

The interconnection exchange and complex systems properties in power grid network

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Abstract. A case study based on the real data obtained from the Polish PSE System Operator of the highest voltages electrical energy network is shown. The data about the interconnection exchange and some complex networks (graphs) parameters were examined, after the removal of selected nodes. This allowed to test selected network parameters and to show that the breakdown of only three nodes in this network can cause significant drop of its average efficiency.

1 Introduction

The concept of complex systems and related theory give many interesting applications in modelling different real systems [1]. One of examples are power systems which can be exposed on different threats even leading to the risk of potential blackouts [2]. In this short paper, the real electrical network as a graph of nodes and edges is shown. Some of this network topological parameters are given and the interconnection exchange as an example of the power system security is shown. Selected parameters of complex networks are calculated and the removal of some network nodes caused by failure was done. This leads to the changes in the whole network topology shown in tables. The most important is the drop of network efficiency and in turn, the increase of transmission costs.

The paper is organized as follows: after the short Introduction in Section 2 we show the complex systems and networks theory. Section 3 gives the shape of the EU-PL electricity exchange system. The analysis of real source data based on Network Workbench and Gephi software packages is given in Section 4. Section 5 shows the paper summary.

2 Complex systems and networks

The idea of complex systems refers to the concept of systems S understood as beings B , which consist of n elements $E = \{e_1, e_2, \dots, e_n\}$, that pose m attributes $A = \{a_1, a_2, \dots, a_m\}$ with k possible long- or short-range relations $R = \{r_1, r_2, \dots, r_k\}$, finally giving $S = B(E, A, R)$ [3,4]. Usually, the definition of complex systems is referred to the Aristotle's rule: the whole is more than the sum of its parts [5].

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Complex systems show many interesting features in both: spatial and temporal domains. Among them there are complex networks of nodes and relations (edges) based on graphs $G = \{V, E\}$ with n nodes (vertices $V = \{v_1, v_2, \dots, v_n\}$) connected by m edges $E = \{e_1, e_2, \dots, e_m\}$. Such graphs are usually characterized by special features. The length of the shortest path d_{ij} calculated as the sum of the ℓ_{ij} distances (paths) between all possible paths in the graph between the nodes i and j , $d_{ij} \geq \ell_{ij}$, $\forall i \neq j$ is usually quite low even then the size of network (its diameter) is big. It can be used to measure the scattering of the network [6]. The parameter defined as $\varepsilon_{ij} = 1/d_{ij}$, $\forall i \neq j$ can represent the network efficiency (if $d_{ij} = \infty$, then $\varepsilon_{ij} = 0$). The high network efficiency is high means low costs of its operation (e.g. costs of energy transmission during the interconnection exchange). If network of vertices has k_i edges that connect each vertex to other k_i nodes then the ratio between the number E_i of edges that exist among these k_i nodes and the number of total possible vertices connections, give the clustering coefficient C_i of node i . For clique $C_i = 1$, for random graphs $C_i \rightarrow 0$, but for complex networks this parameter can vary [7]. Graphs with high value of C are called small worlds.

3 The interconnection exchange between systems

The interconnection exchange is an inseparable element of the power system operation. From the system point of view, it allows, during the high demand, to import energy from another county in order to provide electricity supply to consumers, and to transfer energy to another country when the surplus energy is produced. The existence of such connections significantly increases the energy security of the power system. This is the key future of plans related to the energy independence and energetic security in different countries of the EU (European Union). However, in order to assume that the whole system will be stable one of the key aspects is the quality of the supplied energy. The fluctuations in RMS (root mean square) of voltage value, high harmonic content, or frequency fluctuations [8] should be as low as possible. Moreover, the supply reliability and continuity shown by SAIDI parameter (*System Average Interruption Duration Index*) or SAIFI (*System Average Interruption Frequency Index*) parameter are of great importance [8]. If the topology of power networks nodes connections is resistant to the net damages caused by different random events then the country economy is attractive for investors [9,10]. In Poland the PSE as the National System Operator, is responsible for the reliability of the highest voltages energy networks, while the local Distribution System Operators (DSO) are responsible for the remaining high-, medium-, and low-voltage lines.

