Power Grid Safety Assessment Based on Linguistic Casual Network Under Uncertanties

Eugene V. Brezhnev[1], Vyacheslav S. Kharchenko[2], Artem V. Boyarchuk[3]
Centre for Safety Infrastructure Oriented Research and Analysis
National Aerospace University ” KhAI”
Kharkiv, Ukraine
E-mail: [1] milesone@list.ru, [2] v.kharchenko@khai.edu, [3] a.boyarchuk@khai.edu

Abstract – **This paper is devoted to the solution of problems connected with power grid safety. States of power grid are specific conditions of power grid determined by voltage, current and frequency fluctuations. Criticality of grid is a marginal state of grid with nearly to loss of stability. The state of power grid is determined by states of its systems, conditioned by their mutual influence of different nature. These influences cause the change of state of each system during grid life cycle. Problem is closely related to risk to NPP safety due to state of power grid. When grid is close to loss of its stability (call it as grid instabilities) NPP risk increase. It means the power grid conditions might affect NPP safety. Problem is to evaluate risk of NPP-PG interconnections. The proposed approach is based on application of Bayesian Belief Network, where nodes represent different grid systems, and links are stipulated by different types of influences (physical, informational, geographic, etc.). The grid safety is evaluated by its criticality. The criticality and influence are treated as the linguistic values. It is suggested to evaluate criticality of system, considering the change of criticalities of all connected systems. Conditional probabilities are also represented by linguistic values. To demonstrate the approach to the grid safety analysis, Russian Sayano–Shushenskaya hydro power station accident is reviewed. BBN is suggested as a tool for NPP PG risk assessment.**

Keywords-power grid; computing with words; safety; influence; Bayesian Belief Network

I. INTRODUCTION

A. Motivation

The power grid (PG) is an interconnected network composed of power-generation stations, high-voltage transmission lines, lower voltage distribution systems, and other support components. PG is a highly controlled, dynamic and distributed network combined of different systems. This complexity of engineered systems is a consequence of several factors: the sheer size and interconnectivity of the PG, the safety requirements, the need to balance electricity supply and consumption – throughout the grid at all times, and the nature of electricity that it is generated as it is used. This means the PG requires continual surveillance and adjustment to ensure supply always matches demand.

Disturbances in PG operation can originate from natural disasters, failures, human factors, terrorism, and so on. Outages and faults will cause serious problems and failures in the interconnected power systems, propagating into critical infrastructures such as Nuclear Industries, Telecommunication systems, transportation systems, etc.

Therefore, it is of high priority to consider PG safety, mutual influence of its systems and forecast possible accidents and failures, considering their severity and high costs of recovery.

B. Work Related Analysis

There are a lot of approaches and techniques of PG safety assessment. An approach to PG safety analysis, taking into consideration technical, organizational, and individual aspects, is proposed by Linstone [1]. The PG safety analysis is supplemented by a set of geographic and economic aspects developed by Kaiser [2]. An approach for PG safety assessment, based on processing statistical data related to PG operation, is proposed by Holmgren and Molin [3]. The main task of the safety statistical analysis is to determine the failure probability distribution function and to assess power grid risk. Lack of statistics prevents the use of traditional statistical methods for PG safety assessment.

Beside well known techniques of probabilistic and deterministic PG safety analysis, there are a lot of different approaches used for PG safety assessment. Logic methods (Fault Tree Analysis and Event Tree Analysis), used for safety analysis, are applied in research done by Bedford and Cooke [4] and Hoyland [5]. Typical PG safety analysis techniques are connected with equipment failure analysis, environment and human factor. Nowadays, a new type of grid hazards – intentional attacks occur. This type of hazards is analyzed by the use of probabilistic approach together with conditional probabilities calculation. However, mutual influence of systems, taking into account dynamical aspects of functioning and variation of risks caused by their failures, is not considered. Recently, network modeling has been revived due to computer technology progress and increase of interest in complex systems analysis. Achievements in a graph theory for complex systems analysis are reviewed by Albert and Barabasi [6]. A topology of North American Power System is analyzed. Graph is used as a model by Albert [7]. Evaluations, specifying Power System topology, lack of connectivity, while demounting vertexes that connect transmitting substations, are calculated. Two types of power grid safety hazards are analyzed: random failures and antagonistic (intentional) attacks.

