RESEARCH PAPER

GIS-ANALYSIS OF THE URAL POWER GRID VULNERABILITY TO THE IMPACT OF SLEET AND WIND

Andrey M. Karpachevskiy[1*], Oksana G. Filippova[1], Pavel E. Kargashin[1]
[1]Lomonosov Moscow State University, Geography faculty, department of cartography and geoinformatics, Leninskie Gory 1, 119991, Moscow, Russia
***Corresponding author:** karpach-am@yandex.ru
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ABSTRACT. In this paper, we describe an experiment of complex power grid structure and wind and sleet mapping of territory using two different network indices: standard edge betweenness centrality and new author's index – electrical grid centrality. Such analysis of the network allows to identify power lines with high load which could be vulnerable elements of the power grid. It is very important for strategic planning of power grids to reduce the risk of accidents by distributing loads across several lines so that they will be able to reserve each other. As a case territory for this research, we took the Ural united power system in Russia which is greatly exposed to different sleet and wind according to the statistics of the power grid operator. The degree of natural hazard consequences could be compensated by the network structure through alternative paths of energy supply or vice versa – increased if they are absent. At the same time, in this paper we consider that power grids have their own features from the graph theory point of view, for example multiple (parallel) edges, branches, different types of vertices. The existing index of edge betweenness centrality does not perfectly cope with them. We compare two indices characterizing power line importance within the system – betweenness centrality and electrical grid centrality and analyze the network structure features together with the spatial distribution of sleet and wind. As a result, we could identify bottlenecks in the study network. According to this study the most vulnerable power lines were detected, for example 500 kV Iriklinskaya CHP – Gazovaya and 500 kV Yuzhnouralskaya CHP-2 – Shagol power lines, that supply big cities such as Chelyabinsk and Orenburg and a bunch of industries around them.

KEY WORDS: GIS-mapping; graph centrality; network analysis; power grid structure; sustainable power supply

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INTRODUCTION

Structural vulnerability of geographical networks

Power grids are complex geographical objects that supply consumers with electricity. Sustainability of energy supply is necessary for the efficient functioning of the economy. The sustainability of any transport network is primarily determined by its configuration and structure (Bugromenko 1987; Tarkhov 2005). The sustainability of a network is its specific property, which allows to identify «bottlenecks» in the power grid, particularly the elements that are most prone to emergency situations. Environmental conditions of a network are equally important because they can cause great damage to the infrastructure. Some natural hazards can lead to emergency situations of local or even national scale. The consequences may become even more threatening when the supplied territory covers multiple settlements, important facilities, etc. However, the degree of damage depends not only on the impact of wind and sleet but also on the spatial structure of the network. For example, an isolated power system of Sakhalin is highly susceptible to cascading failures. It means that the failure of one network element will inevitably lead to the failure of another due to the predominantly dendritic network structure. On August 24, 2016, a short circuit occurred on the 220 kV power transmission line Yuzhno-Sakhalinskaya power plant – Kholmsk due to strong winds and heavy rainfall. As a result, 12 out of 18 municipalities of the island (the central and northern parts) were left without electricity.

GIS tools allow to carry out spatial analysis of the power grid sustainability taking into account natural hazards data. Network analysis methods help to model emergency blackouts and predict their consequences. This article discusses the experience of GIS analysis of the sustainability of the power grid in the Ural united power system (UPS) using network centrality measures and spatial data on natural hazards.

The analysis of the sustainability of transport systems began with an attempt to formalize their representation in a machine-readable form and apply mathematical modelling methods to such data. Sustainability analysis is based on the methods of studying the network structure using graph theory. The analysis of complex networks originated in the early 2000s and has become the new stage of network analysis theory development.

A complex network is a system that has a certain non-trivial relationship of elements (Pagani and Aiello 2013). This direction emerged from narrow research related to the concepts of the random graph, scale-free network and «small world» models. The «random» graph model, or the Erdős-Rényi model, describes the equal probability distribution of graph parameters (Erdős and Rényi 1959). In scale-free networks the number of edges between nodes follows the power-law distribution, thus it is uneven. In «small-world» models the typical distance between two randomly selected vertices grows proportionally to the logarithm of the vertex number in the network (Watts and Strogatz 1998). A schematic representation of the most common network models is shown, for example, in the paper (Hines and Blumsack 2008).

The geographical study and mapping of network structure are more common for road and railroad transport. In 1974 U.S. Federal highways were first studied using the graph model (Garrison 1974). The vertices of that graph were represented by settlements, and the edges by the roads connecting them. Indicators such as Koenig number and topological accessibility were calculated for each vertex. In addition, the characteristics describing the whole graph were calculated – topological diameter and degree of connectivity. The well-known PhD thesis of Kansky contains the transformation principles of the cartographic representation to the graph model. He also developed several indices, known as Kansky indices. These indices characterize the level of network development. In the Soviet Union, graph theory found its application in the Carpathian Ukraine railway network analysis. For example, Shabliy (1976) calculated indices characterizing the network configuration based on graph theory. Also, researchers proposed an index of integral transport accessibility characterizing the efficiency of roads based on graph theory (Bugromenko 1987). The PhD thesis (Chibryakov 2015) presents a method of mapping structural indices for the railway networks study. The author calculated the β index characterizing connectivity of transport networks and mapped it. In addition, the author proposed a topological approach to the generalization of transport networks, which considers topological models of different complexity levels at different mapping scales.

