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Original Research/Review

Power grid failure simulations using PLANS and NetworkX combined with Monte Carlo algorithm

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Abstract

Using the Monte-Carlo method, the susceptibility of the power network to node failures was examined, both in terms of the use of specialized software that is used in the power industry and tools for analyzing complex network graphs. The use of specialized software in the power industry provides specific insights into the functioning of the power network, while tools for analyzing complex network graphs offer a broader perspective on network behavior. The obtained results and the observed analogy between the results of the analysis carried out in specialized software and in the tool for graph analysis of complex networks are presented. It has been shown that the obtained results are convergent for both software packages, although their application focuses on slightly different aspects of the system's functioning.

Keywords: simulations, complex networks, graphs, power engineering, monte-carlo.

1. Introduction

Simulation of power grid failures is an important tool that enables the study of power systems' behaviour during emergency situations. Conducting simulations allows for understanding how changes in the network can affect its stability, as well as identifying potential weak points and issues that require improvement.

In this article, author focuses on the use of two popular tools for simulating power grids: the PLANS software and the NetworkX library in Python, combining them with Monte Carlo method. PLANS is a tool for simulating power grids, which allows for modelling, simulating, and analysing power grids. On the other hand, NetworkX is a Python library that enables the creation and manipulation of graphs, which is particularly useful in analysing power grids. Article presents the process of modelling a power grid network in PLANs and analyses its stability before and after a failure. Author then demonstrates how the NetworkX library can be used to model the same network in Python and how to use algorithms to analyse its stability. In both cases Monte Carlo method is used to make sure the obtained results are reliable. The article presents different approaches to modelling and analysing power grids and compares their advantages and disadvantages. Moreover, in the context of simulating failures, it demonstrates the benefits of using tools such as PLANS and NetworkX in research on power systems.

1.1. Recent research

In recent years, a lot of research has been done on power grids in the context of complex network theory. In recent work [21], authors presented new mathematical models and algorithms for power grid modelling, analysis, and computation. The publication focuses on the use of complex network theory to solve problems related to load balancing, cost minimization and improving grid stability. Another paper

[2] describes a comprehensive analysis of electric power networks using the tools of complex network theory. The publication presents several techniques, such as centrality, community, and correlation analysis, to better understand the behaviour and properties of power networks. Squartini and Garlaschelli in their paper [20] illustrate various challenges in modelling power grids as complex networks. The authors emphasize the importance of accurately characterizing network components, such as transmission lines and power sources, to obtain more accurate power grid models. Xiangyu [22] and Moradiamani [14] greatly explain modern complex networks resilience both in structural and operational aspects. Nie in his work [16] developed complex network model from China power grid and concluded, that renewable energy and micro-grid and electricity markets are the direct cause of structural changes occurring in China's power grid and in order to achieve interconnections in the future, it is important to give greater consideration to the security and coordination of power grids that span multiple regions.

All these publications emphasize the importance of using complex network theory to model and analyse power grids. The theory provides a better understanding of the complex relationships between grid elements and how their properties affect grid stability and performance. Further research in this area can help improve the management and design of electric power grids and increase their efficiency and reliability. None of these works, however, addresses the topic in the way this article does, where strictly specialized software and a library for analysing mathematical graphs are compared.

2. Complex systems and networks

The theory of systems and complex networks is a relatively new branch of science that emerged from a growing interest in research on complex systems, such as social networks, transportation networks, biological and technological systems. Both fields of research come from the fields of mathematics and physics, and their development is associated with progress in the field of computer science and communication. The history of systems theory dates to the second half of the 20th century, when a new branch of mathematics – control theory – was created, which dealt with the design of automatic control systems. This theory became an inspiration for the developing theory of systems [5], which allowed for describing complex systems using mathematical models. In the 1960s and 1970s, the theory of systems developed rapidly, and its application covered not only automation but also a wide range of other fields, such as economics, social sciences, and biology.

