TOPOLOGICAL ANALYSES OF AN IMPROVED POWER TRANSMISSION NETWORK OF SOUTHEAST EUROPE USING CLUSTERING METHODS

Kanevce Aleksandra
Faculty of Computer Science and Engineering
Skopje, Macedonia

Bogojeska Aleksandra
Faculty of Computer Science and Engineering
Skopje, Macedonia

ABSTRACT

In this paper clustering analysis of the power transmission network of South East Europe is used to identify the grouping clusters of the network and the links and nodes that connect them. This can help to assess the critical points of the network and the isolated islands. The topological analyzes of how this network should be developed in the future to satisfy the common market for electricity in this region is presented in this paper. In order to achieve this, the Girvan – Newman modularity function for the hierarchical clustering of the network is used. Taking into account the results of the clustering analyzes for the original network (the present network) and impact of the countries in the cluster formation we have proposed improved network. The results show substantially enhancement in terms of integration and compactness of the power transmission network. With this network upgrade, the impact of the countries in the power transmission network to the grouping in strongly connected modules is significantly reduced so the network can support the planned common market for electric power in the Southeast Europe.

Keywords: power transmission network, modularity function clustering.

I. INTRODUCTION

Many systems around us can be effectively represented by elements of interaction. The scientific projection of these interactions and their analysis is performed using networks representation. The Internet, telephone networks, WWW, collaboration networks, airline routes, power networks, social networks, different biological networks, are some of the examples of this type of systems. Last decade significant step in the development of algorithms that analyze the complex networks structure and their characteristic has been made. [1]

One of the characteristics of the systems analyzed includes their ability of grouping elements with similar characteristics. These groups are commonly referred as clusters, modules or communities. The process of detecting these dense groups of nodes into clusters is called clustering. The modular analysis of a system can reveal the organizational structure and emphasize the groups of nodes in the network that are more similar and highly inter-connected. [2] Looking into the modules at different scales helps exploring the network evolution and detecting stable intermediate building blocks that accelerate the emergence of complex systems.

One can be aware of many different clustering algorithms based on different approaches. Recently developed algorithms that use so called modularity function for clusters detection compare the strength of the module to a null model, other multi-resolution algorithms are exploring the clusters of different levels of modularity, links clustering algorithms generate clusters of links by assigning community to each link instead to node. [3]

In our work we consider a power transmission network, which is representative of the man-made complex networks. These networks play crucial role in our society, which motivates the research and practice on analyzing the structural and organizational properties that contribute to higher reliability and robustness of these networks. The elements and modules of these networks perform individual and collective tasks such as generating and consuming electrical load, transmitting data, or executing parallelized computations. One can study the topological organization of the network, the failure of random elements and thus the overall network vulnerability by analyzing its modular organization. The analysis of the electric power networks can be seen in many papers. Some of them include basic network characteristics analysis [5], and some analyze the network in more detailed way [4], [6] whether by analyzing its robustness or partitioning using specific network properties.

According to the agreements that are already signed as the Energy Community Treaty [7] and Southeast Europe Regional Electricity Market (SEE REM) [8] and South-East Europe Cooperative Initiative [9], the Southeast Europe should have a single trade for electricity in the future. In order to accomplish this, it is necessary to have adequate power transmission network. Using hierarchical clustering algorithm we are analyzing the topology and the structure of the upgraded power grid of the Southeast Europe compared by our previous results presented in [10] where the same analysis on the original network was done. The analysis includes exploring the distribution of the clusters in the network in terms of the states in this region and the capability of the transmission network in the region to meet these requirements.

This paper is organized as follows. Section II presents the methods and the data used for the analyses of the topological characteristics of the power transmission network of Southeast Europe. In Section III shows the results and discussion and conclusions from our work.