The work (Guimer and Amaral 2014) was devoted to the analysis of more than 3 thousand airports and air transport networks around the world. They were the first who found out that degree centrality values determine connectivity and sustainability to a lesser degree than betweenness centrality, i.e. the number of routes passing through the edge or node.

Only at the end of the twentieth century similar methods were used for power grids. One of the first studies in which graph theory was applied to the analysis of the structure and sustainability of power grids was devoted to the case study of Italy (Crucitti et al. 2005). The authors used a weighted graph in which the weight of edges corresponded to the ratio of its power to load. The main concept in this paper was betweenness centrality. The authors simulated the removal of random edges and analyzed changes in betweenness centrality of the remaining elements.

In another study (Chaitanya et al. 2011), the authors considered topological properties of the Eastern India power grid. As in most other works, the graph was considered exclusively from a mathematical point of view and had no spatial reference. The authors created three types of origin-destination matrices: the incidence matrix, the Laplace matrix, and the adjacency matrix, and then calculated the clustering coefficients, Pearson correlation coefficient, average degree and other indices for graph vertices.

Rosas-Casals et al. (2007) studied different characteristics of the power grid in 23 European countries. They divided network accidents into those that occur randomly and intentionally. By simulating these actions, they calculated the critical probability of disconnecting for a particular vertex in the network. The main concept used by the authors was the node degree. In this kind of work, the results were usually presented in the form of tables. Information about the studied network is presented in the form of a schematic image or a small-scale map that shows the location of network elements and occasionally its parameters. For example, in the study (Rosas-Casals et al. 2007) the color of a vertex corresponds to its degree. Since 2010 many similar studies in which authors simulated blackout of a power grid and determined its impact on the state of the whole network through changes in the values of some theoretic and probabilistic indicators have been conducted (Hines and Blumsack 2008; Nasiruzzaman and Pota 2018).

Northwestern University in the USA conducted an interesting research (Yang et al. 2017). The authors previously constructed an anamorphic map of electric networks so that the density of the network vertices became uniform throughout the territory. Then, using maximum capacity data and the actual length of the network, they calculated the percentage of transmission lines that are most critical in terms of the occurrence of an accident. As a result, the lines with considerable length and capacity made up 10.8% of the total lines number.

The first power grid structure mapping was carried out in (Faddeev 2016). The author studied the structural sustainability of power grids in Russia and other countries of the former Soviet Union. The main concept used in this work was betweenness centrality, which determines the load of a network vertex. An algorithm for removing random vertices was close to those described above. The author created maps of the power grid sustainability based on the obtained results. Sustainability was expressed in terms of the percentage of vertices, the removal of which will lead to cascade failures. The resulting values were aggregated within the united power systems.

A new approach to the analysis of structural characteristics of the power grid as a resource for long-term development was presented in the PhD thesis (Karpachevskiy 2018). The author considered centrality, alternativeness (number of supplying power lines) and topological distance to be the main structural characteristics. Also, he described the content of the electric network structure maps and proposed some visualization methods.

Thus, the study of power grids from the graph theory point of view has begun quite recently. Initially, graph theory methods were used to analyze road and rail networks, later they were applied to power grids. Mapping the structure and sustainability of power grids is a new and poorly developed field in thematic cartography. In our study, we propose a new centrality measure that corresponds to the power grid features and is more representative.

Natural hazards affecting power networks

Power systems are influenced by a variety of natural hazards that are taken into account during the design and construction of electric power lines. The main and the most frequent natural hazards that are studied in this paper are wind and sleet.

The danger of wind lies in the dynamic impact on objects. Strong winds include a wide range of wind meteorological phenomena: typhoons, storms, tornadoes, squalls, etc. The danger of sleet load is associated with significant damage due to the accumulation of ice with a diameter of more than 20 mm on the wires (Atlas of natural… 2012).

According to statistics, these natural hazards cause the most accidents in power systems. The main documents regulating the construction of power lines in Russia are the following:

• The standard of the organization of Federal Grid Company of the Unified Energy System, Norms for the Technological Design of Overhead Power Transmission Lines with Voltage of 35 – 750 kV (FSK-EES.ru, 2014);
• Wiring regulations (PUE7.ru, 2006);
• Building norms 2.01.07-85 «Loads and impacts» (docs.cntd.ru, 2010);

These documents present the zoning of Russia by wind and sleet loads. Each zone has its own value of wind/sleet load impact (Table 1, Table 2).

So, these maps represent the only available and official data about the spatial spread of maximum wind and sleet loads with a probability of 0.04 (one time per 25 years). They are often used to study the natural conditions of a power system operation and development.