The development of systems and complex networks theory has enabled more effective problem-solving and better understanding of complex processes occurring in nature and society. Newman [15] suggests that modelling such networks is often based on an abstracted graph $G = \{V, E\}$ containing n nodes (vertices $V = \{v_1, v_2, \ldots, v_n\}$) connected by m edges $E = \{e_1, e_2, \ldots, e_m\}$. The topology of the graph is represented as an $n \times n$ adjacency matrix $A = \{a_{ij}\}$, where each a_{ij} element is 1 (when vertices i and j are connected by a graph edge) or 0 (if vertices i and j are not connected). The graph can be weighted, where each edge between nodes i and j has a number ℓ_{ij} representing physical distances, cost of transport, communication time, velocity of a chemical reaction, or edge throughput, or unweighted, where we are only interested in the fact of a connection. For any two nodes in the graph, one can calculate the shortest path length d_{ij} as the smallest sum of ℓ_{ij} between all possible paths in the graph between i and j, $d_{ij} \geq \ell_{ij}$, $\forall\, i \neq j$. The efficiency $\varepsilon_{ij} = 1/d_{ij}$, $\forall\, i \neq j$ can also be defined. If $d_{ij} = \infty$, then $\varepsilon_{ij} = 0$.

The short paths between i and j nodes mean high efficiency, and over the whole graph, it can be defined as, according to Latora [11] and Barabasi [3]:

$$\boldsymbol{E(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} 1/d_{ij}}. \tag{1}$$

Given the Equation (1), where d_{ij} is the shortest path between nodes i and j, it is easy to calculate the average efficiency of the whole network. There are two types of network efficiency: global and local. Global one (defined by Equation (1)) refers to the entire network, but for each vertex i there is a possibility to define the local efficiency $E_{loc}(G_i)$, which is the average efficiency of the local subgraphs and defines the fault tolerance of the whole system; it also indicates the efficient communication between the first neighbours of node i when i is removed. It can also become the cost of the entire network, as well as the cost of energy transmission [11]. If the efficiency falls, then the cost rises (for example: in transporting information).

The existence of connections between the nearest neighbors of a vertex i can be described by the clustering coefficient *C*. Suppose that a vertex in the network has k_i edges that connect this vertex to other k_i nodes. All these nodes are node *i* neighbours [6]:

$$\binom{k_i}{2} = \frac{k_i(k_i-1)}{2}. \tag{2}$$

According to [6], the clustering coefficient C_i of node *i* is defined as the ratio between the number E_i of edges that exist among these k_i nodes and the total possible number of node connections

$$C_i = \frac{2E_i}{k_i(k_i-1)}. \tag{3}$$

Going further, the clustering coefficient of a vertex can be defined as the ratio of 3-cliques in which this vertex participates. The clustering coefficient value for the whole network is the average of C_i over all *i*. The distance between two vertices in a network is the number of edges between them in the shortest path. The maximum of all shortest path lengths is the network diameter. The average path length ℓ can be used to measure the dispersal of the network [11]

$$\ell = \langle \ell_{ij} \rangle = \left(\frac{1}{N(N-1)}\right) \sum_{i \neq j \notin V} \ell_{ij}. \tag{4}$$

3. Monte Carlo

The Monte Carlo method is a numerical technique used to simulate random phenomena. The method was named after the Monte Carlo casino, where it was used to simulate games of chance in the 1940s. According to the old paper by Metropolis and Ulam [12], the first concepts of the Monte Carlo method emerged in the 1940s during work on the Manhattan Project to build an atomic bomb. During this work, scientists needed a way to simulate the processes in a nuclear reactor but did not have enough mathematical knowledge to solve the equations analytically. That's when the idea of using Monte Carlo simulation was born, which involved generating random samples from probability distributions and then calculating an average value based on those samples. The Monte Carlo method has also been used in physics, including the study of thermal and quantum phenomena. In 1949, Stanislaw Ulam, one of the creators of the Monte Carlo method, used it to solve the problem of neutron diffusion in a nuclear reactor, which enabled the development of nuclear power. Today, the Monte Carlo method is used in many fields of science, engineering and industry, including finance, biology, chemistry, computer science, medicine and other fields where simulations of random phenomena are needed.