Some methods used for PG safety analysis are qualitative and based on expert evaluations. Analysis results are represented in the form of risk matrix, containing failure effect frequency and severity. Qualitative techniques of safety analysis do not operate numeric data providing results as descriptions, recommendations. The safety assessment is related to qualitative description of frequency of undesired events, damage and threat scenario. In [8] Glass specified that safety of a PG can be improved by implementing of process automation in disturbance situations.

The PG safety is affected by many factors regarding its design, manufacturing, installation, commissioning, operation and maintenance. Consequently, it may be extremely difficult to construct a complete mathematical model for the system in order to assess the safety because of inadequate knowledge about the basic failure events. This leads inevitably to problems of uncertainty in PG safety assessment.

The power grid is a very complex system. It is characterized by huge number of nodes and links between nodes with increasing structural complexity; links between nodes could change over time, have different weights, directions, etc. There are some PG attributes such as self-adaptation, PG self-healing, etc. which keep us aside from adequate understanding of PG nature, behavior types, accident mechanisms, etc.

There are a lot of risks as the inherited essences of PG life cycle. Due to high PG complexity, its dynamic nature these risks are not static. More over PG life cycle is characterized by complicated risk flow when safety and reliability issues might endanger the cyber security and vise verse. The risk associated with PG weakest link could compromise the safety and reliability of PG as a whole.

As an application of probability theory, Bayesian belief network (BBN) proposed by Heping [9] is a powerful tool both for graphically representing the relationships among a set of variables and for dealing with uncertainties in such variables. Many applications have proven that BBN is a powerful technique for reasoning relationships among a number of variables under uncertainty. BBN was successfully applied to ecological risk assessment and fault diagnosis in complex nuclear power systems.

But, traditional BBN requires too much precise information in the form of prior and conditional probability tables, and such information is often difficult or impossible to obtain. In particular, in dealing with indirect relationships, even domain experts may find that it is usually difficult to make precise judgments with crisp numbers, that is, to assign an exact number to the probability that consequences happen given the occurrence of an event. In certain circumstances, a verbal expression, e.g., “very unlikely” or interval value, e.g., 0.15, 0.20 of probabilistic uncertainty may be more appropriate than numerical values.

Common disadvantages of mentioned approaches are as follows: PG safety is considered a static attribute; no consideration for risk flow inside of PG; no consideration provided for mutual influences between power grid systems; there is a lack of publications for PG safety assessment with BBN using linguistic experts’ judgments.

C. Goal of the Paper

To assure the PG safety, it is necessary to consider and thoroughly analyze the nature of interaction among PG systems and evaluate the risk flow. The goal of the paper is to introduce an approach to power grid safety assessment, considering the different type of influence among its systems and evaluate safety using linguistic BBN. This technique can be useful to evaluate PG safety, taking into consideration mutual influences of its systems when all data available are represented by expert’s knowledge.

II. Principles of Power Grid Safety Analysis With Linguistic Casual Network

A. General Principles of Analysis

The PG safety analysis is carried out taking into consideration principles of dynamism, hierarchy, uncertainty, and influence (interaction) of subsystems.

Principle of dynamical analysis assumes to record changes of system criticality during the operation as a result of changes of its states (transition to state of non-operability). At each stage of life cycle, the criticality assessment specification and adjustment of criticality matrices [10], taking into consideration probable changes, are carried out.

The principle of hierarchy assumes representation of grid structure as a hierarchy.

The principle of influence of subsystem failures of i-level (on subsystem failure criticality of the same level) and influence on subsystems of (i-1)-level (higher) is important.