We assume that joint analysis of electric networks and maps of natural hazards is necessary for the accurate identification of «bottlenecks» in power grids and determining the degree of their vulnerability. GIS is the most appropriate and efficient method for conducting spatial analysis of natural hazards along with the network structure analysis.

MATERIALS AND METHODS

The study area

A preliminary study based on the actual data about failures has revealed the power systems for which the assessment of sustainability is most relevant (Karpachevsky and Filippova 2018). The Ural united power system (Fig. 1) consists of nine regional power systems: the Republic of Bashkortostan, Kirov region, Kurgan region, Orenburg region, Perm Krai, Sverdlovsk region, Tyumen region, Khanty-Mansi and Yamalo-Nenets Autonomous districts, Udmurt Republic, Chelyabinsk region. The combination of complex and sometimes irrational configurations of the power grid and difficult environmental conditions (mountain terrain often leads to considerable wind and sleet loads) causes the maximum number of failures among all power systems, including high voltage power grids. According to the Ministry of energy data on emergency shutdowns at electric power facilities in the Ural UPS (minenergo.gov 2019), there were 245 failures on power lines with a voltage of 110 kV and above. A third part of the failures was caused by wind and sleet loads.

Power grid graph

In the power grid graph, power plants and substations act as vertices, and power lines act as edges. Electric network, however, has its own features (Karpachevsky and Novakovsky 2019):

• Different functional types of vertices: sources (power plants) and consumers (electrical substations);

Table 1. Maximum wind pressure for different zones with a return period of 25 years

Zone	Wind pressure, Pa
I	Less 400
II	400-500
III	500-650
IV	650-800
V	800-1000
VI	1000-1250
VII	1250-1500

Table 2. Maximum sleet load on wires for different zones with a return period of 25 years

Zone	Sleet thickness on wires, mm
I	Less 10
II	10-15
III	15-20
IV	20-25
V	25-30
VI	30-35
VII	35-40

Fig. 1. Schematic map of the main power transits in the Ural UPS

• One-direction flow at one point in time: electricity moves from sources to consumers in general, but the direction could be changed;
• The presence of multiple edges (parallel edges connecting same vertices);
• The presence of branches – edges connecting three or more vertices, which are named hyperedges in the graph theory terminology (Karpachevsky and Novakovsky 2019; Newman 2018);
• The graph is non-planar – there are no vertices at intersections of power lines, flow switching is possible only at the vertices of the graph;
• The hierarchy of the graph edges depends on the power line voltage;
• The weight of an edge is determined by the capacity of the power line.

We collected the initial data using visual identification of the power grid objects. We used mosaics of high-resolution space images (Bing, QuickBird, GeoEye, etc.) available on map services. Identification of power lines was based on a topological approach. According to this approach, the unit of mapping is a power line circuit (not the power line itself, because it can consist of several circuits), so that we could trace a line along the circuit as a graph edge. On a space image we could recognize power lines using single pylons and the composition of pylon species. We defined the pylon species composition as a regular stable combination of anchor and intermediate pylons on the line (Kargashin et al. 2016). The composition of pylons species depends on the geographic features of the territory, climatic loads, current typical pylon design, number of circuits and nominal voltage. In addition, various topomorphological relations – a set of repeating spatial configurations such as branches, cuts, furcations, etc. – were taken into account during the identification of power lines (Karpachevsky 2018). We carried out image interpretation using the Google Earth application, which provides free access to the mosaic of space images. The results of interpretation were assessed using some existing schemas, documents and maps. It was concluded that the accuracy of the resulting network is sufficient for spatial and network analysis (Karpachevskiy et al. 2020).

To minimize the effect of boundary on the modelling (Tikunov 1997) we expanded the network: in addition to the network of the studied territory, we included power lines crossing the boundary of the power system and some linking lines, which provide inter-system communication, as well as adjacent vertices.

Identified objects were topologically corrected. Below is a formalized list of topology rules that must be followed when constructing a power grid graph:
• The graph should be non-planar;
• There should be no hanging vertices – each power line should start at a point (power plant/substation) and end at a point;
• Self-intersections are not allowed;
• «Stand-alone» nodes are not allowed – each power plant/substation must have connected power lines.

A weighted graph should be used to perform the analysis. In this case, the weight of the edges corresponds to the inverse value of the power lines capacity which depends on the voltage (Table 3) (Faybisovich 2012).

Network analysis

Centrality measures from the graph theory are popular tools for assessing the edge significance (load) in graphs. In the case of transport networks, betweenness centrality is often used. For calculating the edge betweenness centrality, it is convenient to use the NetworkX library in the Python programming language. This function is rather simple and takes the graph itself and the weight attribute as input parameters. Betweenness centrality for a vertex or an edge is determined as the number of shortest routes passing through this element. The experience of using betweenness centrality has shown high efficiency in investigating not only geographical networks (Rosas-Casals et al. 2007; Faddev 2016), but also social ones (Scott and Carrington 2011).

