Study on post-earthquake network connectivity and reliability of electric power system

J.Q. Lin, Y.S. Chen & J.L. Liu
Key Laboratory of Earthquake Engineering and Engineering Vibration，Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China

15 WCEE
LISBOA 2012

SUMMARY
In this paper, the post-earthquake working states of electric power systems are studied. Based on a two-value working state hypothesis of network elements, the electric power system (EPS) network model is built. The adjacency list memory structure method for EPS model is suggested to storage the data of network model. Then the adjacency list-based depth-first algorithm is developed by combined the adjacency list memory structure method with the depth-first algorithm to analyze the network performance of EPS. Following the studying of earthquake reliability for simple elements, the entire network reliability analysis process for a whole EPS based on Monte Carlo method is present with a flow chart. Finally the post-earthquake network connectivity and reliability of a practical EPS under Wenchuan Ms8.0 Earthquake are studied. The results indicate that the two methods developed in this paper are effectively to acquire the damage information in the seismic disaster area.

Keywords: electric power system network model; connectivity; reliability; depth-first algorithm; Monte Carlo method

1. GENERAL INSTRUCTIONS

As a main component of lifeline engineer system, electric power system (EPS) plays an important role in ensure the normal running of social economic system and people's daily life. However, the broad distribution and complicate combination form make it very vulnerable to earthquake. Once the EPS is stricken by earthquake, even the direct economic loss of itself is acceptable, the serious secondary disasters and other difficulties caused by power failure will prevent the smooth developing of post-earthquake emergency relief work. The connectivity of EPS which reflects the working state of the whole EPS, is mainly refer to the connective capacity between the converting station and power plant. So the network reliability of EPS is regard as a main parameter to reveal the working capacity of EPS, and is often used to study to post-earthquake performance of lifeline systems. Deeply research the network connectivity and reliability of EPS under earthquake is an important subject for reducing the seismic loss and promoting the post-earthquake relief work.

So many researchers have done a lot work in this domain. Ang and Pirea (1992) studied the seismic probabilistic reliability assessment process of electric power transmission system using probatilistic reliability model; and then Vanzi (1996) present the methodology and application for seismic reliability study of electric power networks, according to the working state analysis of each elements. Liu *et al* (2002) developed Monte Carlo Method based seismic reliability analysis method, and the method was used to study the seismic reliability of EPS in Taiwan.

In china, Wan *et al* (1995) present a fast topology analysis method based on breadth first algorithm; Li *et al* (2000) investigated the seismic damage characters of EPS and gave some reference suggestions on improving the aseismatic capability of EPS. Wang *et al* (2001) developed a topology identification method for power network based on incidence matrix; Li *et al* (2002) first studied the seismic reliability of large EPS by directly getting disjoint mini-paths and disjoint mini-cuts of systems using De. Morgan's laws and basic Boiean laws; Wang *et al* (2002) studied the connectivity judgment method for electrical power network based on relation data base; Song (2003) accomplished the reliability evaluation of composite power systems using artificial intelligence techniques; Du *et al* (2005) investigated the reliability of the power supply network system; Zhong *et al* (2005) proposed a method of power systems reliability assessment based on rough neural network; while Hua (2007) present a power system topology analysis method too via incidence matrix algorithm's improvements using Gaussian elimination algorithm; Wen *et al* (2007) summarized the aseismic reliability research work in EPS; Cui (2008) studied the matrix colouring method and its application in network topology analysis of power system.

Although a lot helpful work has been done, there are many defects need to be improved in this domain. Such as the variance still exist between the simulated network model and the practical EPS, no considering the working state of electric wire, and the computing method is even too complicated, and so on. After thoroughly understanding these drawbacks, an EPS network model is developed in this paper. Using the graph network connectivity theory, the network connectivity analysis method based on depth-first algorithm is designed to study the electrical transmission ability of EPS. Following the earthquake reliability analysis of each simple element in EPS such as the power station, the converting station and the power transmission line respectively, the network reliability analysis model for EPS is built using adjacency list memory method. The entire network reliability analysis process for a whole EPS based on Monte Carlo method is present with a flow chart. Finally the two present methods are used respectively, to study the post-earthquake network connectivity and network reliability of a practical electric power system under Wenchuan MS8.0 Earthquake.