The safety of all influenced subsystems must be reconsidered.

The principle of uncertainty takes into consideration information incompleteness and uncertainty related to the conditions that cause PG accidents.

The principle of the weakest link risk flow is based on assumption that PG safety might be evaluated on risks associated with the weakest link of the grid.

The PG safety is an integral value composed of grid systems safety values. The grid safety is determined by uncontrolled mutual influence among grid systems. It is worth to note that influence exists on all grid levels and have to be taken into consideration when providing grid systems safety.

B. Types of Influences Between Power Grid Systems

According to the *principle of influence*, all influences (or relationships), existing in PG, can be divided into several hierarchy levels. The influence is an ability of one PG system to determine the state, characteristics or processes in other systems. Any type of influence is a time dependent value. The changes in NPP state and characteristics stipulate the changes in the influence value.

Generally, influences could be classified into different types [11]:

– Physical $I_{phys}(S_1 \rightarrow S_2)$ – a physical reliance on electricity flow between PG systems S_1 and S_2;

– Informational $I_{inform}(S_1 \rightarrow S_2)$ – a reliance on information transfer between PG systems S1 and S2 (via through I&C systems);

– Geographic $I_{inform}(S_1 \rightarrow S_2)$ – a local event occurred in PG system S1 affects power grid’s system S2 due to physical proximity;

– Logical $I_{logical}(S_1 \rightarrow S_2)$ – an influence that exists between power grid systems S1 and S2 that does not fall into one of the about categories;

– Organizational $I_{organiz}(S_1 \rightarrow S_2)$ (influences through policy, regulation, markets). An influence that exists due to policy or procedure that relates a state change in one elements of PG to subsequent effect on other systems;

– The societal influence $I_{organiz}(S_1 \rightarrow S_2)$ that one PG system may have one of societal factors as public opinion, fear and confidence, for example, staff of other PG system.

The modern PG has become the informational infrastructure. As a result a new type of influences might be introduced in the scope of analysis. For example, physical state of one system might influence the informational state of other system, etc.

The formalization of influences between PG systems is very helpful for its safety assessment based on criticality matrices. Generally, criticality matrix is represented as FMECA table. The traditional FMECA [12] is the most widely used reliability analysis technique on the initial stages of system development.

For example, if PG system S_1 consists of three subsystems S_{11}, S_{12}, S_{13} then criticality matrix which represents the system S_1 might be presented as shown in the Table 1.

TABLE I. CRITICALITY MATRIX FOR SYSTEM S_1

System S_1		**Severity of Failure Mode**		
		H	M	L
Failure rate	H	🟥	S_{12}	🟥
	M	🟥	🟨	S_{13}
	L	S_{11}	🟨	🟨

Traditionally, the criticality assessment is performed by calculating the criticality accident (failure) as a product of its severity and probability:

$$Crt(S_i) = P(S_i) \times Sev(S_i), \quad (1)$$

where S_i is PG system; $P(S_i)$ is probability of S_i accident; $Sev(S_i)$ – severity of accident consequences.

According to the principle of hierarchy, the grid structure might be represented as a hierarchy. In this case, the safety of PG systems of higher level hierarchy might be evaluated as a sum of criticalities of power grid systems of lower level hierarchy. For example, considering the criticalities of S_{11}, S_{12}, S_{13} as subsystems of S_1, its total criticality could be calculated as:

$$\begin{aligned} Crt(S_i) &= P(S_1) \times Sev(S_1) + P(S_2) \times Sev(S_2) + \\ &+ P(S_3) \times Sev(S_3) = \sum_{i}^{I} P(S_i) \times Sev(S_i). \end{aligned} \quad (2)$$

Another approach might introduced considering the weakest link of PG. In this case the system total criticality might be equaled its weakest link criticality.

It is suggested to treat criticality as PG system's safety inverse value. The more system criticality the less its safety and vice versa.