However, as we can see from the previous section, this approach does not take into account some features of the power grid graph. For power grids it is much more reasonable to use centrality that we call electrical grid centrality. We have developed a programming code for its calculation (Fig. 2). The features of this index are listed below:

1) Shortest paths are calculated only between generation points and substations, paths between two substations are not taken into account;

2) For the generation points subset we considered only power plants with an installed capacity of 200 MW and higher – this corresponds to the power which typically requires transportation using power transmission lines with a voltage of 220 kV and higher;

3) Betweenness centrality for an edge is calculated as the sum of the fraction of all-pairs shortest paths that pass through the edge. For power grids the number of shortest paths between two points is usually determined by the number of multiple edges, so that there is no need for the calculation of fractions.

4) Normalization of indicators for ordinary graphs is performed by division by n(n - 1), where n – number of vertices. This expression corresponds to the number of edges in the complete graph. In a power grid graph it does not make sense to take into account complete graph because there is no need to link all generation points with each other. Thus, the number of possible edges between generation points is subtracted from the number of possible edges in the complete graph;

5) Lines with branches (hyper-edges) in NetworkX are deconstructed to simple edges, new vertices adjacent to these simple edges are included in the graph. These vertices become involved in ordinary centrality calculation. In the case of electrical grid centrality, these vertices are excluded from short paths calculation.

6) Ordinary function for reading shapefiles in NetworkX creates a simple graph object. We have developed a function for reading the power grid shapefile as a multigraph.

7) Multiple (parallel) edge values have no difference from ordinary edges in the case of betweenness centrality. In the case of electrical grid centrality, these values are distributed equally (divided by the number of multiple edges) to reflect the load decrease.

Table 3. Capacity of power lines

Nominal voltage, kV	Capacity (average value), MW	Weight, (1/MW)*100
35	10	10
110	37.5	2.6
220	150	0.6
500	900	0.1

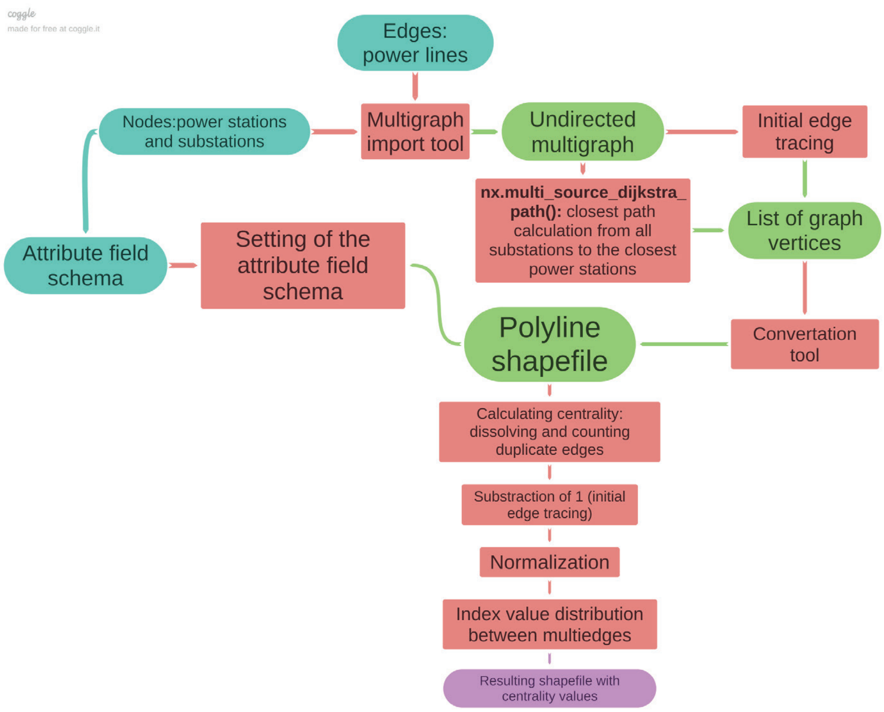

Fig. 2. Algorithm of the electrical grid centrality calculation

Natural hazards data

We used maps of wind and sleet loads impact from Wiring Regulations. We georeferenced and digitized them, obtaining vector layers for the joint analysis with the results of network analysis (Fig. 3, Fig. 4).

The zones of wind impact in this territory have sublatitudinal boundaries and almost coincide with the boundaries of natural zones due to the flat topography and the large extent of the territory from west to east. The central part of the study area (almost 50%) lies within the wind zone II. It covers Kirov, Sverdlovsk, Tyumen, Perm regions and Khanty-Mansi Autonomous Okrug. Wind pressure increases when moving north and south. In the northern part (Khanty-Mansiysk and Yamal-Nenets Autonomous Okrugs) it is caused by the absence of a natural barrier and the drift of cold air masses from the Arctic Ocean. Continentality increases from north to south (Chelyabinsk and Orenburg regions). Moreover, wind speed increases here due to the treeless territories of the steppe. Almost the entire plain territory lies in zone II of sleet load. The northwest of Kirov region is characterized by minimal values of ice thickness (less than 10 mm). Sleet thickness is higher in the mountains (zone IV and V) beginning from the foothills of the Urals. The foothills (at an altitude of 300-500 meters) and the hills adjacent to the Ural Mountains correspond to the sleet load zone III.

