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VULNERABILITY OF THE ROMANIAN POWER TRANSMISSION GRID

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***Abstract*—The vulnerability of power transmission systems is examined using a scale-free model of network structure and failure propagation. The topologies of the Romanian power systems are analyzed to estimate their reliability based on the Barabasi model. A commonly used power system reliability index is computed using a simple failure propagation model. The results are compared to the values of power system reliability indices previously obtained using standard power system reliability analysis methods. The author suggests that scale-free network models are useful for estimating aggregate power systems reliability.**

***Index Terms*—Loss of Load Probability (LOLP), scale-free graph / networks, power transmission system reliability**

I. Introduction

TOPOLOGICAL analysis of the graphs associated to World Wide Web networks, to railway / air traffic connections, to power transmission systems of electrical energy / heat, as well as the ones associated to inter-human contacts, and to various contagious diseases spreading, has led to surprising results. In these cases, connectivity distribution at graph level is extremely irregular. The term *scale-free* (no scale restrictions) was introduced by physicist Albert Barabasi and his colleagues from University of Notre Dame, Indiana, the USA, in 1998 [1] . Mapping the WWW network, they discovered that it has no regular connectivity distribution (the so called random connectivity). They found that, in general, many such networks expand by adding new vertices to the existing connections (lines), so the new vertices are attached, preferably, to ones already present in the network. The characteristic of $scale-free$ type networks is that for a certain node k the probability P_k^n that this should be directly connected with other n vertices in the network decreases according to the following relation $\rho \cdot n^{-\gamma}$, meaning that it has a power type distribution. Pareto Distribution, together with the one suggested by the linguist George Zipf are, in their turn, examples of power type distributions, associated to disparate phenomena, such as the popularity of www sites, various individuals' health status, or the frequency of using certain words in documents. The special interest in such *scale-free* type networks is primarily due to their degree of connectivity. Its exact assessment clearly influences the way in which the network is operated, including the way in which it responds to cascading events / events generated by the same cause (earthquakes, violent storms, etc), that may have a dramatic impact on network security. It is noteworthy that, in the case of an accidental cut off in a node / connection, a *scale-free* type network acts differently as compared to a *random connectivity* type network [2]. Therefore, a *scale-free* network faces the difficulty more effectively than a *random connectivity* one, because, in the first case, it is improbable that such an accidental cut off should affect a key node in the network. On the other hand, *scale-free* networks are vulnerable to attacks, a hacker being able to destroy the whole network by intelligently identifying the key vertices in it and annihilating them.

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This is why we think that identifying parameters ρ and γ at Romanian Power Grid level and identifying the key vertices is very important. The present article focuses on identifying the above mentioned parameters, on evaluating the LOLP indicator [3] and on comparing it to the estimated values at the level of other Power Systems; in a subsequent stage, our research will attempt at rigorously approaching, the aspects regarding the key vertices.

II. Failure propagation in a scale-free electric network

Starting from an accidental malfunction/interruption of a connection (line / transformer for Power Transmission System), a node (bar) respectively, the indicator associated to the probability of load loss, " Loss of Load Probability " as it is defined by ANRE (National Agency for Energy Regulation [3], can be determined.

In the case of accidental cut off in a line, the probability that a node should be deprived of power as well essentially depends on its number of connections. Thus, for a node k which has only one connection $(n = 1)$, the probability that it should have no power is 1. Therefore, at network level, 1 node - 1 connection, LOLP is ρ. If the number of connections n associated to node k increases, then it is expected that the probability of it being cut off should decrease ratably. Hence, the probability that an accidental connection cut off propagation should trigger node k cut off from the network is:

$$P\{node\, n \Rightarrow\} = \sum_{n=1}^{\infty} P_k^n / n = \sum_{n=1}^{\infty} \rho \cdot n^{-\gamma-1} \qquad (1)$$

In a continuous form, corresponding to a very large system, relation (1) is written:

$$P\{node\, n \Rightarrow\} = \int_{n=1}^{\infty} \rho \cdot n^{-\gamma-1} dn = \rho/\gamma \qquad (2)$$