It should be noted that criticality matrix might be used to represent different states of environment and its influence on PG systems. We suggest to use the environmental FMECA where different natural hazards (earthquake, flooding, etc.) are considered as different failures modes characterized by its probability and severity for the nearest PG systems. This probability of system accident (natural disaster) and its severity could be handled as linguistic or numerical variable. Hence, criticality is also treated correspondently either linguistic or numerical variable.

A linguistic variable is characterized by a quintuple (x, T(x), U, G, M) in which x is the name of variable; T(x) is the term set of x, that is, the set of names of linguistic values of x with each value being a fuzzy number defined on U; G is a syntactic rule for generating the names of values of x; and M is a semantic rule for associating with each value its meaning.

The set of state Ω_{Si} of any PG system S_i is determined as:

$$\Omega_{Si} = \{Crt(S_i)=High,\ Crt(S_i)=Medium,\ Crt(S_i)=Low\}. \quad (3)$$

Any accident or failure of power grid system leads to the change of criticality of all connected systems due to principle of risk flow. When a failure of one system occurs, the criticalities of all dependent systems are recalculated.

The prognosis and assessment of PG system service life, based on real time measurements, will help to identify grid systems most likely to fail. The potential estimation methods and equipment service life prediction for complicated systems consist of deterministic, statistical, physical-statistical and methods based on expert knowledge. These methods are used to predict the probability of accident of any system S_{ij} of S_i.

This criticality assessment is used to support the subjective expert judgment expressed by linguistic variable on the initial power grid system state. The more system criticality calculated on (2) the more confident expert's opinion on the criticality of each node of PG.

C. Bayesian Belief Network as a Model for Power Grid's safety assessment

BBN is a classical causal network represented as a pair N= {(V, E), P} where V and E are the nodes and the edges of a Directed Acyclic Graph (DAG), respectively, and P is a probability distribution over V. Discrete random variables $V = \{X_1, X_2, ..., X_n\}$ are assigned to the nodes while the edges E represent the causal probabilistic relationship among the nodes. Each node in the network is annotated with a Conditional Probability Table (CPT) that represents the conditional probability of the variable given the values of its parents in the graph. The CPT contains, for each possible value of the variable associated to a node, all the conditional probabilities with respect to all the combinations of values of the variables associated with the parent nodes. For nodes that have no parents, the corresponding table will simply contain the prior probabilities for that variable.

The principles behind BBN are Bayesian statistics and concentrate on how probabilities are affected by both prior and posterior knowledge. In order to extend the classic BBN into fuzzy BBN which is capable of dealing with linguistic variables, fuzzy numbers and their operations must be used.

The state of each PG system is determined by types of influence mentioned above. The Figure 1 represents a fragment of network, which characterizes the PG, where S_1, S_2 are the parent nodes and system S_3 is a child node.

Generally, the several BBNs might be required to represent only one PG. These networks have the same nodes as PG systems, but different types of influence, which stipulate the different causal links (physical, geographical, organizational, logical, informational and societal) between nodes. The different types of influence are characterized by its own weight. The more weight of the given type of influence (according to the expert judgments) the more PG sensitive to this type of influence.

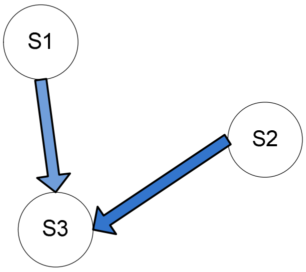

Figure 1. A fragment of network, which characterizes the PG.

Apparently, the physical influence is more important, when PG safety is considered. But all types of influences should be considered to provide more accurate PG safety evaluation. For each type of influence might be introduced its own type of PG system particular criticality. It means that PG could be more vulnerable to the change of one type of influence and, at the same time, be insensitive to other type influence change.