3.1. Monte Carlo and power grids

Using the Monte Carlo method and scripts that automate calculations, simulations were carried out for various scenarios in which individual network nodes were turned off. Such tests were carried out multiple times for different cases so that the final results would be reliable and averaged. However, in the case of power grids, such a test method cannot always show the actual possible behavior of the network since it is important to be aware that we do not have all the electrical parameters of the network when simulated in PLANS.

In the case of tests carried out on data in the form of a graph, author considers only the topological structure of the network, since the graph form itself has no way of describing the features and parameters strictly belonging to the electrical nature of the structure under test.

4. Source data

Apart on the problems related to IT tools supporting power engineering modeling and simulation another problem is the lack of real power grid networks data. Having in mind that for each country power grid system is important element of its critical infrastructure, many specific and detailed data aren't and cannot be available. Thus, for calculation experiments we are forced to use some existing data sets. The original IEEE118-Bus System was derived from a portion of the American Electric Power

System as of 1962 (see Fig. 1). It is a basic power systems test case that was considered in many papers during last 60 years (for example [17], [4], [18] and [2]). According to Kuznecovs' work [10], the IEEE118-Bus test case data was digitized manually and become a standard test case for electric utilities industry.

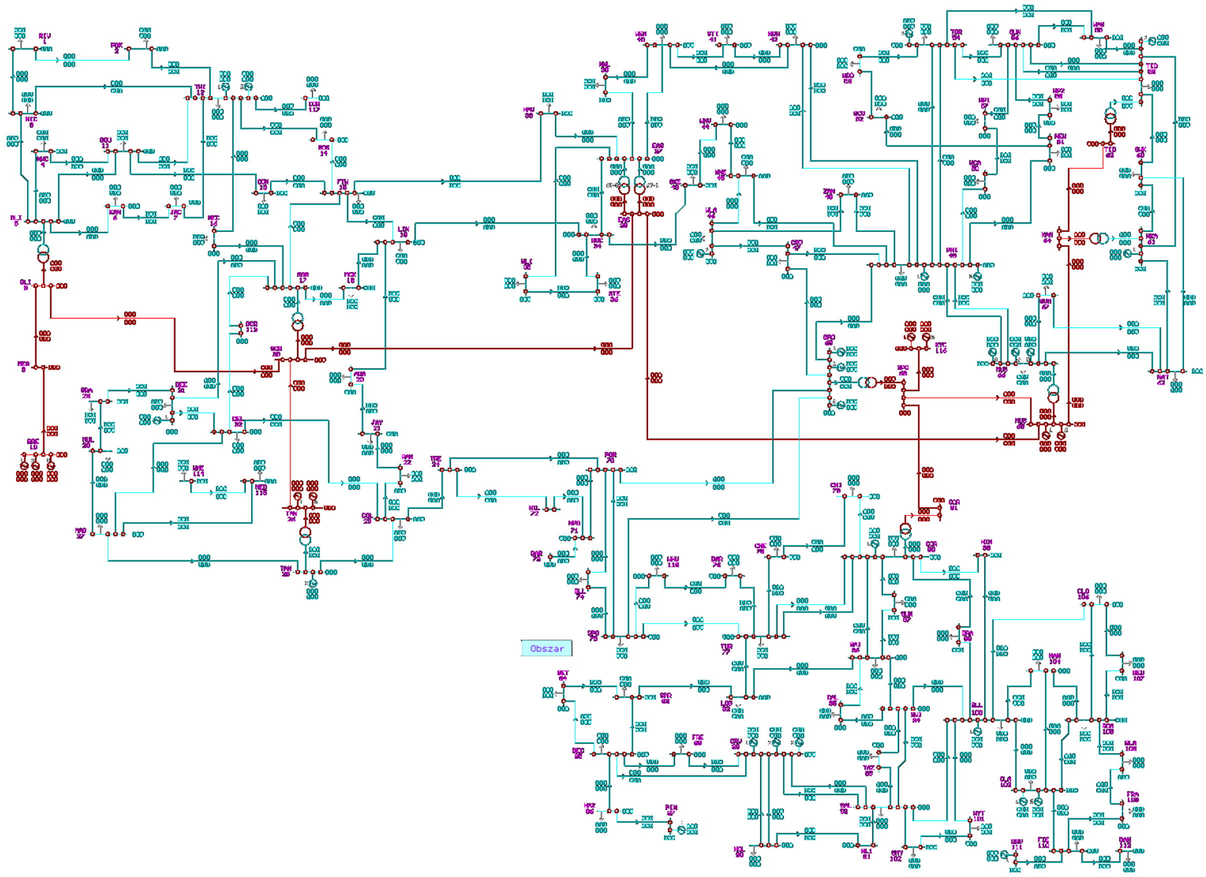

Fig. 1: Power grid model used in analysis. Own illustration made in PLANS.

5. PLANS

PLANS (see Fig. 2) is a Polish software tool for simulating power grids. It is used in the electric industry for over 20 years. This program allows the user to model various failure scenarios, such as line overloading, short circuit, equipment damage, etc., and to analyse the effects of these failures on the entire network. Within the PLANS program, the user can create models of