2. NETWORK ANALYSIS MODEL AND DATA STORAGE

2.1. Network Analysis Model

For the easy to analyze the connectivity of EPS, assume that the damage of EPS network element meets two conditions: (1) the post-earthquake work state only exist two choices, yes or no; (2) the damage among all elements are independent. This means each element in EPS network model is in two-value working state, as indicated in Eqn. 2.1.

$$x_i = \begin{cases} 1 & \text{element } (i) \text{ is effictive} \\ 0 & \text{element } (i) \text{ is uneffictive} \end{cases} \tag{2.1}$$

Using above hypothesis, the two-value working state of EPS network element can be integrated into EPS connectivity analysis model. According to the difference between the combination mode of node element and side element in EPS network model, the EPS network connectivity model can be divided into three kinds as follow.

(1) Node weighted network model (Va): only the damage state (x_v) of power station and converting station are considered, while the damage state (x_a) of the power transmission line is neglected, this means the power transmission line maintain in good condition all along.
(2) Side weighted network model (vA): only the damage state (x_a) of power transmission line is considered, while the damage state (x_v) of power station and converting station are neglected, i.e. the power station and converting station maintain good.
(3) General weighted network model (VA): not only the damage state (x_v) of power station and converting station are considered, the damage state (x_a) of the power transmission line is also take into account. Recent studied results indicate this model is more precise in simulating the post-earthquake connectivity of EPS.

For Va and VA network model of EPS, due to each converting station have an input and an output port, the network connectivity of EPS is refer to both input and output port. However, only the network connectivity between output port of converting station and power station is studied in this paper, the basic principle is shown in **Fig. 2.1**. Assuming that the power station (S) and converting station (T1) is good, converting station (T2) is damaged, power transmission line (L1 and L2) is good, although the input port of T2 is connect with S, the output port of T2 is not connect with S due to the function losing of T2 itself, i.e. the converting station (T2) is not connect with S.

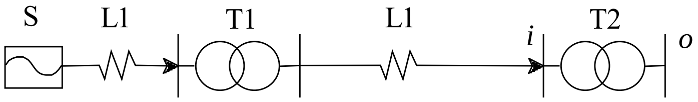

Figure 2.1. Connectivity sketch of an EPS

Similarly, assuming the seismic damage probability of each EPS network elements is a real number from 0 to 1, and in multi-value states with no dependent each other, i.e. element multi-value state hypothesis, as shown in Eqn. 2.2.

$$x_i = \begin{cases} x_i \geq p_0 & \text{element } i \text{ is effective} \\ x_i < p_0 & \text{element } i \text{ is uneffective} \end{cases} \quad (p_0 \in [0,1]) \tag{2.2}$$

By adding the element multi-value state hypothesis into EPS network model, the network reliability analysis model for EPS is built.

2.2. Adjacency List Memory Method for EPS Network Model

In order to realize the computer storage of EPS network model, the model is designed to be General weighted network model (VA). The defined node type is given in **Table 2.1**, this definition is not only apply to head nodes, but also the table nodes. The difference is that the states of head nodes refer to the nodes of network model, while the states of table nodes refer to the sides of network model. Then the head nodes (*vertex*) and table nodes (*adjvex*) of *nodeType* are defined. For a node *vertex*[*i*] in the network model, every node adjoin to it *adjvex*[*j*] is composed to a single-chain-table with head nodes. For easy to access the adjacency list of every node randomly, all the head nodes are storage in a vector orderly formed the adjacency list of EPS network model.

Table 2.1 Node data type and the VC++ code

	struct nodeType			code	struct nodeType { int vNo; float state; nodeType *link;}
Data type	int	float	nodeType		
Keywords	vNo	state	*link		
illustration	Node No.	state	Linked list pointer		

The analysis of EPS network connectivity is to judge whether the electric power can be transform from power station to converting station. In fact, there may be many power stations in one EPS. To simplify the question, a pseudo source point which connects with all power stations is often assumed, so the multi-source and multi-terminal question can be simplified to one-source and multi-terminal question.

3. NETWORK CONNECTIVITY ANALYSIS METHOD

3.1. Basic Theory of Depth-First Search Algorithm

In Depth-First Search Algorithm, the node which has the maximum depth is extended first. The search is beginning from the tree root along with a branch, then to a neighbour of a neighbour of the branch, and so on. After coming to a “dead end”, that is, to a vertex with no unprocessed neighbour, backtrack on the path until another path is found, and so on, until all the paths are processed. The basic procedure of Depth-First Search Algorithm follows:

(1) Initialize all nodes to the ready state, and mark them with unprocessed node. *Visited* [*i*]=0， *i*=1， 2， …， *n*；
(2) If node *vertex*[*i*].*vNo*=*i* is effective, i.e. *vertex*[*i*].*state*=1, then this node is accessed, and mark it

with processed node, visited[i]=1.