RESULTS

We calculated both edge betweenness centrality and electrical grid centrality for the Ural UPS network. We took lines not only within the Ural UPS, but also lines from bordering power systems that form cycles with lines from the Ural UPS and lines connected to big power stations. After that, we overlaid output shapefiles with sleet thickness and wind pressure layers.

The analysis of the power lines location in various sleet thickness and wind pressure zones showed that many of them are located in the most dangerous areas. Moreover, it is necessary to take into account the age of lines. So, the 500 kV lines Kropachevo – Ufimskaya, Kropachevo – Privalovskaya, Privalovskaya – Zlatoust and Zlatoust – Chelyabinsk pass through the area with the maximum sleet load and through the zone II of wind load. This transit was built in the 1950s-1960s. Listed lines have low relative centrality values of 1.44%, 0.007%, 1.44% and 5.7%, which means that their outage would lead to redistribution of the load without cascade failures.

The same situation is observed for the 220 kV lines from Kama hydroelectric power plant (HPP) to the power substations of Yekaterinburg. These lines were built in the 1950s-1960s and are located on the western foothills of the Urals. This territory combines severe sleet and wind conditions. The centrality of these lines is very low (less than 1%), which does not allow us to speak about the critical level of consequences due to emergency situations.

Fig. 3. The main power transits in the Ural UPS overlaid with the sleet load zones

Fig. 4. The main power transits in the Ural UPS overlaid with the wind pressure zones

In the 1970s-1990s, several power lines were built linking the regional power systems and crossing the Ural Mountains. They are located in heavy sleet zones. For example, the 500 kV Kalino – Tagil line passes through the zone IV of sleet thickness, however, its centrality is zero. Among all the other lines built after 1990, the most critical are the 220 kV lines located in the wind pressure zone III: Urengoy – Nadym (centrality 0.5%), Urengoy – Pangody (centrality 0.1%) and Urengoy CHP power plant – Tarko-Sale (centrality 0%). In the southern part of the power system, several lines are located in the wind pressure zone III: the 500 kV Iriklinskaya CHP power plant – Magnitogorskaya (centrality 40%) and the 500 kV Iriklinskaya CHP – Gasovaya (centrality 53%). Thus, among all the transmission lines of the Ural UPS, the most unfavorable conditions are observed for the lines crossing the Ural Mountains, because mountainous areas are characterized by the thickest sleet.

In addition, there are several lines with large centrality values (more than 50% of the maximum value). Such lines make up less than 1% of the total number of lines. Emergencies on them can be dangerous due to the lack of backup power transmission routes. All these lines have a power plant as a feeding centre, i.e. they are the initial link of further electricity transmission. Also, two of those lines connect the Surgut CHP-1 with substations. This indicates that this power plant in the network is a local centre and there are no alternative energy sources in the territory of its service.

Joint analysis of the network location and natural hazards may help to identify bottlenecks in the system. We took the results of network analysis and created a table of bottlenecks of the Ural UPS (only 500 kV). A bottleneck is an edge of the network that has high betweenness centrality (>50 % of the maximum value), is located in high wind pressure and/or ice thickness zone (zone III and above) or was built in the 1960s and earlier. These lines are the most critical parts of the power system which should be carefully serviced (Table 4).

Thus, there are two lines that have several critical factors. The 500 kV Yuzhnouralskaya CHP-2 – Shagol power line has the maximum value of the modified centrality in the entire graph. This line serves the Chelyabinsk industrial hub and is part of the intersystem transit of electricity between the Urals and the Volga UPS. An outage of the line will lead to a failure in the power supply, first, in the city of Chelyabinsk and its agglomeration with a total population of more than 1.5 million people, and second, in the largest enterprises of the Southern Urals: Chelyabinsk Metallurgical Plant, Zinc Plant, and Chelyabinsk Electrometallurgical Plant.

The 500 kV Iriklinskaya CHP – Gazovaya power line (Fig. 5) mainly serves the largest plants of Orenburg region (Ural Steel Plant, Mednogorsk Copper-Sulfur Plant), and also provides electricity to the railway, the cities of Orenburg, Mednogorsk, Kuvandyk, Orsk, Novotroitsk and a number of settlements with a population of about 800 thousand people. In general, the Iriklinskaya CHP is the most powerful in the Southern Urals: its capacity is almost 2500 MW, which allows it to provide power to almost the entire Orenburg region. In addition, part of the electricity is exported to Kazakhstan, which makes the line a geopolitically important object.