II. METHODS

A. Modularity function

In this work we focus on the effective fast community detection algorithm based on the Girvan-Newman Modularity Function [11]. This modularity function presents one of the biggest breakthroughs in cluster detection. The equation proposed compares the quality of a given cluster, with the quality of a random graph by finding the difference of the fraction of edges that fall into the cluster, and the expected number of edges distributed at random, Equation (1). A positive number less than 1, means that the number of edges in the group is greater than the number at random i.e. the cluster is well defined. Number between zero and -1 means that the analyzed edges don't form a good cluster. The randomization of the evaluated edges is done with preserving each vertex degree. The Girvan-Newman modularity measure is defined as follows:

$$Q = \frac{1}{2m}\sum_{ij}\left[A_{ij} - \frac{k_i k_j}{2m}\right]\delta(c_i, c_j), \qquad (1)$$

where A_{ij} is the weight of the edge between vertices i and j, $k_i = \mathrm{sum}_j(A_{ij})$ is the sum of the weights of the edges attached to node i, c_i is the community to which node i is attached, $\delta(c_i, c_j)$ is the Kronecker delta symbol where $\delta(u, v) = 1$ if $u = v$ and 0 otherwise, and $m = 1/2\ \mathrm{sum}_{ij}A_{ij}$. The matrix A represents the adjacency matrix of the graph.

The algorithm developed by Blondel et al. [12] uses a hierarchical agglomerative method, where at the beginning each node represents one cluster. Nodes, and later clusters are merged trying to maximize the modularity, exploring the full topology of the graph. This algorithm uses a greedy technique, where communities are represented with supervertices. At the start all nodes are in a different community, but as each node chooses a new community, the communities are replaced with supervertices. Two supervertices are connected if an edge exists between any two nodes from the two supervertices. Again, at each step the modularity is calculated from the initial topology. These steps are repeated iteratively until a maximum of modularity is reached. Therefore the hierarchical clustering results in several partitions. After the first step the partition found consists of many communities of small sizes. At subsequent steps, larger and larger communities are generated due to the aggregation in supervertices.

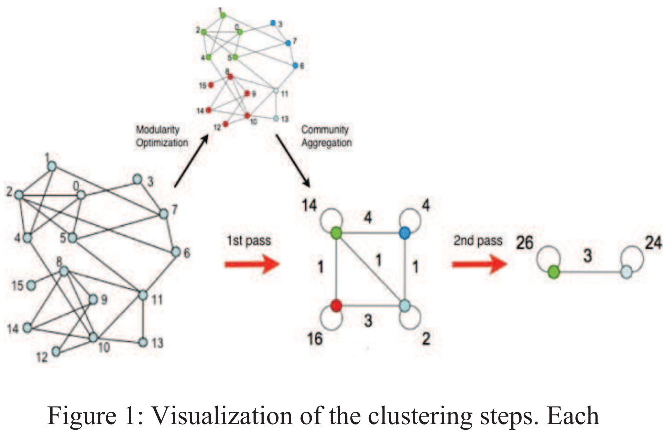

Figure 1: Visualization of the clustering steps. Each iteration has two phases: one where modularity is optimized by allowing only local changes of communities; one where the found communities are aggregated in order to build a new network of communities. [12]

B. Data – Southeast Europe power transmission network

The power transmission network of the Southeast Europe, analyzed in this work, includes the following countries: Macedonia, Serbia, Bulgaria, Albania, Kosovo, Croatia, Bosnia and Herzegovina, Montenegro, Slovenia, Greece and Romania. We are considering power transmission lines of 440kV and upper voltage levels. The power network of European network of transmission system operators for electricity (ENTSO) is used [13].

The Southeast European power grid consists of about 240 nodes (which represent the transformers and the generation capacities) and 280 lines. Each node represents a transformer in the power grid. It is assumed that the electricity generators are connected to the nearest node, i.e. to the nearest transformer in network. For the purposes of this paper we added new 6 lines to the existing structure, to see the improvement of the network integration.

We represent the power transmission network with a graph where transformers are represented by vertices of a graph (nodes) and the connecting power transmission lines are represented by graph edges. The basic mapping of the network is an undirected, unweighed graph $G = (V, E)$. V is the set of vertices, here represented as nodes, and E is the set of edges, the interactions between them.