(3) For every node neighbour to *vertex*[*i*].*vNo*, *advex*[*j*].*vNo=j*, *j*=1,2,…,*n*. If it is not accessed and the path <v_i ,v_j> is good, then starting depth-first search from *vertex*[*j*].

At last, the depth-first searched chain of network model from node *vertex*[*i*].*vNo=i* is derived. Whether the node is included in this chain can be regard as the criterion to judge the connective between the power station and converting station.

3.2. Adjacency List Based Depth-First Search Algorithm

Combining the storage method of EPS network model with depth-first search algorithm, the adjacency list based depth-first search algorithm is developed. In this algorithm, every calling of the search process in each cycle will check all the nodes adjoin to the source node *i* in essence, and adjacency list based depth-first search algorithm is used to process the neighbour nodes which is not accessed. Because the total nodes in a graph is not more than *n*, the elapsed time for investigating all the neighbour nodes of the total nodes using the adjacency list storage method is $O(n)$. When the elapsed time for accessing the head node, the whole time is $O(n+m)$. In which, *n* is the sum of nodes in graph, *m* is the sum of by-passes. When the adjacency list matrix is used to storage the graph data, the total elapsed time to check all the neighbour nodes of *n* nodes is $O(n\times n)$, and the total computer memory is $6(n\times n)$ bytes.

4. NETWORK RELIABILITY ANALYSIS METHOD OF EPS

For EPS is a large and complicated network system, the study of EPS network reliability is not easy. In this paper, each component of EPS is taken out to be studied, that means the earthquake resistant reliability of power station, converting station and power transmission line are investigated first. And then the network reliability analysis model of EPS is developed using adjacency list storage method. The network reliability of EPS is studied by Monte Carlo Method, and the basic ideal and procedure are as follows.

(1) Basic ideal: by comparing the element failure probability with a large number of random numbers, reveal the damage state of each network side approximately. In every simulation cycle, judge the connective state of the source node and the distribution nodes. After a large number of simulation cycles, the probability evaluation of the connective ability can be derived by computing the connective or not connective frequency of each node. That means the accurate probability analysis is substituted by approximate frequency.

(2) Analysis procedure:

a) Calculate the earthquake resistant probability (p_i) of every element in EPS network model.

b) Generate a large number of random numbers uniform distribute at [0, 1], and then simulate the seismic reliability of each network element by matching the random number with network element.

c) Compare the matching random number with its seismic reliability of each element. When $x_i \geq p_i$, the element is effective and assign it 1; if not, the element is not effective and assign it 0.

d) According to the above rule, check the network connectivity of the EPS network reliability model with adjacency list storage. The connectivity indicate the accessibility from source node to the other distribute nodes and marked with C_{ij} , if can be connected $C_{ij} = 1$, otherwise $C_{ij} = 0$, in which i=1,2,⋯,n-s indicate the No. of converting station in the network model, and j=1,2,⋯,N indicate the times of simulate cycles.

d) Repeat step d) for many times until the required precision is reached. Then $\sum_{j=1}^{N} C_{ij} / N$ can be used to indicate the connective reliability from power station to the converting station with No. *i*.

(3) According to the basic ideal and analysis procedure above, the flow chart of EPS network reliability analysis can be developed, as shown in **Fig.4.1**.

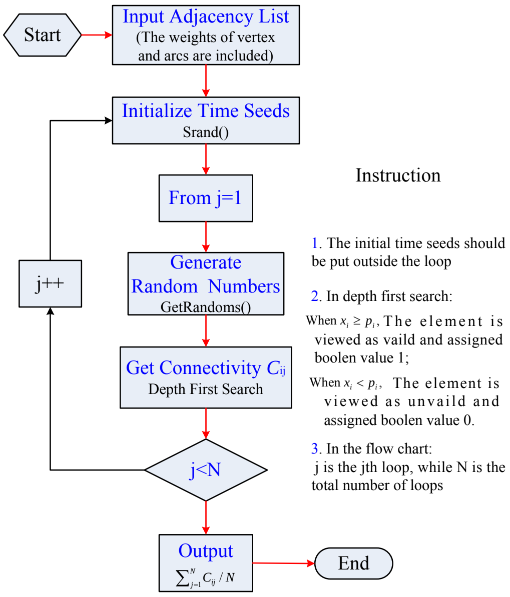

Figure 4.1. Flow charts of network reliability analysis based on Monte Carlo method

