transmission infrastructure and underscores the value of complex network analysis in infrastructure planning and resilience enhancement.

KEYWORDS

Power Grid Networks, Complex Networks, Network Analysis, Centrality analysis, Network robustness

1 INTRODUCTION

A power grid is a network of power plants, substations, transformers, transmission lines, and distribution systems that deliver electricity to consumers. In fact, it is the backbone of a nation that efficiently transports electricity from various locations and from various sources to consumers, allowing reliable access to power across a wide area and plays a vital role in managing fluctuation in energy demand. This is why the resilience of such a system is very important. The resilience of a power grid system refers to its ability to withstand, respond to, and recover quickly from disruptive events such as natural disasters, equipment failures, or sudden demand surges. The lack of resilience in a power grid system caused a disastrous situation in many countries. In recent history, Bangladesh has also faced many such disastrous incidents. On October 4, 2022, the national power grid in Bangladesh failed around 2 PM, causing a blackout that affected 75–80% of the country. The blackout was caused by a transmission line tripping in the eastern part of the country. In November 2014, Bangladesh experienced its worst power outage, leaving the entire country without electricity for about 10–12 hours. This outage was considered one of the world's biggest blackouts, affecting around 150 million people. Therefore, a rigorous study of Bangladesh's power grid network remains an important topic of research.

Power grid infrastructure analysis through complex network theory has emerged as a crucial approach for understanding system vulnerabilities and enhancing resilience. Foundational studies like Pagani et al. [13] established the framework for analyzing power grids as complex networks. Arianos et al. [3] advanced this by introducing specific vulnerability measures such as *efficiency* and *net-ability*, while Liu et al. [12] developed methods for identifying critical nodes through centrality analysis. Region-specific studies demonstrate how network characteristics vary across different power systems. Espejo et al. [7] analyzed the European grid's topology, focusing on number of lines, characteristic path length, network diameters and global clustering coefficients among countries. Kim et al. [11] examined South Korea's power grid, finding distinct topological features that influence its vulnerability patterns. Das et al. [5, 6] provided valuable methodological approaches for analyzing power systems of West Bengal and Odisha - two states of India. Research specific to Bangladesh's power infrastructure remains limited. Hasnain et al. [1] conducted a preliminary vulnerability analysis, but lacked comprehensive network metrics. Jamal et al. [10] focused on smart grid implementation prospects rather than topological analysis. This gap in detailed complex network analysis of Bangladesh's power grid underlies the significance of the current study.

To address the existing research gap in power grid analysis, this study investigates the power grid network of Bangladesh through the lens of complex network theory. We conduct a detailed examination of various network properties, including node and edge features, degree distribution, centrality metrics, clustering analysis, and robustness evaluation. Our findings reveal critical structural insights and vulnerabilities within the grid. The network exhibits a barely scale-free topology ($\gamma = 2.05$) and a low clustering coefficient (0.055), indicating a hierarchical, tree-like structure. While this configuration is efficient for power distribution, it remains highly susceptible to targeted disruptions. To mitigate these vulnerabilities, we propose an algorithm designed to enhance the robustness of the network against random failures. This comprehensive study offers valuable contributions toward improving the resilience of Bangladesh's power grid infrastructure.

The rest of the paper is organized as followed. In Section 2 we define the terminologies used throughout the paper. In Section 3 we describe how the data is aquired and preprocessed. In Section 4, we perform in-depth analysis of the network. Section 5 contains a simple algorithm to increase resilience of the network. Finally, Section 6 is the conclusion.

2 PRELIMINARIES

In this section, we define the terminologies used throughout the paper. For basic terms and terminologies of network science, we refer to [4].

A network (graph) is called textitscale-free if the degree of the vertices obeys the power-law distribution. Thus $P(k) \propto k^{-\gamma}$ where γ is a constant, and in a scale-free network, $2 < \gamma < 3$.
Global Clustering Coefficient is the fraction of closed triplets over all triplets in the network. *Assortativity* is the Pearson correlation coefficient of degrees between pairs of linked nodes. It measures the tendency of nodes to connect with similar-degree nodes. *Community* is a group of nodes within a network that are densely connected internally but sparsely connected to the rest of the network. *Betweenness Centrality:* of a node measures the fraction of shortest paths that pass through a given node. *Closeness Centrality:* is the reciprocal of the average shortest path distance from a node to all other nodes. *Degree Centrality:* of a node is the number of edges connected to a node. *Robustness* The ability of a network to maintain its structural and functional properties under failures or attacks.

