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The use of Extended Petri Nets in Analyzing the Reliability of MV / LV Distribution Transformer Stations

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Introduction

Studies aimed at analysing and evaluating the reliability properties of electrical equipment are vital for the proper operation of equipment in companies involved in the distribution of electricity. The results of this analysis have the potential for contributing to the optimal design and operation of power equipment in the future.

The systematically increasing unit power rating of stations and MV lines increases the risk of exclusion of larger power values in the event of their failure, and therefore greater restrictions in the supply of electricity to consumers. This results in considerable material losses and, in extreme cases can lead to health hazards or the loss of human life.

Certainty the supply of electricity to consumers is a serious problem for network companies, especially for those distribution companies directly responsible for servicing customers. Power outages are responsible for economic and financial losses of distributors as resulting from the costs of repair as well as the reduction of power consumption by the public during the time of failure.

The commonly used methods in reliability theory to calculate the parameters characterizing the failure rate of subjects in the case of stations do not fulfil their function. The main reason is the fact that they can only be used in cases, where the probability density distributions of the time of proper operation to breakdown as well as the time of repairing the various equipment components have exponential distributions. In relation to stations, this condition is not met. The individual functions are characterized by log-normal distributions, Weibull, or gamma. Only a few are characterized by exponential distributions. In this case it is possible to apply simulation methods that take into account the form of the probability density functions at various times. Such methods include those based on extended Petri networks, the Monte Carlo method, a method based on neural networks, or based on genetic algorithms.

In this article the author presents the results of a verification of the suitability of a method based on extended Petri networks to analyse the reliability of MV / LV transformer distribution stations. The results obtained by using the simulation program, as based on the terms of extended Petri nets, were compared with the results derived from empirical analysis of station failures.

Theoretical basis of the extension of Petri nets

The theory and concept of Petri nets emerged in the search for a simple and effective method of describing and analysing of information and data flow in processing systems. They are abstract models of information flow, with which it is possible to model, in a uniform language, the systems and processes of information transfer. The major advantages of Petri nets are: a uniform language to describe different levels of abstraction (detail), the possibility of a simple transition to the next level as well as the ability to correctly assess the selected model's level of abstraction. An advantage of Petri nets is also the possibility of simulating multiple concurrent processes. This type of a situation exists in most technical systems, which consist of many technologically interrelated pieces of equipment and machinery that are subject to independent factors, such as: external interference, aging processes, human factors, etc. [1–4].

Carl Adam Petri as a starting point in his work made the assumption, that the notion of a state is inadequate as a basic and key concept to describe the cause and effect relationships in a system, since it is related to the existence of a synchronization of the time scale. Petri net theory is based on the concepts of condition as well as event. The concept of a state is used in an indirect way and is defined by a set of conditions that in any given situation independently (in parallel) apply. In this theory, a set of concurrent conditions is referred to as a configuration. A configuration is a mapping of a simulated (modeled) system both in time and space. In order to properly present a model of an analysed dynamic system in terms of extended Petri net, it is necessary to interlink configurations, that can occur in the system and its environment. These configurations are described by sets of conditions that apply to a given situation. Changing a configuration is equivalent to changing the existing conditions, which are subject to the operation of elementary events and changes [2–4].

Petri nets are defined by the expressions [2, 5]

$$< A,T,F,\mu_0,R >, \qquad (1)$$

where A – the set of all places ($A = S \cup L$); S – elementary place; L – decisive place; T – transition; F – neighbouring relations ($F \subset A \times T \cup T \times A$); μ_0 – the initial marking of the network, R – set of network records.

S elements are called elementary places. They perform the function of determining the condition. If a place is empty, it means that the condition is not met. If there is a marker in the place, then the condition is met. *L* places are called decisive; they describe the relationship between a transition and register values in Petri net. The state of a place equal to one fulfils the condition (true), and zero does not fulfil the condition (false).

A helpful feature of working with Petri nets is the graphical representation of various elements from the set representing the network.