5. EXAMPLE STUDY OF NETWORK CONNECTIVITY AND RELIABILITY

5.1. Regional EPS Network Model

An EPS with 220kV or more transfer capacity in southwest China is selected as the example to study the network connectivity and reliability of EPS under M_S 8.0 Wenchuan earthquake. The geographic connectivity graph of EPS in this domain is shown in **Fig. 5.1**, and its network model for computer simulating is **Fig. 5.2.** According to the specific of actual conditions and characters, the work state of each element in this EPS network model is estimated under the designated earthquake. The node weighted network model (Va) and general weighted network model (VA) for the example EPS is established respectively using the method given in Charter 2.1, and then the element reliability can be calculated of the two network model. The element reliability results, shown in **Table 5.1-Table 5.3**, are embedded to the network reliability analysis model by adjacency list storage method.

Figure 5.1. A practical EPS geographical connectivity map for somewhere

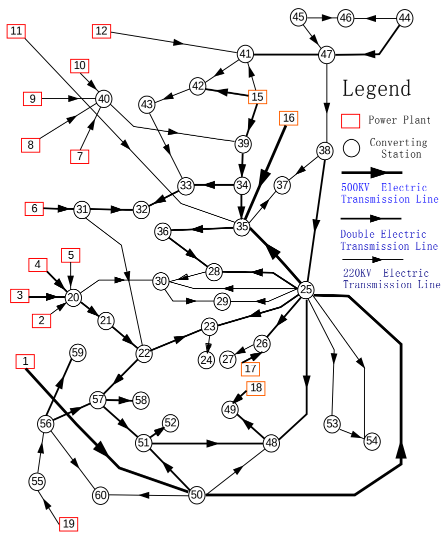

Figure 5.2. Basic model of the practical EPS in somewhere

Table 5.1. Earthquake reliability results of the power plants

No.	Power station	intensity	Reliability of power stations under the given earthquake				
			0.05g	0.10g	0.20g	0.40g	0.80g
1	Zipingpu	Ⅷ	0.9976	0.9567	0.8428	0.7310	0.5960
2	Yingxiuwan	Ⅶ	0.9970	0.9658	0.8118	0.7253	0.6225
3	Yuzixi	Ⅶ	0.9967	0.9583	0.8636	0.7015	0.5716
⋮	⋮				⋮		
17	Chengxi	Ⅶ	0.9984	0.9617	0.8226	0.7404	0.5865
18	Chengchang	Ⅶ	0.9986	0.9423	0.8569	0.7684	0.6180
19	Xiaoguanzi	Ⅶ	0.9980	0.9493	0.8455	0.7515	0.6220
Remarks			15、16、17、18 is railway station				

Table 5.2. Earthquake reliability results of the converting stations

No.	Converting station	intensity	Reliability of converting stations under the given earthquake				
			0.05g	0.10g	0.20g	0.40g	0.80g
20	Ertaishan	Ⅷ	0.9953	0.9607	0.8235	0.7641	0.6247
21	Chongyi	Ⅶ	0.9976	0.9678	0.8518	0.7119	0.5620
22	Taihe	Ⅶ	0.9992	0.9313	0.8683	0.6963	0.5836
⋮	⋮				⋮		
54	Mianfeng	Ⅶ	0.9965	0.9640	0.8382	0.7611	0.5858
55	Linqiong	Ⅶ	0.9966	0.9645	0.8437	0.7636	0.5644
60	Xujiadu	Ⅶ	0.9953	0.9388	0.8339	0.7115	0.6156

Table 5.3. Earthquake reliability results of the electric transmission lines

No.	electric transmission lines			Reliability of electric transmission line under the given earthquake				
	Starting	→	Terminal	0.05g	0.10g	0.20g	0.40g	0.80g
1	1	→	50	0.9974	0.9531	0.8628	0.7725	0.6823
2	2	→	20	0.9956	0.9416	0.8832	0.7772	0.6679
3	3	→	20	0.9967	0.9731	0.8566	0.7948	0.6601
⋮		⋮				⋮		
74	56	→	60	0.9982	0.9581	0.8704	0.7697	0.6863
75	57	→	51	0.9983	0.9432	0.8747	0.7811	0.7043
76	57	→	58	0.9968	0.9575	0.8641	0.7768	0.6842

5.2. Network Connectivity Analysis Results

The Depth-First Search Algorithm code is written using C++ language under MS VC++ 6.0 conditions. The calculating program will start and save the calculated results automatically after reading the network model data files. Part of the arranged calculated results is shown in **Table 5.4**. In addition, to study the "weight" of nodes in network model, No. 25 node which has the maximum "weight" value is designated to be disabled based on general weighted network model (VA), and the calculated results of this model is listed in **Table 5.4** too. The calculated results indicate that the Depth-First Search Algorithm based on adjacency list storage method is reliable and fast in the analysis of EPS network model.