3 DATA ACQUISITION AND PREPROCESSING

In this section, we describe the data acquisition, preprocessing, and network representation processes.We obtained two official documents from the Power Grid Company of Bangladesh (PGCB) containing detailed information on substations and transmission lines [15, 16]. These documents were in semi-structured PDF format with tabular data spanning multiple pages. Challenges included missing values, inconsistent naming conventions, and duplicate entries.

To convert the data into a machine-readable format, we utilized Claude 3.5 Sonnet [2], a large language model (LLM), for data extraction and parsing. The PDF files were processed using prompts specifying the desired CSV output format, accompanied by few-shot examples to guide the model in producing structured results. This process generated two CSV files, representing substations and transmission lines, respectively.

Subsequent manual preprocessing was necessary to address inconsistencies and ensure data quality. This included the resolution of naming variations such as "Barishal" vs. "Barisal," "Bogra" vs. "Bogura," and "Comilla North" vs. "Comilla (N)." Additionally, entries like "HVDC-Ishurdi" and "Ishurdi HVDC" were standardized to maintain consistency. The preprocessing process required extensive manual effort, involving 133 edits in the All_Substations.csv file and 278 corrections in the Transmission_Lines.csv file. In total, over 10 man-hours were invested in data cleaning to ensure accuracy and consistency for further analysis. This meticulous approach was essential to derive meaningful insights from the complex network analysis.

After preprocessing, a node represents either a power plant or a substation, while an edge represents a transmission line. The edges are undirected and weighted, with the edge weight indicating the distance between adjacent nodes.

4 NETWORK ANALYSIS

In this section, we provide our analysis of the network. We used Python libraries Pandas [14] and NetworkX [8] for analyzing the network and Matplotlib [9] for visualizations.

4.1 Node Analysis

The power system contains 205 grid substations with varying transformer capacities distributed across different grid circles and Grid Maintenance Divisions (GMDs). Analysis of the substation data reveals several key insights about the network's node characteristics.

Capacity Distribution: The transformer capacities show significant variation across substations, ranging from 20 MVA to 2250 MVA. The largest substations by capacity are Bogura (W) and Madunaghat at 2250 MVA each, followed by Aminbazar at 1885 MVA. The capacity distribution shows a right-skewed pattern, with most substations having capacities below 500 MVA and fewer high-capacity nodes. Figure 1 illustrates the capacity distribution in a histogram.

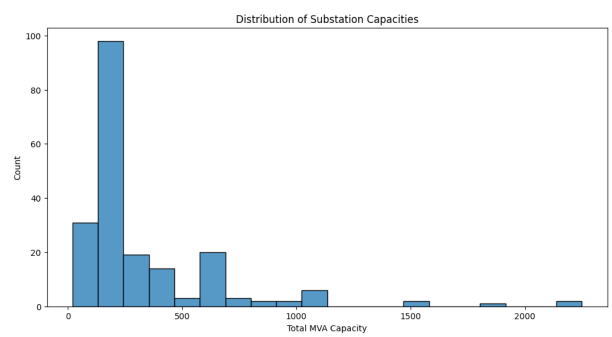

Figure 1: Distribution of substation capacities showing a right-skewed pattern. Most substations have capacities below 500 MVA, with fewer high-capacity nodes above 1000 MVA. This distribution reflects the hierarchical nature of the power system, with a small number of large substations serving as major transmission hubs.

Geographic Distribution: The substations are organized into seven major grid circles: Dhaka (North), Dhaka (South), Bogura, Khulna, Chattogram, Cumilla, and HVDC. The Dhaka region (North and South combined) has the highest total installed capacity at approximately 26,705 MVA across 75 substations. This is followed by Bogura (10,896 MVA), Khulna (10,083 MVA), and Chattogram (9,130 MVA).

GMD-wise Analysis: At a more granular level, the substations are managed by 25 Grid Maintenance Divisions (GMDs). The analysis shows that:

- Dhaka (E) GMD has the highest mean substation capacity at 387.5 MVA
- Dhaka (C) manages fewer but larger substations with a mean capacity of 472.5 MVA
- Khulna (N) and Aricha GMDs have lower mean capacities at 157.4 MVA and 175 MVA, respectively

- The number of substations per GMD varies from 2 (Narsingdi, Aricha) to 12 (CTG-N)

This node distribution pattern reflects the power system's design to meet varying regional demands, with higher capacities concentrated in major load centers like Dhaka while maintaining broader geographic coverage through smaller substations in other regions.