Considering the types of influence mentioned it is assumed that the total PG system criticality is a function of power grid system's particular criticalities, stipulated by the particular types of influence, i.e.,

$$Crt(S_i) = f(Crt^{org}(S_i), Crt^{fhys}(S_i), Crt^{geo}(S_i), Crt^{\log}(S_i), Crt^{soc}(S_i), Crt^{\inf}(S_i)) \qquad (4)$$

where $Crt\ (S_i)$ - the total power grid system criticality; $Crt^{org}(S_i)$ – particular criticality of power grid system, conditioned by organizational influence in PG; $Crt^{fhys}(S_i)$ – particular criticality of power grid system, conditioned by physical influence in PG; $Crt^{\log}(S_i)$ – particular criticality of power grid system, conditioned by logical influence in PG; $Crt^{\inf}(S_i)$ – particular criticality of power grid system, conditioned by informational influence in PG; $Crt^{soc}(S_i)$ – particular criticality of power grid system, conditioned by societal influence in PG.

Depending on the scale used to evaluate criticality, each PG system could be characterized by the tuple of its criticalities values, considering the types of influence, which determine these criticalities.

Example of power grid system criticality tuple is shown in the Table 2.

TABLE II. EXAMPLE OF POWER GRID SYSTEM CRITICALITY TUPLE

	Type of influence					
	Physical	***Informational***	***Geographic***	***Logical***	***Organizational***	***Societal***
PG Si	***Criticalities caused by the given type of influence***					
PG S1	H	H	M	L	L	L
PG S2	H	M	M	L	L	H
…..						
PG Sn	L	H	M	M	M	L

This tuple might be interpreted as combination of risks for particular PG systems due to different type of influences caused by other systems inside of PG.

The following task is to calculate the particular criticality, stipulated by the given type of influence. We suggest using BBN to evaluate the criticalities of the PG systems.

According to approach, it is suggested to construct BBN for each type of influence. Each node of BBN is represented by criticality matrix. Nodes are connected by links, which represent the different types of influence.

Hence, BBNs, which describe the PG system safety, consist of set of nodes. For each node the set of state is introduced. As mentioned, the state of node is characterized by a value of its criticality, calculated according to (2).

Every node also has a conditional probability table (CPT), associated with it. Conditional probabilities represent likelihoods based on prior information or past experience. A conditional probability is stated mathematically as, i.e., the probabilities of power grid system (child node) being at state characterized by expressions "Criticality is High (Medium, Low)", considering all possible combinations of other PG systems (parents' nodes) criticalities (High, Medium, Low).

As mentioned these conditional probabilities might be represented by linguistic values (for example High, Medium, Low).

Fragment of linguistic CPT is shown in the Table 3.

TABLE III. FRAGMENT OF CPT

S_1			**S_2**			**S_3**	
Criticality			***Criticality***			***Criticality***	
H	***M***	***L***	***H***	***M***	***L***	***H***	**…**
+			+			P(Crt(S_3)=H/Crt(S_1)=H, Crt(S_2)=H)=*High*	…
+				+		P(Crt(S_3)=H/Crt(S_1)=H, Crt(S_2)=M)=*Low*	…
						…….	..
	+		+			P(Crt(S_3)=H/Crt(S_1)=M, Crt(S_2)=H)=*Low*	…

Let us consider the fragment of BBN of S_1, S_2, S_3 represented on Figure 1., where criticality of S_3 (child node) is conditioned by criticalities both of S_2, S_3 (parents' nodes).

According to [13], probability of S_3, being at one of the established state Ω_{S3} depending on the states of parents nodes, could be determined as:

$$P(S_3^{(k)}) = \sum_i \sum_j P(S_3^{(k)} / S_1^{(i)}, S_2^{(j)}) * P(S_1^{(i)}) * P(S_2^{(j)}), \qquad (5)$$

where $P(S_3^{(k)})$ – a probability for S_3 being at *k*-th state; $P(S_3^{(k)} / S_1^{(i)}, S_2^{(j)})$ – a conditional probability for PG system S_3 to be at *k*-th state, provided system S_1 being at *i* th state and system S_2 being at j – th state; $P(S_1^{(i)})$ – probability for S_1 being at *i*-th state determined by expert, taking into account value (2); $P(S_2^{(j)})$ – probability for S_2 being at j-th state determined by expert, taking into account value (2).