Table 4. Bottlenecks of the Ural UPS (most critical factors are highlighted in red)

Power line	Electrical grid centrality, % of maximum value	Wind pressure zone	Ice thickness zone	Year of construction
500 kV Yuzhno-Uralskaya CHP-2 – Shagol	100.0	2-3	3	1964
500 kV Iriklinskaya CHP – Gazovaya	53.0	3	2-3	1992
500 kV Iriklinskaya CHP – Magnitogorskaya	40.0	2-3	3	1976
500 kV Surgutskaya CHP-1 – Pyt-Yakh	85.0	1	1	1976
500 kV Surgutskaya CHP – Holmogorskaya	85.0	1	1	1985
500 kV Karmanovskaya CHP – Udmurtskaya	71.0	2	2	1968
500 kV Votkinskaya HPP – Vyatka	66.0	1	2	1976
500 kv Kropachevo – Ufimskaya	1.4	2	3	1961
500 kV Kropachevo – Privalovskaya	<1.0	2	3-4	1961
500 kV Privalovskaya – Zlatoust	1.4	2	3	1961
500 kV Zlatoust – Chelyabinsk	5.7	2	3	1961
220 kV Kamskaya HPP – Kalino	<1.0	1	3	1965
500 kV Kalino – Tagil	<1.0	1	3	1974
220 kV Urengoy – Nadym	<1.0	2-3	1	1980
220 kV Urengoy – Pangody	<1.0	3	1	1985
220 kV Urengoy CHP power plant – Tarko-Sale	<1.0	2-3	1	1982

Fig. 5. Most critical lines in the Ural UPS (highlighted in pink)

DISCUSSION

We wanted to compare the network model with the real geographical distribution of natural hazards, supplementing this comparison with data on the age of the infrastructure. This is the first fundamental difference from the previously considered works, where networks without a real geographical reference were used for modelling.

In Fig. 6 and Fig. 7 we can see an example comparison of calculation results obtained using different methods. Calculated values were additionally normalized by their range since the calculation algorithms in both instruments generate results in different scales.

For both methods, several corridors are clearly distinguished, representing the sequence of the most loaded power lines: the 500 kV Karmanovskaya CHP – Udmurtskaya and Votkinskaya HPP – Emelino (both with centrality values of 0.50 or higher). Considered lines are not connected to each other with an adjacent line in both calculation results: when using the usual centrality, the connecting line with a close value is the 500 kV Karmanovskaya CHP – Votkinskaya HPP, when using a modified tool, there is a cascade of lines forming a loop and passing through the Vyatka substation (near Kirov). Because of this, in the case of modified centrality, the centrality of the 500 kV Votkinskaya HPP – Vyatka line is greatly increased. The second corridor includes the 500 kV Demyanskaya – Pyt-Yakh power line. This is because these lines are connecting subgraphs of regional power systems and account for the main share of the interregional capacity flow transit. Both corridors are connected to the largest generating capacities: the first corridor is directly connected to Karmanovskaya CHP and Votkinskaya HPP, as well as to Reftinskaya CHP. However, in the second case, when using a modified tool, this relationship is not clearly traced since the centrality is distributed over multiple edges proportionally to avoid overloading of the lines. Similarly, the 500 kV Demyanskaya – Pyt-Yakh line is connected to the Surgutskaya CHP cascade by neighbouring lines.