In a graphical form the elementary places are marked as circles. If a circle is empty, it means, that a condition related to it is not met. If, however, in a circle there is a marker (usually in the form of a black circle), then the condition related to it is met (Fig. 1).

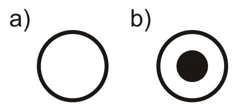

Fig. 1. The method of marking places in the terms of Petri nets: a) inactive place; b) the active place

T transitions contain logical conditions of the network and control the movement of markers. With each transition $t_i \in T$ is related to a procedure ρt_i, describing the modification of the network register values.

In graphic form, they are presented as squares, rectangles, and often as thick lines (Fig. 2).

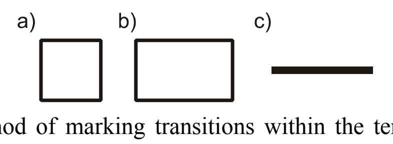

Fig. 2. Method of marking transitions within the terms of Petri nets

L is a place of decision; it describes the relationship between T transitions and network registers. In the drawings, they are presented as a triangle with an arrow that points to the occurrence of the relationship between a condition and an event (Fig. 3).

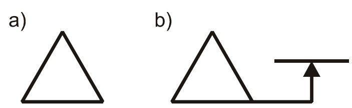

Fig. 3. Method of indicating decisive places in terms of Petri nets

For there to be an inducement (activation) of a transition the condition must be fulfilled

$$\forall A_j \in I(t_i): \mu(A_j) \neq 0, \qquad (2)$$

where

$$I(t_i) = \{A_j / A_j \in A \wedge (A_j, t_j) \in F\}, \qquad (3)$$

as well as

$$\mu(A_j) = \begin{cases} 0, & \textit{when } A_j \in S \textit{ and place is empty or} \\ & A_j \in L \textit{ and the condition is not met} \\ \neq 0, & \textit{in opposite case,} \end{cases} \qquad (4)$$

where $I(t_i)$ – a set of input places; $\mu(A_j)$ – the state of place A_j.

In case of an activation of the ti transition there is a change in the network markings according to the following principles

$$\forall S_j \in I(t_i): \mu(S_j)^* = {}^*\mu(S_j) - 1 \wedge \forall S_k \in 0(t_i): \mu(S_k)^* = \\ = {}^*\mu(S_k) + 1, \qquad (5)$$

where $^*\mu(S_n)$, $\mu(S_n)^*$ – marking the S_n position before and after activation of the transition t_i; $0(t_i)$ – a set of output places of transition t_i, where

$$0(t_i) = \{S_k / S_k \in S \wedge (t_i, S_k) \in F\}. \qquad (6)$$

A stimulation of the transition causes an execution of the associated procedures, where the execution of the *T* transition will not delay the movement of the marker. Network registers are memory cells holding variables available from all network transits.

A sample graph of a subject (device), as drafted in terms of Petri nets, is shown in Fig. 4.

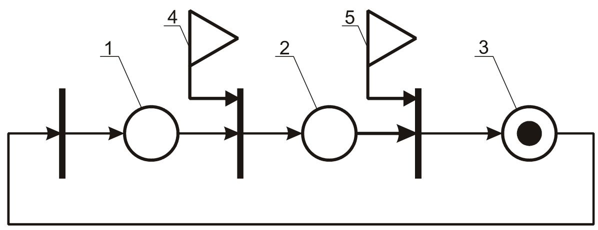

Fig. 4. An example of a configuration graph of a subject (device): 1 – an event involving the proper operation of the subject, 2 – an event involving the failure (damage) of the subject, 3 – an event involving the device awaiting for its readiness to be used, 4 – a place of decision as conditional on the change of the event from readiness to a failure, 5 – a place of decision as conditional on the change event of failure to awaiting of activation in a state of readiness

Assuming that at the time of switching the subject is fit (undamaged), the marker is in position 3 – awaiting for activation in a state of readiness. After "firing up" the network, there is an unconditional transition of the marker to position 1, or the proper operation of the site. This operation continues until, the condition is fulfilled and the subject breaks down (condition 4). In that case, there is a transition to position 2, the failure of the subject. This event continues until condition 5 is fulfilled, or the subject is repaired. In that case, there is a transition of the marker to position 3 Naturally, in practice additional transitions conditioning the transition of a subject from a position of correct operation (1) directly to a position of awaiting for activation to a position of readiness to be used (3) are necessary.