Starting from an accidental cut off in a node i (bar), the probability that it should propagate and lead to a cut off in the second node j from the network can be estimated by means of the following relation:

TABLE I
SYNOPSIS OF DATA FOR THE CONSIDERED GRAPH AT RNPG LEVEL

N	L	T
254	1039	131

$$P\{node\, n \Rightarrow (i,j) \Rightarrow node\, j\} = \rho/(2\gamma) \quad (3)$$

because it is expected that in 50% of the cases the new distribution of powers / currents in the network after the accidental cut off in node k should not lead to a cut off in node j, the connection (i,j) being able to transfer the new power flux a posteriori resulting from the event associated to node k.

For the general case, the following can be written:

$$P\{node\, n \Rightarrow (i,k,j) \Rightarrow node\, j\} = (\rho/(2\gamma))^2 \quad (4)$$

respectively

$$P\{node\, n \Rightarrow (i_1,\dots,i_{n+1}) \Rightarrow node\, j\} = (\rho/(2\gamma))^n \quad (5)$$

Integrating at network level (N the number of vertices), the following is obtained:

$$LOLP = \int_{n=1}^{N} \rho \cdot n^{-\gamma} (\rho/(2\gamma))^n dn \quad (6)$$

III. ESTIMATION OF PARAMETERS ρ AND γ IN THE CASE OF ROMANIAN NATIONAL POWER GRID (RNPG)

Figure 2 gives a pictures of the Romanian network graph.

For a correct evaluation of LOLP, and, consequently, of the global vulnerability at NES level, a topological analysis of this network graph was performed. The results are presented in table I.

N is the number of nodes (vertices), L is the number of power lines, and T is the number of transformers.

Power distribution is seen in the histogram in 1, which indicates the number of vertices in the graph according to the number of connections n corresponding to them. We can notice that the vertices with 2 and 3 connections are the most frequent.

The regression equation which allows the estimation of the desired parameters ρ and γ, according to its relation indicated for the power distribution:

$$P_n = \rho \cdot n^{-\gamma} \quad (7)$$

If probability P_n is estimated through the relative frequency f_n, according to the above histogram for the case $n \geq 2$, we obtain (figure 2):

$$Log(f_n) = Log(\rho) - \gamma \cdot Log(n) \quad (8)$$

Correspondingly, the regression line is present in 3, and the results obtained from the estimation by the method of the smallest squares and imposing the norm condition at the level of power distribution are presented in table III.

For RNPG, the importance of each node is now determined based on the number of connections made to other nodes in