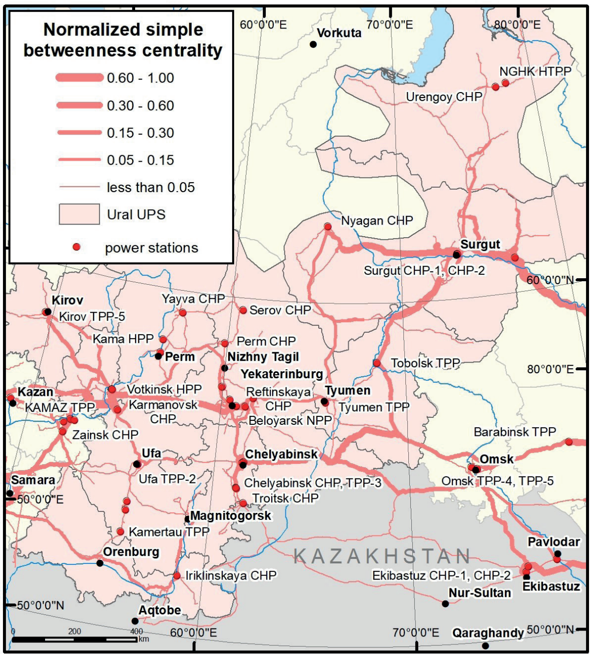

Fig. 6. Betweenness centrality calculated in NetworkX using standard function

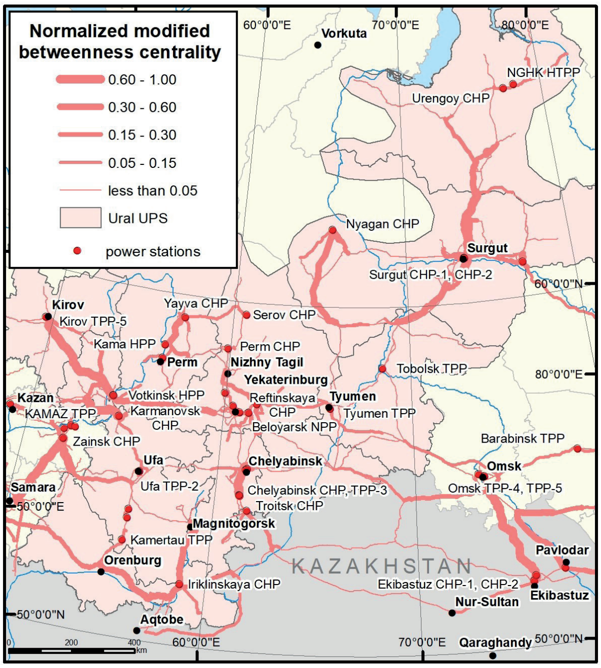

Fig. 7. Electrical grid centrality calculated using author's script

Visualization of the results clearly shows that the use of a modified tool for calculating the power grid centrality is more objective. When using the classic centrality calculation tool, routes are built between all nodes of the network, regardless of their functional purpose. Because of this, the resulting centrality values are inadequately overestimated. The flow of capacity is in the direction from the power plant to the substations, which is taken into account in the modified tool. Therefore, in the second method, the concentration of the most loaded lines is observed mainly near power plants. For example, let us consider the site to the east of Chelyabinsk. Here the power lines form a cycle that consists of the following 500 kV overhead lines: Kurgan – Vityaz, Voskhod – Vityaz, Voskhod – Barabinskaya, Kurgan – Aurora and Tavrichesky – Aurora. This cycle closes in Omsk through a corridor of several 220 kV power lines. When calculating the classic centrality, the normalized values on these edges of the graph are biased, since the traditional algorithm uses not only power plants, but also substations to calculate centrality. In this cycle, there are power plants only in Omsk. They were used for the calculation when using the modified tool (Fig. 8, 9).

As mentioned above, the classical centrality calculation tool does not consider multiple edges. In power systems, the presence of multiple edges is a standard solution for improving the reliability of energy supply: in the case of outage of one line a backup is used. When using the classic routing tool, only one of multiple edges is randomly selected and the entire load is distributed to it. In the modified tool, the resulting centrality value is distributed proportionally to the number of edges. This approach gives a more objective picture of the distribution of centrality values in the network. So, Fig. 10 and 11 show the 500 kV Reftinskaya CHP – Tyumen 1 and 2 lines. When using the classical centrality tool, only the 500 kV Reftinskaya CHP – Tyumen 2 participates in the calculation. In reality, the transit of electricity is carried out on both lines equally, so the results obtained using the modified tool are more accurate.

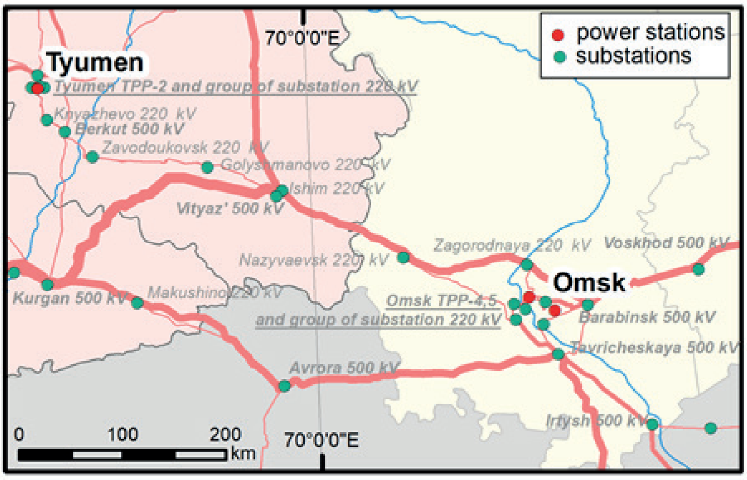

Fig. 8. Enlarged fragment of the territory of Omsk – visualization of betweenness centrality

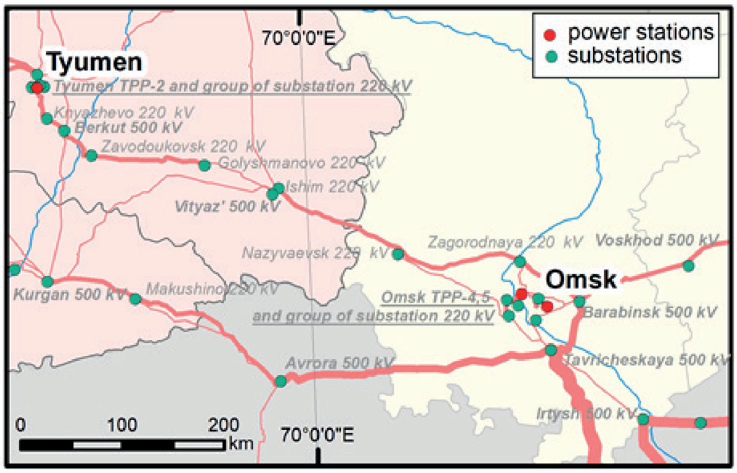

Fig. 9. Enlarged fragment of the territory of Omsk – visualization of electrical grid centrality