power grids that include information about the location and characteristics of individual grid elements, such as transmission lines, transformers, generators, etc. The program also allows the user to enter various network parameters, such as voltage, current, impedance and other characteristic parameters of network elements. PLANS natively uses proprietary KDM format, described further by Kanicki [7].

Once the power grid model is entered, PLANS allows the program to simulate various failure scenarios, such as line overload, short circuit, equipment failure, etc. The program analyses the effects of these failures on the entire network, calculating, among other things, the values of current, voltage and power in individual network elements, as well as identifying the causes and locations of failures. Thanks to the documentation by program authors [23], a script can be written in the proprietary JMP language that automates computational activities, which allowed to perform simulations for this paper with multiple variants and iterations.

5.1. Case study – PLANS

PLANS utilizes the Newton-Raphson algorithm to calculate internal network convergence during iterative calculations, resulting in fast calculation results. Sereeter describes this algorithm in detail [19]. To employ Monte Carlo with the Newton-Raphson methods, the process begins by loading data on the power system being studied and checking its consistency. Next, the algorithm selects a variable N, which indicates the number of random nodes chosen for simulation. Using the Newton-Raphson method, power flows are calculated, and data consistency and correctness are checked again. If the algorithm has not completed the required number of simulation calculations for a given N, the system state is restored, and the algorithm performs another simulation with a different N. Once the required number of repetitions has been performed, the algorithm checks whether the last N is equal to the maximum number of assumed failed nodes. If it is, the calculation concludes. If not, the algorithm increments the variable N, restores the system to the initial state, and returns to the simulation of failure for N random nodes.