Currently, the HVDC bridges are used as interconnections, such as the connection of Poland and Sweden via the Swe-Pol Link sea line, and the HVDC Back-to-Back solution in the connection of the Polish and Lithuanian systems (LitPol Link). These are expensive and often difficult to implement, but they replace traditional solutions (direct AC connections). It turns out, however, that under certain conditions such a transmission is much more advantageous and provides an acceptable return on investment. The HVDC SwePol Link HVDC line, launched in year 2000, provides a combination of Polish and Swedish systems. It is implemented as an undersea cable line that connects two converter stations connected to the Polish and Swedish systems. The connection between the Polish and Lithuanian systems is not a typical HVDC bridge. This connection consists of only one converter station, which connects the systems. This connection has most of the advantages of a typical HVDC bridge and is used when the systems between which the energy exchange is to take place are not synchronized (as in this case). Figure 1 shows the annual energy exchange balance from the European Network of Transmission System Operators for Electricity report and the graph of all energy exchanges in Europe [11].

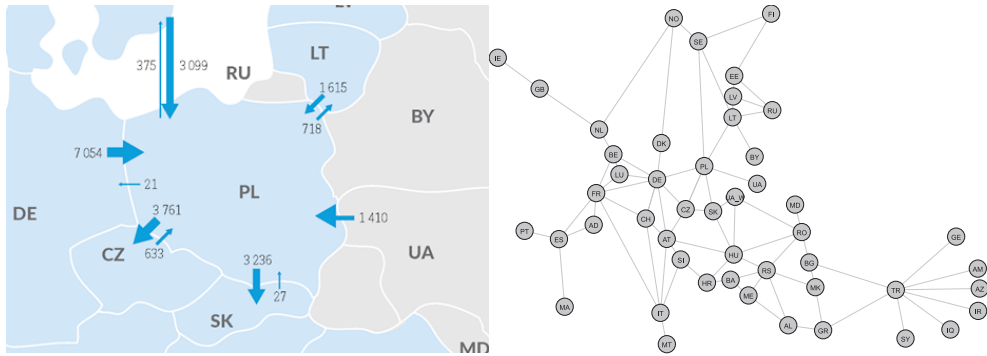


Fig. 1. Electricity exchange between Poland and neighboring countries in GWh (left) and power system interconnection in Europe as a graph of a complex network (right).

Table 1. Shows the energy exchange balance between Poland and neighbouring countries in GWh per year [11].

Table 1. Interconnection system exchange balance data for Poland and its neighbors.

Year \ A [GWh]	Germany	Czech Republic	Slovakia	Ukraine	Lithuania	Sweden	Total balance
2009	-5483	6737	2274	-199	-	-1140	2189
2010	-5167	5364	1415	0	-	-267	1345
2011	-4705	8208	3028	-59	-	-1236	5236
2012	-5877	8754	3498	-1005	-	-2545	2825
2013	-4909	7663	3051	-1029	-	-253	4523
2014	-9153	7158	3496	-685	-	-2984	-2168
2015	-10644	9549	4926	-67	50	-3491	323
2016	-8740	6693	4185	-957	-596	-2587	-2002
2017	-7319	5571	4372	-895	-1042	-2974	-2287
2018	-7033	3128	3209	-1410	-897	-2724	-5727
2019	-7541	-1810	1916	-658	-1401	-1043	-10537

4 Case study

In this Section, the power grid based on PSE data is analyzed (see Fig. 2). All data has been entered into the Gephi software package and the real network consists of 124 vertices and 175 edges. Because of security reasons we are not able to show all details relating to node's physical location. But this graph is enough to examine the complex network features presented in Section 2. The nodes and edges in the graph refer to the physical objects in the transmission network: the nodes are transformers or power distribution stations, the edges are transmission lines.

Figure 3 shows the graphical analysis of the network (from Fig. 2) degree centrality. The count of the number of node connections is converted into a 0...1 scale (the node with the highest number has the value 1 whereas the other ones as the ratio of the largest one). The more blue is the node's color, the more important is the node.