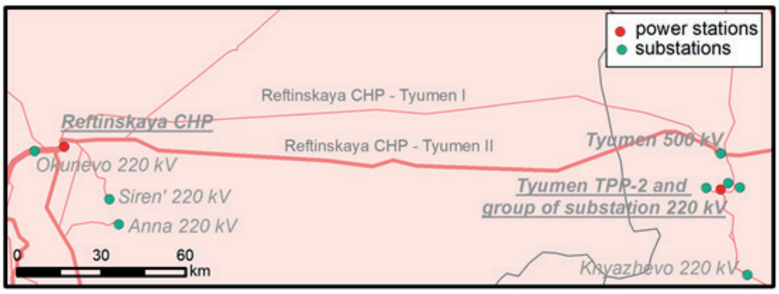

Fig. 10. Enlarged fragment of the territory of Tyumen – visualization of betweenness centrality

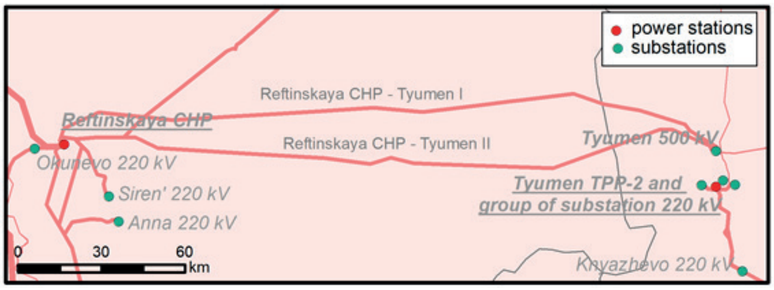

Fig. 11. Enlarged fragment of the territory of Tyumen – visualization of electrical grid centrality

Another aspect of power grids that affects the accuracy of calculations is the presence of hyperedges, that is, edges connecting three or more vertices. When using the classical centrality tool, the points for the calculation will also be used for branching along with power plants and substations, which may lead to incorrect centrality values. In a modified tool, branch points are not taken into account in the calculation.

It was found that the use of standard betweenness centrality is limited due to the characteristics of the grid graph: the presence of multiple edges, specific topomorphological relations, different functional types of vertices and some other features. Thus, the use of this index does not allow one to divide the nodes into sources and consumers and regulate the direction of the electricity flow. The vertices of branches are perceived by the algorithm as independent vertices and they also participate in the calculation of indices, distorting the results. Regulation of multiple edges usage in centrality calculations and interpretation of the received results is not obvious. Usage of electrical grid centrality allows to separate vertices and edges by functional types/hierarchy and assign them different roles in the network, as well as to manage topological relationships in the graph depending on the type of transport network. It is also recommended to topologically simplify the places of branching to avoid inaccuracies in the calculations and exaggeration of the centrality of power lines.

CONCLUSIONS

As a result, the calculation of centrality indices for power line networks allows to visualize some aspects of the spatial distribution of power grid sustainability. The less even distribution reflects the higher vulnerability of the power grid towards sleet and wind.

Firstly, the choice of network analysis index depends on the purpose of the work, quality and completeness of the initial data, and availability of special skills of the user. At the same time, it is very important to understand the difference in centrality measures in relation to power grids. Betweenness centrality is an illustrative index for any geographic network, but it does not consider some features of power grids. Suggested in this study electrical grid centrality index is more appropriate for analysis.

Secondly, we analyzed the spatial distribution of natural hazards, particularly sleet load and wind pressure, in the study area together with the results of network analysis. Additionally, we took into account the age of lines. Such analysis showed that joint use of knowledge about network features and natural hazards may help to identify bottlenecks in the power grid. A bottleneck is a «thin» element of a network that has very high betweenness centrality (>50% of maximum value), is located in zones of severe natural hazards impact (zoned 4 and 4) and/or has worn-out infrastructure.

Thus, using the electrical grid centrality and methods of geoinformation analysis, we identified a list of lines that are vulnerable to a particular factor. Special attention should be paid to lines that have a combination of these critical factors. It was found that two such lines are located in the southern part of the power system. They serve the largest enterprises of the Southern Urals and provide electricity to about 3.5 million people, as well as export electricity to Kazakhstan. Disconnecting these lines can cause serious damage to the population and economy of the entire Ural UPS.

Moreover, we could see that complicated sleet and wind conditions are connected with Ural Mountains, at the same time Ural is an old industrial region with many plants and populated cities, thus the power grid network began to develop quite a long time ago. So that, we have a set of aged power lines with high centrality vulnerable to strong wind and sleet.

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