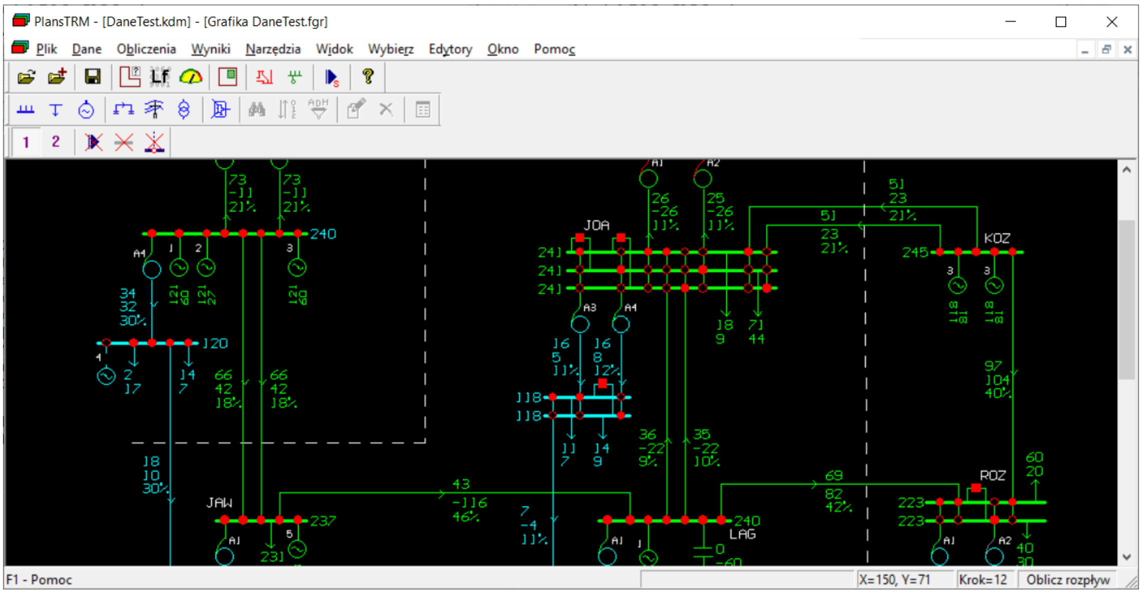

Fig. 2: PLANS main window. Own illustration.

To calculate this data, simulations were conducted where one to five nodes were progressively removed from the network. Each simulation was repeated 1000 times to obtain reliable and averaged results. During the simulations, PLANS attempted to compute results based on the remaining nodes, and the percentage of cases where it failed to do so was calculated for each number of removed nodes. The resulting failure rates were then tabulated in Table 1, providing insights into the network's vulnerability to node failures and the likelihood of computational failures in PLANS simulations as the number of removed nodes increased.

Table 1: Graph simulation results (NetworkX). Author’s calculations.

Failed nodes	**1**	**2**	**3**	**4**	**5**
% of grid system failures	94.94 %	98.57 %	99.08 %	99.95 %	100 %

Table 1 indicates the percentage of cases in which PLANS was unable to compute results for n nodes randomly removed from the grid. It is notable that even the failure of a single node in PLANS simulations often resulted in the entire network being unable to function (as shown by the more than 94% failure rate in Table 1). This is due to the energy balance algorithm being unable to stabilize this parameter, leading to the physical structure of the grid being unable to operate as well. Table 1 highlights the significant impact of node failures on the network's functionality and emphasizes the contrast between PLANS simulations and the behaviour observed in the analysed graph of the complex grid, as discussed in more detail in Section 6.

6. NetworkX

NetworkX is a Python library for creating, manipulating, and studying graphs and complex networks. The library provides many functions and tools for modelling and analysing different types of graphs, such as directed, undirected, weighted, and unweighted graphs, bipartite graphs, graphs with vertex and edge labels, etc. NetworkX is a popular library in fields such as social network analysis, network biology, data science, economics, social sciences, and other fields involving complex networks, used in many works, for example by Kollu [8] or Kurniawan [9]. NetworkX applications include, but are not limited to social network modelling, biological, transportation, financial and Internet network analysis.

6.1. Case study - NetworkX

In this Section, the power grid data (based on the 220kV and 400 kV connections from original test model) obtained from modified IEEE 118 bus modified for Poland conditions (data from Fig. 1 has been entered manually into the yEd software and finally imported into the NetworkX software package). The data was analysed in the form of a mathematical graph. In this case study, each power grid node represents a separate vertex of the mathematical graph. The connections between nodes became graph edges. This means that the network of graph connections is the same as the real power grid model in PLANS.

To ensure compatibility with the simulations conducted in PLANS, the cases analysed ranged from 1 to 5 nodes being randomly removed from the network. Each iteration of node removal was repeated 1000 times to ensure robust and reliable results. The purpose of this extensive analysis was to capture a comprehensive understanding of the network's behaviour and assess its vulnerability under different failure scenarios.

The code implemented in the script aimed to compute and analyse various parameters characterizing the structure of the power grid. The analysis focused on evaluating the impact of node failures on the network's performance and stability. Notably, the analysis in PLANS indicated that the structure became unusable when 5 nodes failed, as evidenced by the lack of convergence in Newton's method.

According to the Monte Carlo method random removes of nodes in PLANS were tested and the probability that PLANS will be able to calculate the grid stability was noted.