Now we are going to remove some nodes from the network starting from the nodes with the highest degrees. We assume that when it is done this could cause the major negative effects (for example after the terroristic attack). After each removal the graph properties are shown in Table 2.

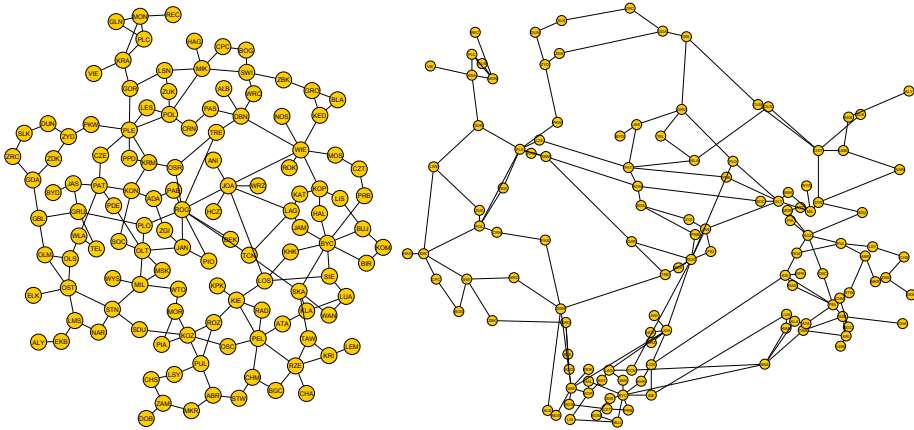


Fig. 2. Graph based on PSE power grid network: organic layout (left) and physical (geographical) layout (right).

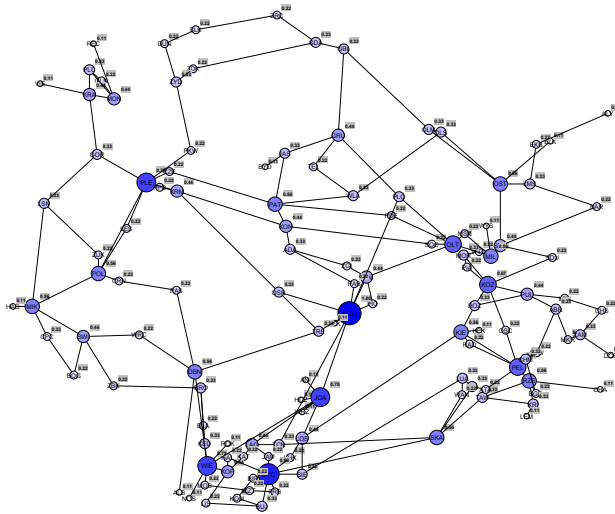


Fig. 3. The graph nodes centrality for Fig. 2 (right).

The description of parameters given in Table 2 can be found in literature, see for example [12]. It can be seen that after the removal of 3 nodes the average network efficiency falls more than 25%.

Table 2. Averaged data from the analysis of the modified graphs.

Number of Removed Nodes	0	1	2	3 (avg.)
Nodes in graph	124	123	122	121
Edges in graph	175	166	158	151
Average vertex degree	2.823	2.699	2.59	2.5
Graph density	0.023	0.022	0.021	0.021
Local efficiency	0.114	0.1	0.101	0.097
Average efficiency	0.216	0.156	0.191	0.171
Average clustering coefficient	0.131	0.117	0.124	0.121
Average path length	5.984	6.8	6.93	7.92
Graph diameter	16	17	17	20.67

5 Summary

This paper shows the data about the energy interconnection exchange and the analysis of complex network parameters of real data obtained from PSE network. The removal of some nodes in analyzed network caused the drop of network average efficiency by more than 25%. The efficiency is related to the cost of whole network operation: high efficiency means low costs. In turn the breakdown, damage or accidents in the nodes of the highest degree can significantly increase the cost of whole network operation. We show that it is enough to break 3 vertices to cause such a situation.

Authors' alphabetical order means equal contribution.

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