Whereas linguistic BBN is used for PG safety analysis all probabilities in formula (5) are represented as linguistic variables.

The probability for system S_1 of being at the state described by expression Criticality - High" is calculated as

$$
\begin{aligned}
&P(Crt(S_3)=High))=\\
&P(Crt(S_3)=H / Crt(S_1)=H, Crt(S_2)=H)*P(Crt(S_1)=H)*P(Crt(S_2)=H)+\\
&+P(Crt(S_3)=H / Crt(S_1)=H, Crt(S_2)=M)*P(Crt(S_1)=H)*P(Crt(S_2)=M)+\\
&+P(Crt(S_3)=H / Crt(S_1)=H, Crt(S_2)=L)*P(Crt(S_1)=H)*P(Crt(S_2)=L)+\\
&+P(Crt(S_3)=H / Crt(S_1)=M, Crt(S_2)=H)*P(Crt(S_1)=M)*P(Crt(S_2)=H)+\\
&+P(Crt(S_3)=H / Crt(S_1)=M, Crt(S_2)=M)*P(Crt(S_1)=M)*P(Crt(S_2)=M)+\\
&+P(Crt(S_3)=H / Crt(S_1)=M, Crt(S_2)=L)*P(Crt(S_1)=M)*P(Crt(S_2)=L)+\\
&+P(Crt(S_3)=H / Crt(S_1)=L, Crt(S_2)=H)*P(Crt(S_1)=L)*P(Crt(S_2)=H)+\\
&+P(Crt(S_3)=H / Crt(S_1)=L, Crt(S_2)=M)*P(Crt(S_1)=L)*P(Crt(S_2)=M)+\\
&+P(Crt(S_3)=H / Crt(S_1)=L, Crt(S_2)=L)*P(Crt(S_1)=L)*P(Crt(S_2)=L).
\end{aligned}
$$

Similarly all system S_1 of being at the state described by expression Criticality – Meduim and Criticality-High.

Semantics of linguistic variables are supported by fuzzy sets. Fuzzy sets are obtained by the means of fuzzy arithmetic for triangular fuzzy numbers.

A triangular fuzzy number denoted by M = <m, α, β>, has the membership function:

$$
\mu_M(x)=\begin{cases} 0, \ for \ x \le m-\alpha \\ 1-\dfrac{m-x}{\alpha}, \ for \ m-\alpha < x < m \\ 1-\dfrac{x-m}{\beta}, \ for \ m < x < m+\beta \\ 0, \ for \ x \ge m+\beta \end{cases} \tag{6}
$$

The point m, with membership grade of 1, is called the mean value and α, β are the left hand and right hand spread of M respectively.

If M = <m, α, β> and N = <n, γ, δ> are two TFNs then their addition is expressed as:

$$M \oplus N = <m+n, \alpha+\gamma, \beta+\delta>. \tag{7}$$

Multiplication $M \otimes N$ of two TFNs is not necessarily a triangular.

A good approximation is as follows:

$$M \otimes N = <m,\alpha,\beta> \otimes <n,\gamma,\delta> \cong <mn, m\gamma+n\alpha, m\delta+n\beta>. \tag{8}$$

Division of two TFNs is

$$\frac{M}{N} \cong \left\langle \frac{m}{n}, \frac{m\delta+n\alpha}{n^2}, \frac{m\gamma+n\beta}{n^2} \right\rangle. \tag{9}$$

These fuzzy arithmetic operations are used to calculate new linguistic probabilities represented by TFNs. These fuzzy probabilities usually do not match any linguistic term in the initial term set (High, Medium, Low), so a computing with words (CWW) procedure is needed to express the result in the original expression domain.