A structural reliability assessment model based on extended Petri network is very convenient for analysis, especially for complex and sophisticated networking systems. It allows for the determination of many parameters of reliability, such as [5]:

- Intensity of the failure;
- Intensity of power interruptions to customers;
- Distributions of periods of correct operation of individual circuit elements;
- Distributions of periods of failure of individual elements;
- Downtime distributions of individual elements as a result of the failure of others;
- Distributions of periods in the supply of electricity to consumers;
- Distributions of periods and number of outages of electricity to customers.

This breadth of information concerning reliability is not provided by virtually any analytical method. It should be noted, that a model based on Petri networks enables an analysis regardless of the types of distributions of reliability functions as well as the functions of recovery of individual components of the considered system.

Reliability analysis of pole-mounted distribution transformer stations in a block system

MV/LV pole-mounted distribution transformer stations are characteristic of rural areas and outlying towns. They have a simplified block structure, do not have busbars. A structural diagram of such a station is shown in Fig. 5.

Because damage to any device crashes the entire station, the station possesses a serial fallibility structure, as shown in Fig. 6.

The model of an analysed MV / LV station in the terms of extended Petri nets as shown in Fig. 7

Within network locations, as marked in Fig. 7, the following conditions apply to station operations:

S1 – MV cable head is working properly;

S2 – MV cable head is damaged;

S3 – cable head is operational and ready for use (not in use);

S4, S13 – MV insulator is working properly;

S5, S14 – MV insulator is damaged;

S6, S15 – MV isolator is operational and ready for use (not in use);

S7 – MV arrester is working properly;

S8 – MV arrester is damaged;

S9 – MV arrester is operational and ready for use (not in use);

S10 – MV breaker is working properly;

S11 – MV breaker is damaged;

S12 – MV breaker is operational and ready for use (not in use);

S16 – MV / LV transformer is working properly;

S17 – MV / LV transformer is damaged;

S18 – MV / LV transformer is operational and ready for use (not in use);

S19 – LV insulator working properly;

S20 – LV insulator is damaged;

S21 – LV isolator is operational and ready for use (not in use);

S22 – LV cable head is working properly;

S23 – LV cable head is damaged;

S24 – LV cable head is operational and ready for use (not in use);

S25 – the station is operational and supplying power to users;

S26 – the station is turned off (damaged or operational and awaiting activation) and does not power users.

The operation of the model starts from a state, in which the T1 transition is activated and the transition of the marker from place S3 to S1. Then, due to satisfying the condition of transition of T6, followed by its activation and the transition of the marker from place S6 to S4, etc., until satisfying the condition of transition T40, its activation and the transition of the marker from place S26 to S25. Then, in a given period of simulation in accordance with the specified probability distributions of activation of an individual switch. The times are recorded for markers in particular places of the analysed system. On their basis, it is possible to specify the intensity of individual events, as well as the probability density distributions of the time spent in places under varying conditions.

Input data for the simulation was determined on the

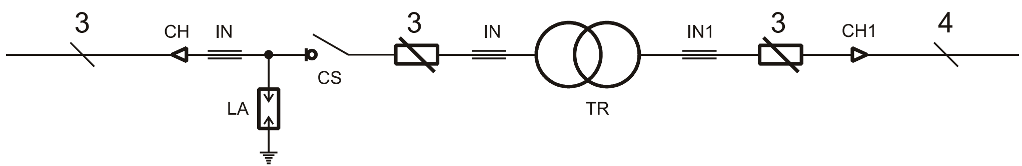

Fig. 5. Structural diagram of the overhead MV station: CH – MV cable head; IN – MV insulators; LA – MV lightning arresters; CS – MV disconnectors; TR – MV / LV transformers; IN1 – LV insulators; CH1 – LV cable head

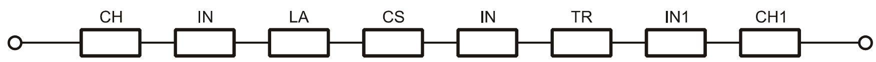

Fig. 6. Reliability model of a basic overhead pole-type station (as shown in Fig. 5)

basis of empirical data from 10 years of observation of power stations. On its basis the probability density distributions were determined for the time of correct operation of equipment to its damage and the time of failure (Table 1). All times are given in hours.