Despite a decrease of only 4% in the average global efficiency (from an original value of 0.211691 to 0.202462), the minimum local efficiency values show a significant decrease of 40%. This decrease was observed by considering the worst-case scenario for the entire simulation process, similar to the simulation process in PLANS where the lack of network balance makes operation completely impossible. Milanovic (2017) [13] suggests that in power grids, the local efficiency parameter is more crucial to consider in worst-case scenarios. Hence, although the results obtained in PLANS do not directly reflect the decrease in global efficiency, results highlight the importance of evaluating the local efficiency parameter in such situations (see Fig. 4).

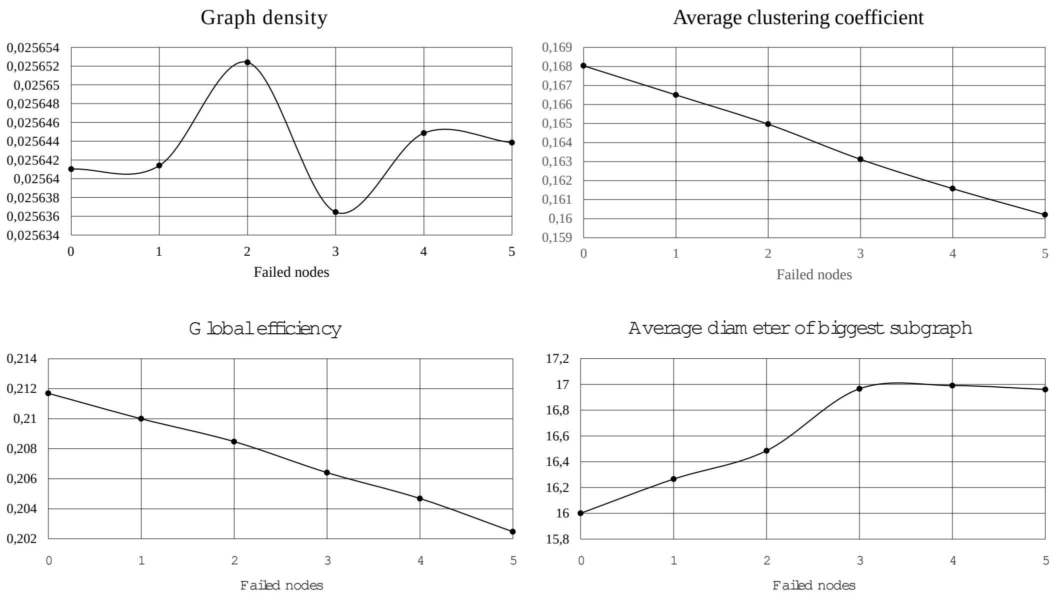

Fig. 3: NetworkX analysis results. Author’s calculations.

The results obtained through NetworkX analysis, as illustrated in Figure 3, indicate that the graph representing the power grid model does not exhibit the same drastic reactions as the original model does during the simulation process. This is evidenced by the parameter values obtained through the NetworkX analysis, which are notably different from those obtained through the PLANS simulation. Of particular note are the values of the local efficiency parameter, which show a significant drop of more than 40%

in the extreme case of five failing nodes (as shown in Figure 4). In contrast, the behaviour of the PLANS model cannot be compared to these values, as the PLANS simulation appears to exhibit a different pattern of degradation in response to node failures, and the behaviour of PLANS model cannot be compared to these values.

The simulation results provide insight into how the transmission structure behaves under different scenarios, revealing that the structure becomes fragmented when three or more nodes fail. This fragmentation can pose a significant challenge for the operation of an electrical network, as it may lead to the isolation of certain nodes or regions of the network, which can result in power outages or other issues. While such fragmentation may not have a significant impact on typical graph parameters in a mathematical graph, it can still be a cause for concern as it can lead to the division of the graph into smaller subgraphs if nodes are removed. This highlights the importance of considering the behaviour of a network under various failure scenarios, rather than solely relying on general graph parameters when assessing the performance and reliability of an electrical network.