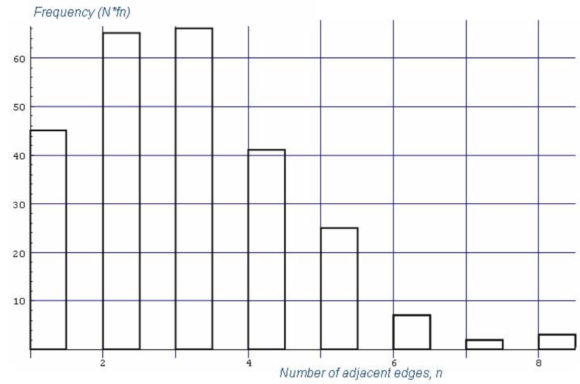

Fig. 1. Connectivity for the analyzed graph

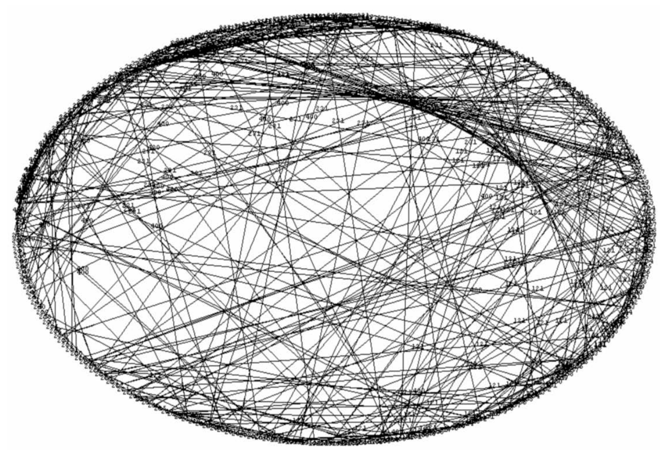

Fig. 2. The Romanian Power Graph

TABLE II
THE IMPORTANCE FACTORS (IF) FOR RNPG

Node	U (kV)	ID	IF
19	231	BUS0022GUTIN2A	1.27
28	231	BUS0032BUCSD2	1.26
33	231	BUS0037BRADU2	1.25
8	400	BUS0010GUTINAS4	1.25
20	231	BUS0023FAI2	1.23
22	400	BUS0025GIAL4	1.23
58	400	BUS0063CONSTANTN14	1.22
143	400	BUS0160MEDGS4	1.22
14	400	BUS0016GIALOM4	1.22
46	231	BUS0050DUMVRA2	1.21
184	231	BUS0397FOCSANI2	1.21
211	231	BUS0681BACAUS2	1.21
55	400	BUS0056PELICAN4	1.20

that the nodes with many connections, thus important, that are called ”hubs”. Table III presents the most important nodes.

[1]RNG - Romanian National Grid; WS - Western System, USA; EI - Eastern Interconnect, USA; BS/SE Brazilian Southern / South -Eastern; IEEE - IEEE Reliability Test System (version 2)

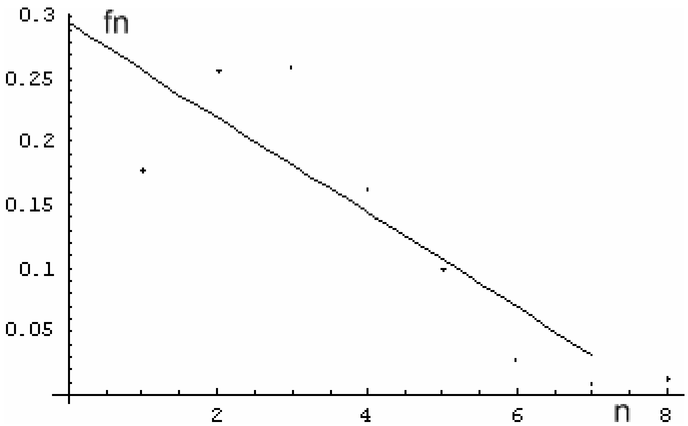

Fig. 3. Regression used for estimating parameters

TABLE III
COMPARATIVE PRESENTATION OF TOPOLOGICAL PROPERTIES OF ROMANIAN, NORTH AMERICAN (USA), AND BRAZILIAN POWER SYSTEMS

Power System [1]	ρ	σ_ρ	γ	σ_γ	LOLP
RNG	0.78	+0.073 -0.058	2.67	0.134	0.02776
WS [4]	0.85	+0.092 -0.083	3.09	0.047	0.026
EI [4]	0.84	+0.067 -0.062	3.04	0.059	0.026
BS/SE [5]	-	-	-	-	0.047

IV. CONCLUSION

This article has intended to assess LOLP value at Romanian National Grid level for the first time, as far as the author knows, and has also attempted at determining its vulnerability to cascading events. The model is easy to implement, provided that the network / graph and the limit conditions are correctly identified. The obtained values, presented in table III, prove the following: - the higher the values of the γ scale factor, the "stronger" the system is, at least from the perspective of cascading events propagation - the higher the values of factor ρ , the more the frequency of the nodes identified at the limit of the analyzed graph increases (generating nodes, receptor nodes respectively, from the total amount of nodes N).

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Paul Ulmeanu graduated from the Polytechnic Institute in 1987. In 2007 became professor of Reliability, Maintainability and Risk. His special fields of interest included power systems, and reliability and maintainability. He is currently Professor at Power Engineering Faculty, Polytechnic University of Bucharest.