The CWW is used to express the result in the original expression domain. CWW procedure uses the linguistic assessments and makes computations with them. Foundations and applications, providing the current status of theoretical and empirical developments in CWW, can be found in [14].

A linguistic aggregation operator based on the extension principle acts according to

$$S^n \xrightarrow{\tilde{F}} F(R) \xrightarrow{app_1(\cdot)} S, \tag{10}$$

where S^n symbolizes the n Cartesian product of S, $\tilde{F}$ is an aggregation operator based on extension principle, F(R) the set of fuzzy sets over the set of real number R, app_1: $F(R) \longrightarrow S$ is a linguistic approximation function that returns a label from the linguistic term S, whose meaning is the closest to the obtained unlabeled fuzzy number, and S is the initial term set.

According to (5), the probabilities for system S_1, being at the state described by expression "Criticality - High", "Criticality – Medium" and "Criticality-High" might be calculated.

The power grid system S_i state, conditioned by the given type of influence, is determined on the criterion:

$$
\begin{aligned}
&Crt(S_i)=arg\,max(P(Crt(S_i)=High),\\
&P(Crt(S_i)=Medium), P(Crt(S_i)=Low),
\end{aligned} \tag{11}
$$

where $P(Crt(S_i)=High)$ – a probability of power grid system of being at the state described by linguistic value High; $P(Crt(S_i)=Medium$ – probability of power grid system of being at the state described by linguistic value Medium; $P(Crt(S_i)=Low$ – probability of power grid system of being at the state described by linguistic value *Low*.

III. HPP ACCIDENT CASE STUDY BASED ON LINGUISTIC CASUAL NETWORK

To demonstrate the approach to the power grid safety analysis, using the linguistic BBN, Russian Sayano–Shushenskaya HPP failure (August, 2009) is reviewed [15]. This HPP is one of the largest (together with Bratskaya HPP) one, used for power control of the whole power system with installed capacity - 6,4 mm kW, annual output - 22,8 bln kW p.h. Ten hydraulic units, each of 640 kW, are installed in the plant.

The BBN is built for fragment of Siberian power systems. BBN's nodes are criticalities matrixes of Sayano–Shushenskaya HPP – S_1, Mayansk HPP – S_2, Bratskaya HPP– S_3, Thermal Power Plant (TPP) of Bratsk – S_4.

Only physical influence is considered to evaluate state of S_1 when conditional probabilities are expressed in linguistic values. Each node of Siberian power systems is completed by linguistic conditional probabilities table (see Table 4).

The increasing of load from Bratskaya HPP and Mayansk HPP increased the criticality of S_1 and, finally, led to destruction of HPU – 2 (S_{32}). Increasing of criticality of S_1 led to increasing criticality of S_4.

TABLE IV. FRAGMENT OF SIBERIAN POWER SYSTEMS CONDITIONAL PROBABILITIES TABLE (BEFORE ACCIDENT)

Mayansk HPP, S_1			**Bratskaya, HPP S_2**			**Sayano–Shushenskaya HPP, S_3**	
Criticality			***Criticality***			***Criticality***	
H	***M***	***L***	***H***	***M***	***L***	***H***	**…**
+			+			$P(Crt(S_3)=H/Crt(S_1)=H, Crt(S_2)=H)=$*High*	…
+				+		$P(Crt(S_3)=H/Crt(S_1)=H, Crt(S_2)=M)=$*High*	…
						…….	..
	+		+			$P(Crt(S_3)=H/Crt(S_1)=M, Crt(S_2)=H)=$*Low*	…

According to (5) the linguistic probabilities of S_3 being at the different states are calculated as:

$$P(Crt(S_3)=High))=High;$$
$$P(Crt(S_3)=Medium))=Low;$$
$$P(Crt(S_3)=Low))=Low.$$

Considering (7), it is suggested that before Sayano–Shushenskaya HPP accident its criticality value might had been *High*.