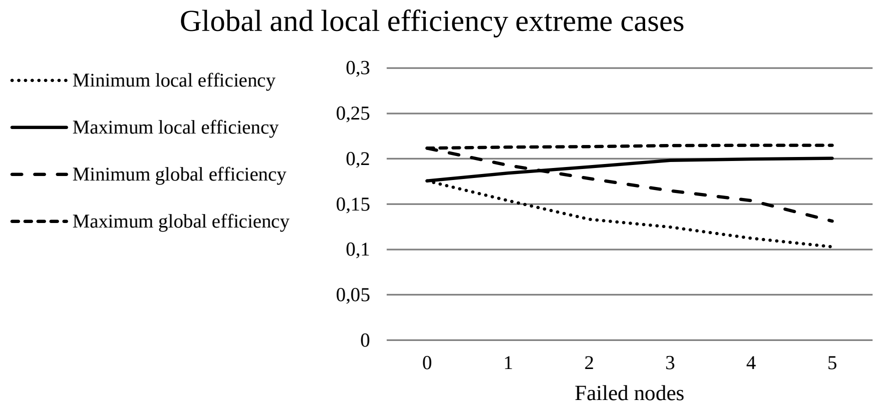

Fig. 4: NetworkX analysis extreme cases. Author’s calculations.

Figure 3 provides insights into the behaviour of the power grid model when analysed as a complex network using NetworkX, while Figure 4 specifically focuses on the local efficiency parameter as an indicator of network performance. Together, these figures enhance our understanding of the power network's behaviour as a complex network, shedding light on its response to node failures and the significance of preserving efficient information exchange within the network structure. However, in the case of a power grid, the separation of transmission system parts can severely affect its operation, as shown by the simulations. Furthermore, the simulations indicate that the system can maintain its operation in only a small fraction of cases, making it imperative to address the issue of node failures in the power grid.

7. Conclusion

This article presents two methods for modelling and analysing power grids in the context of failure simulation: the PLANS software and the NetworkX library in Python. The process of power grid modelling in PLANS software was described, and it showed how the NetworkX library can be used to model the same grid in Python. The comparison was not solely focused on speed but rather on examining the different aspects of the system's functioning that each software package emphasizes. Specialized software used in the power industry often provides comprehensive and domain-specific functionality tailored specifically for analysing power networks. On the other hand, graph analysis tools offer a more generalized approach for analysing complex network structures, which can provide additional insights into the network's behaviour.

The analysed power grid appears to be in good shape from a topological perspective, but a worst-case scenario analysis reveals its topological vulnerability to node failures. The results suggest that this real power grid is not particularly fault-tolerant, making it less suitable for analysis. When running simulations on a graph, some parameters may not experience significant changes throughout the simulation process. This highlights the importance of specialized software designed for narrow areas of application, particularly due to the unique parameters involved. In the context of analysing a power grid, these unique parameters would include the real electrical properties of the nodes and transmission lines. While the PLANS simulation showed high sensitivity to topological changes (such as failures) in the model structure, mathematical graph analysis exhibited comparatively lower sensitivity. This discrepancy reinforces the idea that simulations run on specialized software provide a more comprehensive understanding of the network's internal behaviour, as they can account for characteristic parameters that cannot be represented in a simple complex network graph.

While tools are available to analyse complex electrical power grid networks, it's important to consider worst-case scenarios. This may have limitations when generalized to other situations but is particularly relevant in this case. As demonstrated, topological graph parameters may not appear much concerning, but in the context of a power grid network graph, operation is almost always impossible. With over five times more elements analysed compared to case Milanovic [13], it can be inferred from their findings that the most valuable results from analysing such parameters is a worst-case scenario analysis – as confirmed by PLANS simulations utilizing the Monte Carlo approach.

It is also worth noting here that there are no publicly available models containing the full set of parameters for the PLANS program used and compared in this work. On the one hand, this is due to the fact that PLANS is mainly used in Poland, and on the other hand it is fully understandable and dictated by national security considerations when it comes to the details of the structures of real transmission networks. Although the unavailability of other source networks models could pose a challenge to the breadth of the study, it still provides a significant advancement in comprehending the susceptibility of power networks to failure. The study's findings can guide and inform future research in this field, contributing to the development of more robust and reliable power systems.

Future research in this area could concentrate on the issue of random edge removal, where failures may have varying characteristics in certain instances.

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