4.2 Edge Analysis

The power transmission network comprises 307 transmission lines with varying voltage levels and circuit configurations. Analysis of these edges reveals key characteristics about the network's transmission infrastructure.

Voltage Distribution: The network operates at three primary voltage levels: 132 kV, 230 kV, and 400 kV. The 132 kV lines dominate the network, accounting for 71.3% (219 lines) of total connections, followed by 230 kV lines at 17.3% (53 lines), and 400 kV lines at 11.4% (35 lines). This hierarchical voltage structure reflects the standard power transmission design where lower voltage lines handle regional distribution while higher voltage lines serve as interstate corridors.

Circuit Configuration: The network employs three circuit types: double, single, and four-circuit lines. Double-circuit lines are most prevalent, comprising 64.2% (197 lines) of the network, followed by single-circuit at 27% (83 lines), and four-circuit at 8.8% (27 lines). This preference for double-circuit configurations provides improved reliability through redundancy while balancing construction costs.

Line Lengths: The transmission lines exhibit significant variation in length:

- The average line length is 28 km, with a standard deviation of 32.6 km
- The shortest connection is 0.12 km while the longest spans 217.2 km
- 75% of lines are shorter than 41.75 km, indicating a predominance of shorter regional connections
- Higher voltage lines tend to have greater lengths, with 400 kV lines averaging 70.9 km compared to 40.5 km for 132 kV lines

The shorter line lengths (especially for 132 kV) reflect the network's emphasis on regional distribution, while the longer 400 kV lines are necessary for efficiently transporting large amounts of power over long distances between major nodes. The right-skewed distribution is typical in transmission networks, where many connections are relatively short, and a few lines span large distances.

Relationship between line voltage & length: The voltage of edges and their length in kilometer distribution provides some insights. Figure 3 shows that high voltage lines tend to be longer than lower voltage connections.

In summary, the edge analysis demonstrates a hierarchical structure with numerous shorter, lower-voltage lines handling regional distribution, complemented by fewer but longer high-voltage lines for bulk power transfer between major nodes.

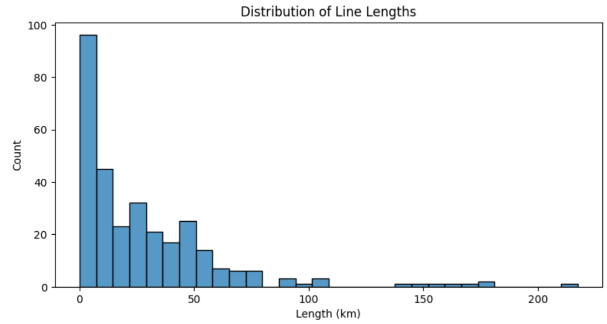

Figure 2: Histogram showing right-skewed distribution of line lengths

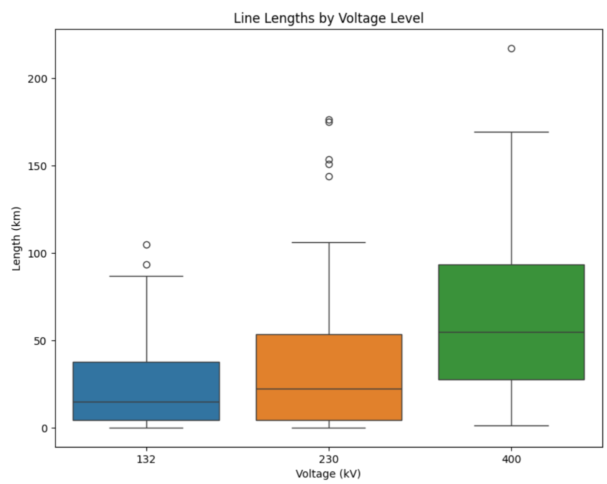

Figure 3: Distribution of line lengths and their relationship with voltage levels. Box plot demonstrating increasing median lengths with voltage levels.