Compare the connectivity results of Va with VA (**Table 5.4**), it can be find that the connectivity results of No. 45 converting station under two model is difference. While the latter is more close to the actual condition, this means VA model is more reliable in connectivity analysis of EPS. Before No. 25 node damaged, the unconnected converting stations is 16 for VA model, while the unconnected converting stations will increase to 23 after No. 25 node is damaged. This means No. 25 node play an important role in this EPS, i.e. the node connected to more power transmission line and is more sensitive in the control of EPS connectivity, and we define this node is more weight.

From the analysis above, it can be found that the node which has a more weight is the key node of the EPS. Whether the key nodes are effective will affect the connectivity of EPS significantly. Moreover if a node has a little input weight but a large output weight, the power transmission line connected to this node is key transmission line, and its working state will influence the connectivity greatly.

Table 5.4. Connectivity results of the practical EPS under Wenchuan MS8.0 Earthquake

No.	Converting station	Va	VA	No.25 node is disabled	No.	Converting station	Va	VA	No.25 node is disabled
20	Ertaishan	0	0	0	41	Tianming	0	0	0
21	Chongyi	0	0	0	42	Taikang	0	0	0
22	Taihe	0	0	0	43	Anxian	0	0	0
23	Majia	1	1	0	44	Yuanjiaba	1	1	1
24	Xinercun	1	1	0	45	Baishiyan	1	0	0
⋮	⋮		⋮		⋮	⋮		⋮	
38	Fenggu	1	1	1	59	Gaoxinxi	0	0	0
39	Yongxing	0	0	0	60	Xujiadu	1	1	1
40	Maoxian	1	1	1	Notes: 1: Connective，0: Not connective				

5.3. Network Reliability Analysis Results

The Win32 console application code for Monte Carlo method is written using C++ language under MS VC++ 6.0 conditions, and the calculating program is used to study the reliability of the example EPS. Due to the layout of pages, only parts of the calculated results are shown in **Table 5.5**. In order to divide the reliable degree of EPS, a reference criterion is given out as shown in **Table 5.6**. Assuming that when more then 2/3 of the reliability values locate in a range defined in **Table 5.6**, the reliability degrades corresponding to this range is regard as the seismic damage degree of the whole EPS.

From calculated results shown in **Table 5.5**, it can be conclude that when the PGA of design earthquake is 0.05 g all the 41 converting stations reliability values locate in [0.8, 1.0], that means the entire EPS network is nearly reliable according to **Table 5.6**; when the PGA of design earthquake is 0.2 g, 28 converting stations reliability values is located in [0.4, 0.8], and that means the entire EPS network is middle reliable; when the PGA of design earthquake is 0.4 g, 36 converting stations reliability values is located in [0.0, 0.4], and that means the entire EPS network is nearly unreliable and most of the network nodes cannot connect to electric power stations. The results achieved from the analysis above indicates the Monte Carlo method is fast and accurate in studying the network connective reliability of EPS, and the calculated data can be used to fast evaluate the post-earthquake reliability of EPS in disaster area.

Table 5.5. Reliability results of connective ability from power station to converting stations.

No.	Converting station	Design intensity	Connective reliability of converting stations under the given earthquake				
			0.05g	0.10g	0.20g	0.40g	0.80g
20	Ertaishan	Ⅷ	0.9999	0.9988	0.9398	0.6842	0.2447
21	Chongyi	Ⅶ	0.9882	0.8761	0.4822	0.1832	0.0225
22	Taihe	Ⅶ	0.9997	0.8869	0.4171	0.1024	0.0043
23	Majia	Ⅶ	0.9999	0.9470	0.4265	0.1575	0.0116
24	Xinercun	Ⅶ	0.9998	0.9324	0.5056	0.1277	0.0103
25	Longwang	Ⅶ	0.9999	0.9667	0.5596	0.2795	0.0707
26	Zhaojuesi	Ⅶ	0.9864	0.7681	0.2935	0.0590	0.0051