IV. CONCLUSION AND FUTURE WORK

The proposed technique may be applied to PG safety value prediction, taking into account its systems influence. The technique is based on the use of dynamical criticality matrices hierarchy. The power grid's capacity used to predict the possible safety change could be improved by implementing of the decision making system.

The technique suggested in the paper is considered as a part of this system. The PG safety assessment is carried out taking into consideration principles of dynamism, hierarchy, uncertainty and mutual influence of systems. BBN is used to predict the particular criticality of PG system, conditioned by the given type of influence. CWW is suggested to determine the probabilities of PG states expressed by linguistic values.

The results of analysis may be used to determine effective safety management strategies.

Consideration of the difference types of influence allows improving the accuracy of PG safety value.

Next step of technique enhancement will be related to consideration of Ukrainian NPP safety analysis, taking into consideration the types of influences of power grid and development of decision making tool-based system.

Main math tool would be based on dynamic BBN which allow considering the changes of systems states and perform safety assessment in time-related manner.

REFERENCES

[1] H. Linstone, "Multiple Perspectives for Decision-Making: Bridging the Gap Between Analysis and Action", North-Holland, Amsterdam, 1984.

[2] A. Kaijser, The Swedish Infrastructure – Historical Development and Future Challenges, Carlsson, Stockholm, 1984.

[3] A. Holmgren and S. Molin, Using Disturbance Data to Assess Vulnerability of Electric Power Delivery Systems, Journal Infrastructure systems, American Society of Civil Engineers (ASCE), Volume 12, Issue 4, pp. 243-251, 2006.

[4] T. Bedford and R. M. Cooke, Probabilistic Risk Analysis: Foundation and Methods, Cambridge University Press, Cambridge, England, 2001.

[5] A. Hoyland and M. Rausald, System Reliability Theory: Models and Statistical Methods, Wiley, New York, USA, 1996.

[6] R. Albert and A.-L. Barabasi, Statistical Mechanics of Complex Networks, Review of Modern Physics, Volume 74, pp. 23-26, 2002.

[7] R. Albert, I. Albert, and G. L. Nakarado, Structural Vulnerability of North American Power Grid. Physical review E., 69, 025193 (R) (Rapid Communication), pp. 95-104, 2004.

[8] R. Glass, Simulation and Analysis of Cascading Failure in Critical Infrastructure, Proceeding of Working Together: R&D Partnerships in Homeland Security, Boston, April 2005, pp. 45-56, 2005.

[9] P. Heping and L. Lin, "Fuzzy Bayesian networks a general formalism for representation, inference and learning with hybrid Bayesian networks", IJPRAI, 14(7), 941–962, 2000.

[10] I. Elyasi Komari, V. Kharchenko, and E. Babeshko, Extended Dependability Analysis of Information and Control Systems by FME(C)A-Technique: Models, Procedures, Application, in Proceedings of the Conference on Dependability of Computer systems, Brunow, Poland, 30 June-02 July 2009, IEEE Computer Society, Los Alamitos, California, pp. 25-32, 2009.

[11] E. Brezhnev, Risk-analysis in critical information control system based on computing with words' model, in Proceeding of 7th International Workshop on Digital Technologies, Circuit Systems and Signal Processing, Zilina, Slovakia, 11-21 November, pp. 67-72, 2010.

[12] J. B. Bowles, "An assessment of PRN prioritization in a failure modes effects and criticality analysis", Journal of the IEST, Volume 47, N: 51-6. 2004.

[13] On-line Tutorial on Bayesian nets and probability:http://www.dcs.qmw.ac.uk/%7Enorman/BBNs/BBNs.htm [retrieved: February, 2013].

[14] L. Zadeh and J. Kacprzyk, Computing with words in Information / Intelligent Systems – Part : Foundation; Part 2, USA, 2001.

[15] "Causes of destruction of Sayano–Shushenskaya HPP hydraulic unit 2", http://zhurnal.lib.ru/b/boris_i_k/prichinyrazruschenijagidroagregata2sschges.shtml [retrieved: December, 2012].