4.3 Network Characteristics

In this section we present the power grid networks's distinctive topological characteristics revealed through complex network analysis metrics. The degree distribution, clustering-coefficient, centrality measures, robustness, and its implications for grid operation and reliability are examined below.

Degree Distribution: The network shows a heavy-tailed degree distribution with an average degree of 2.21, indicating a sparse connectivity pattern typical of power grids. The degree distribution follows a power law with exponent $\gamma = 2.05$ ($R^2 = 0.942$, p-value = 7.192e-07), as shown in Figures 4 and 5.

Network Metrics: The grid exhibits several characteristic features:

- Low global clustering coefficient (0.055) reflecting minimal triangular connections due to the hierarchical tree-like structure
- Near-zero assortativity (0.009) indicating neutral mixing patterns in node connections. This is because a large hub

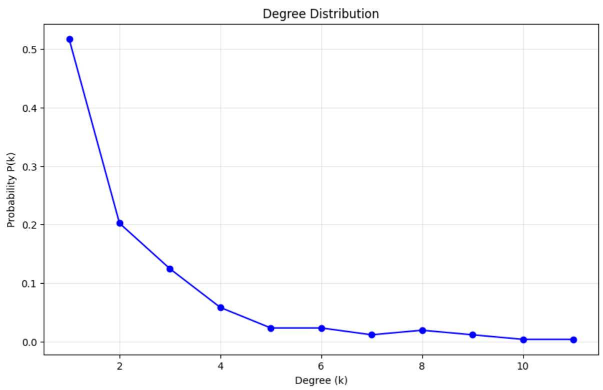

Figure 4: Degree distribution showing the probability of nodes having k connections. The distribution reveals that most substations have few connections, with decreasing probability for higher degrees.

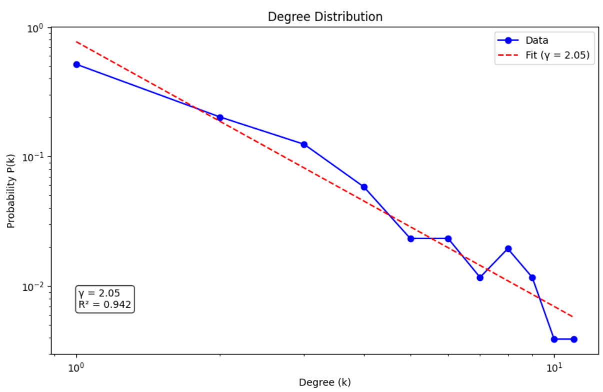

Figure 5: Log-log plot of degree distribution with power law fit (γ = 2.05). The relatively good fit (R^2 = 0.942) suggests a barely scale-free network structure, though the exponent is lower than typical power grids.

doesn't have any additional preference to or against any other large hub.

- Fragmented topology with 24 connected components, the largest containing 208 stations with average line length of 30.47 km

Centrality Analysis: Key substations were identified through various centrality measures:

- Betweenness centrality highlights critical transmission hubs: Meghnaghat (0.196), Comilla N (0.187), and Ashuganj (0.177)
- Closeness centrality reveals similar central nodes: Meghnaghat (0.200), Ghorasal (0.196), and Comilla N (0.195)
- Degree centrality identifies major connection points: Haripur (0.043), Madunaghat (0.039), and Aminbazar (0.035)

Robustness Analysis: The network's resilience was evaluated through random and targeted node removal, as shown in Figure 6. The analysis reveals:

- High vulnerability to targeted attacks on high-betweenness nodes
- Moderate resilience against degree-based attacks
- Strong robustness against random failures

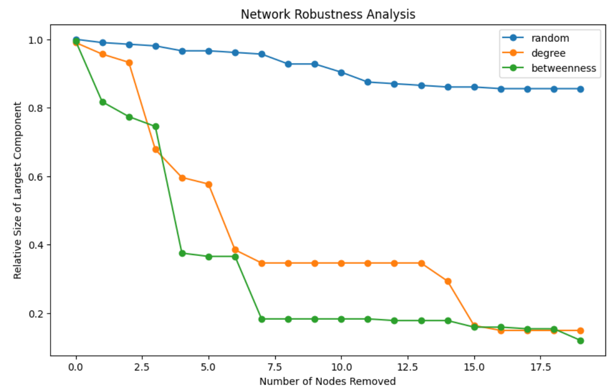

Figure 6: Network robustness analysis comparing random, degree-based, and betweenness-based node removal strategies. The betweenness-based attack shows highest effectiveness in network fragmentation, indicating vulnerability of central transmission hubs.