Graph is represented by an adjacency matrix showing which vertices of a graph are adjacent to which other vertices. Specifically, the adjacency matrix of a graph with n vertices is an $n \times n$ matrix where the non-diagonal entry m_{ij} is the number of edges from vertex i to vertex j, and the diagonal entry m_{ij} number of edges (loops) from vertex i to itself. Adjacency matrix for undirected graph is symmetric and can be represented as follows:

$$A_{ij} = \begin{cases} 1, & \text{if } i \text{ is connectd to } j \\ 0, & \text{otherwise} \end{cases}, \qquad (2)$$

III. Results

The hierarchical network analysis was made in [10]. There two levels of classification are presented where the first level has twenty clusters and the second ten clusters. An interesting property of the network was drawn from the data about how many of the lines which connect two clusters, also connect two different countries. This data showed which of the border transmission lines should be upgraded in the future in order to have integrated network. For the first level of clustering 20% of the lines between two clusters were also border lines. This percentage was a little higher for the second level of clustering, i.e. it was about 22%. It is interesting that although the level of clustering was changed the lines between clusters which are also border lines remained the same. There are six such lines which connect Serbia with Bulgaria, Serbia with Romania, Serbia with Kosovo, Macedonia with Kosovo, Romania with Bulgaria and Croatia and Bosnia.

Because these six cross border lines are selected as bottlenecks of the power network, in this paper we analyse how adding new six lines between these countries will affect the topological properties of the network. The improved network with the added lines are presented on Figure 2 and marked with red color.

Figure 2: Added lines in the power transmission network of Southeast Europe

We explored the characteristics of the transmission network of the Electric power system of Southeast Europe including the six new lines. We have also analyzed two levels of classification and the difference in the topological characteristics of the original network and the improved network.

The first level of classification of the improved network has seventeen clusters (Figure 3) and the second level has ten clusters (Figure 4).

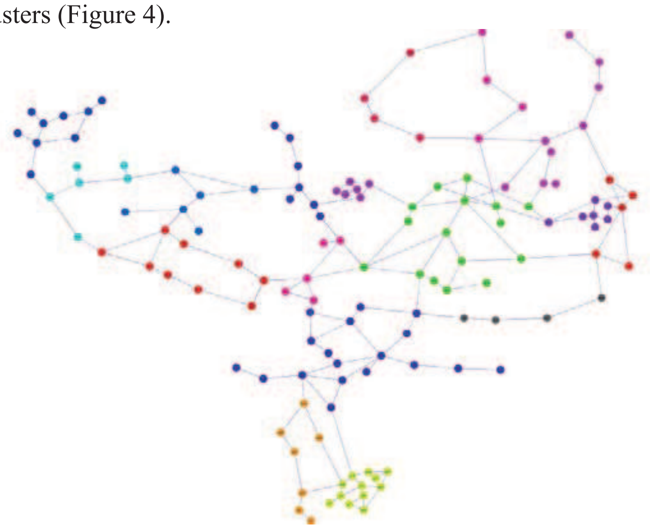

Figure 3: First level of classification of the power transmission network of the Southeast Europe

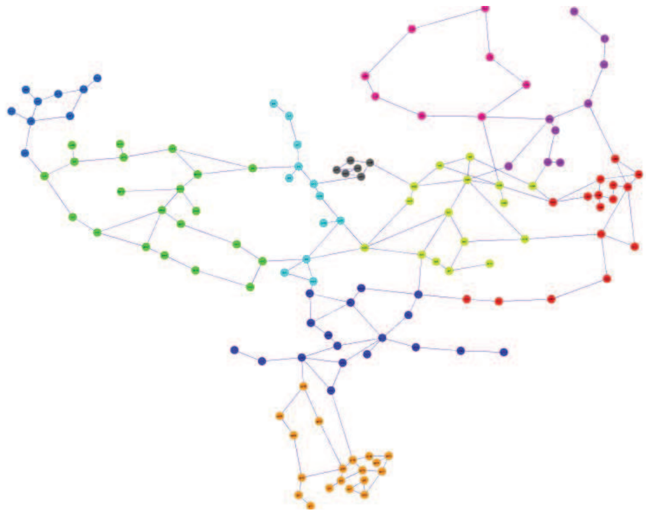

Figure 4: Second level of classification of the power transmission network of Southeast Europe

On Figure 5 the number of countries per cluster is presented for the first level of classification for the two analyzed cases – the original network and the improved network. In both cases most of the clusters are located into one country. In the first case for the original network 70% of the clusters belong only to one country. This percentage is reduced to 65%.