No.	Converting station	Design intensity	Connective reliability of converting stations under the given earthquake				
			0.05g	0.10g	0.20g	0.40g	0.80g
⋮	⋮				⋮		
56	Longxing	Ⅶ	0.9777	0.6769	0.3698	0.1847	0.0545
57	Wuhou	Ⅶ	0.9999	0.8785	0.4305	0.3437	0.0906
58	Tangkanjie	Ⅶ	0.9921	0.7437	0.1613	0.0090	0.0000
59	Gaoxinxi	Ⅶ	0.9734	0.6121	0.1425	0.0191	0.0004
60	Xujiadu	Ⅶ	0.9996	0.8611	0.4424	0.1901	0.0066
	Mean of reliability		0.9950	0.8736	0.4842	0.2070	0.0450

Table 5.6. Evaluation criterion for the electric power systems connective reliability

Reliability degrade	Nearly reliable	Middle reliable	Nearly unreliable
Reliability value range	[0.800,1.000]	[0.400,0.800)	[0,0.400)

6. CONCLUSION

In this paper, a two-value working state hypothesis of network elements is introduced for connectivity analysis of electric power system. Using this hypothesis, the EPS network connectivity model is built. Combining the element multi-value state assumption with network connectivity model, the network reliability model is developed. Adjacency list memory method is introduced to storage the information of EPS network model. A network connectivity analysis method based on depth-first algorithm is designed to study the electrical transmission ability of EPS. Following the earthquake reliability analysis of each simple element in EPS such as the power station, the converting station and the power transmission line respectively, the entire network reliability analysis process for a whole EPS based on Monte Carlo method is present with a flow chart. Finally the present methods are used to study the post-earthquake network connective reliability of a practical electric power system under Wenchuan MS8.0 Earthquake. The results derived from the case study indicates the Monte Carlo method is efficient and accurate in studying the network connective reliability of EPS, and the calculated data can be used to fast evaluate the post-earthquake reliability of EPS in disaster area

AKCNOWLEDGEMENT
This work was financially supported by the Special Research in Chinese Seismological Industry (201008005) from China Earthquake Administration, and the support is greatly appreciated.

REFERENCE

A.H.-S.Ang, J.Pirea. (1992). Seismic Probabilistic reliability assessment of electric power transmission system[A]. *11th* WCEE, **Madrid, Spain**: 5583-5589.

L Vanzi (1996). Seismic reliability of electric power networks: methodology and application [J]. *Structural Safety*, **18: 4**, 311-327.

G.Y. Liu, C.W. Liu, Y.J. Wang. Seismic Performance Analysis of Electric Power Network in Taiwan[A]. *International Conference on Advances and New Challenges in Earthquake Engineering Research*. **Harbin China**, 2002

Wan H., and Li N.H. (1995). Fast topology analysis method based on breadth first method [J]. *Proceedings of the Chinese Society of Universities*, **7(2):** 17-23.

Li T., Li J., Shen Z. (2000). Earthquake damage analysis of electric power system[J]. *World Earthquake Engineering.* **16:4,**19-24.

Wang, X.Z., and Li. X.L. (2001). Topology identification of power network based on incidence matrix[J]. *Power System Technology*. **25: 2**, 10-13.

Li J., He J., Li T. (2002). Seismic reliability analysis of large electric power systems[J]. *Journal of Harbin University of Civil Engineering and Architecture*. **35: 1**, 7-11.

Wang P., Wu X., Lu Z.Y., Lin K.Y. (2002). Connectivity judgment for electrical power network based on relation data base[J]. *Journal of Tianjin University Science and Technology*. **35: 4**, 501-505.

Song Y.T. (2003). Reliability evaluation of composite power systems using artificial intelligence techniques[J]. *Ph.D Dissertation*. Tsinghua University. Beijing.
Zhong B., Zhao Y., Zhou J.Q. (2005). Methods of power systems reliability assessment based on rough neural network[J]. *Journal of Chongqing University (Natural Science Edition)*. **28: 7**, 38-42.
Hua J. (2007). Study and application of Gaussian elimination algorithm in power system topology analysis. *Master Dissertation*. Shan Dong University. Ji-Nan.
Wen B., Niu D.T., Zhao P. (2007). An overview on aseismic reliability research in electric power system[J]. *Journal of Catastrophology*. **22: 4**, 86-90.
Cui Y. (2008). Matrix coloring method and its application in network topology analysis of power system[J]. *Power System Protection and Control*. **36: 16,** 52-56.