This topology suggests a network designed for efficient power transmission rather than redundancy, with critical hubs that require particular attention in grid maintenance and security strategies.

5 ENHANCING NETWORK RESILIENCE

In this section, we provide an algorithm to increase the robustness of the existing power grid network.

First, we identify the top k nodes with the highest betweenness centrality. These nodes are crucial for maintaining network connectivity as they frequently lie on the shortest paths between other node pairs. Strengthening the connections around these key nodes helps make the network more resilient to random failures or targeted attacks. Next, for each selected node, we identify its non-leaf neighbors, which are neighbors with a degree greater than two. This step ensures that we focus on reinforcing connections around structurally significant nodes rather than peripheral ones. After identifying the relevant neighbors, we look for missing edges between distinct pairs of these neighbors. If an edge does not already exist between two nodes, we consider it a potential new connection. We then select the shortest missing edge based on distance and add it to the network. By choosing the shortest edge, we minimize the cost of reinforcement while maximizing the network's connectivity. This process continues until all k nodes are evaluated and edges are added as necessary. The algorithm ultimately returns an enhanced version of the original network with improved robustness. The algorithm is formally described in Algorithm 1.

After applying this algorithm, by only adding 6 new edges, we increase the network robustness to random attacks observed in Figure 7.

Algorithm 1: Network Robustness Enhancement

Data: Graph $G(V, E)$, number of central nodes k
Result: Enhanced network $G'(V, E')$
// Select nodes with highest betweenness
; $C \leftarrow \text{TopKNodesByBetweenness}(G, k)$;
foreach $u \in C$ **do**
  // Get non-leaf neighbors
  $N^{+}(u) \leftarrow \{v \in N(u) \mid \deg(v) > 2\}$;
  // Get missing edge set
  $M \leftarrow \emptyset$; **foreach** *distinct pair* $v_i, v_j \in N^{+}(u)$ **do**
    if $(v_i, v_j) \notin E$ **then**
      $M \leftarrow M \cup \{(v_i, v_j)\}$;
  // Add edge to graph
  if $M \neq \emptyset$ **then**
    // Find shortest missing edge
    ; $(v_i^*, v_j^*) \leftarrow \arg\min_{(v_i, v_j) \in M} d(v_i, v_j)$;
    $E \leftarrow E \cup \{(v_i^*, v_j^*)\}$;
return $G'(V, E)$

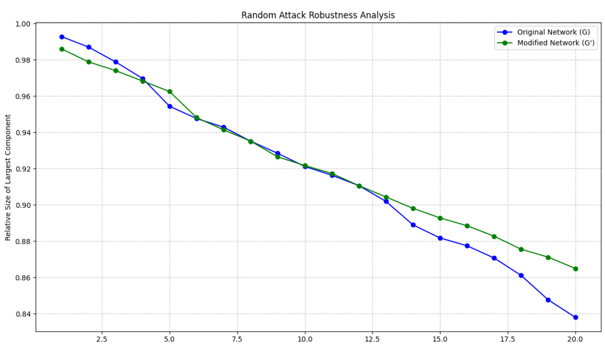

Figure 7: Increasing the robustness of the network to random attack by adding 6 minimal possible new edges

6 CONCLUSION

This study provides a comprehensive complex network analysis of Bangladesh's power grid, revealing critical structural insights and vulnerabilities. The network's barely scale-free characteristics ($\gamma = 2.05$) and low clustering coefficient (0.055) underscore a hierarchical, tree-like topology that, while efficient for power distribution, heightens vulnerability to targeted disruptions. To address these vulnerabilities, we proposed and validated a strategic edge-addition algorithm that significantly enhances network resilience by creating alternative paths between critical nodes. The improved robustness against both random and targeted attacks underscores the practical value of this approach for infrastructure planning. Future research should integrate consumption data, conduct spatial analyses, and compare the network with power grids in other developing nations to provide more comprehensive insights. Collaborating with PGCB on these extensions would unlock additional operational parameters crucial for informed infrastructure planning.

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A CODE AVAILABILITY

The code used for analysis can be found at: https://github.com/MahdeeMushfiqueKamal/Power-Grid-Network-Analysis