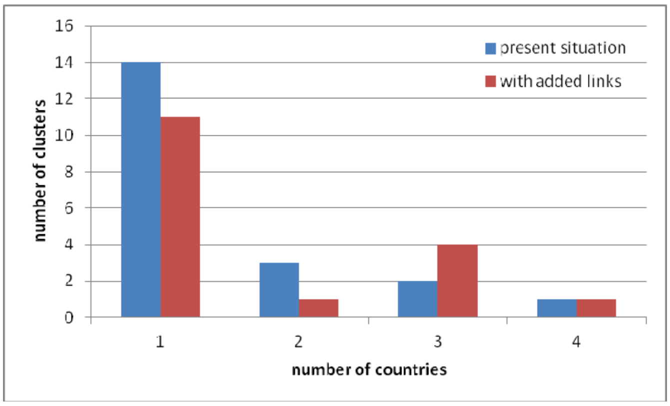

Figure 5: Number of countries per cluster for the first level of classification

Figure 6 shows the fractional number of clusters per country in the two analyzed cases. The fractional number of clusters for a certain country is calculated by dividing the number of clusters in that country by the population (which is proportional to the power consumption in that country). For the original network the smaller countries (by population) are more clustered compared to the bigger countries. Smaller countries such as Montenegro, Slovenia and Bosnia and Herzegovina are more clustered compared to Romania and Greece, which shows that the clusters of those countries are not bounded by the country borders. This may be a legacy of the development of the network from the time when a lot of these small countries were integrated into one country- the Yugoslav Republic. Table 1 presents the data for the average number and standard deviation for the both cases. It can be concluded that the data for the standard deviation is significantly reduced in the second case. This shows that the data for the clustering of the countries for the first case are spread out over larger range of values, i.e. smaller countries have much higher values than the bigger countries. On the other hand, the standard deviation for the second case indicates that the clustering of the countries is more uniquely distributed. This shows that the improved network is no longer constrained by the previous network development and the country's borders.

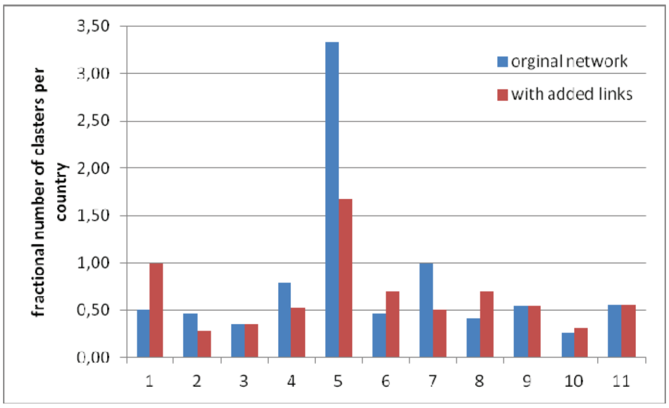

Figure 6: Fractional number of clusters per country (number of clusters/population) for the first level of classification

Table 1: Average value and standard deviation of the fractional number of clusters per country for the second level of classification

	Original network	With added links
Average value	0.79	0.65
Standard deviation	0.87	0.39

We also analyzed the nodes clustering coefficient and the network average clustering coefficient. In the original network only 23 nodes were characterized by a non-zero coefficient and average value of 0.0413. The insertion of the additional links resulted in number of 33 nodes with non-zero clustering coefficient and average value of 0.0559. Therefore, we can see how the addition of the links improves the network connectivity and structural organization.

The conclusion that the improved network is no longer clustered by the country's borders can be drown from the data about how many of the lines which connect two clusters, also connect two different countries. In the original network 20% of the lines between two clusters are also border lines for the first level and 22% for the second level. This number is substantially reduced to 14% for the second level and 6,6% for the first level, which shows that with just adding the six lines the network is more integrated and compact and can support the planned common market for electric power in the Southeast Europe.

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