After carrying out computer simulations for the circuit in Fig. 7 as well as for the assumed distributions of the probability density functions according to Table 1, in a simulation period of 10,000 years, the obtained results were statistically analyzed.

As obtained by simulating the number of failures is 157. Taking into consideration, that the subject of the simulation is a single station, the intensity of failure can be determined by dividing the number of accidents by the simulation time. Thus the obtained intensity of failure is $\lambda_a = 0.0157$ for one year at one station.

On the basis of the data obtained through simulation a parametric and non-parametric verification of the duration of station failure was carried out. The mean value of the sample $\bar{t}_a$ as approximated by the maximum likelihood, based on the dependency [6, 7]

$$\bar{t}_a = \frac{\sum_{i=1}^{i=k} n_i \cdot \overset{o}{t}_i}{n}, \tag{7}$$

where $\bar{t}_a$ – mean value of the sample; $\overset{o}{t}_i$ – medium of the i of a range of the distribution; n_i – the number of failures in the i range of a distribution, n – total number of failures k – number of ranges in a series of a distribution.

The confidence interval for the mean is determined according to the relation [6,7]

$$\bar{t}_a - u_\alpha \cdot \frac{s}{\sqrt{n}} < t < \bar{t}_a + u_\alpha \cdot \frac{s}{\sqrt{n}}, \tag{8}$$

where u_α – the value of the random variable U with a standardized normal distribution, as designated for a given confidence coefficient $1\text{-}\alpha$ from an array of a normal distribution, s – sample standard deviation as calculated according to the relation [6–8]

$$s = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{i=k} \left(\overset{o}{t}_i - \bar{t}_a \right)^2 \cdot n_i}. \tag{9}$$

The resulting mean duration of failure is $\bar{t}_a$ = 8.31 h, with a standard deviation of s = 7.36 h, and a confidence interval for the mean of 7.15 h < t_a <9.47 h

Dependence, from which the failure rate can be determined [9]

$$q = \frac{\bar{\lambda}_a \cdot \bar{t}_a}{1 + \bar{\lambda}_a \cdot \bar{t}_a}. \tag{10}$$

Knowing $\bar{\lambda}$ as well as q can be used to determine the average intensity of repair with dependence [9]

Table 1. The distributions of the probability density of operating devices in pole-mounted MV / LV stations

No.	Station device	Probability density function of the time the device functions properly to its damage		Probability density function of recovery time (failure)	
		Distribution type	Distribution parameters	Distribution type	Distribution parameters
1.	MV/LV transformers	Normal distribution	m = 182660,97 σ= 85904,68	Exponential distribution	λ = 0,1267
2.	MV disconnectors	Normal distribution	m = 174212,96 σ= 98748,49	Exponential distribution	λ = 0, 0632
3.	MV lightning arresters	Normal distribution	m = 183130,81 σ= 88337,44	Log normal distribution	m = 1,4458 σ= 0,7978
4.	MV insulators	Normal distribution	m = 194604,46 σ= 88038,42	Exponential distribution	λ = 0, 1070
5.	MV cable heads	Weibull distribution	b = 205107,90 c = 2,1073	Log normal distribution	m = 2,4076 σ= 0,8713
6.	LV insulators	Normal distribution	m = 231251,14 σ= 93623,72	Exponential distribution	λ = 0, 2318
7.	LV cable heads	Normal distribution	m = 199002,18 σ= 93156,61	Exponential distribution	λ = 0,0752

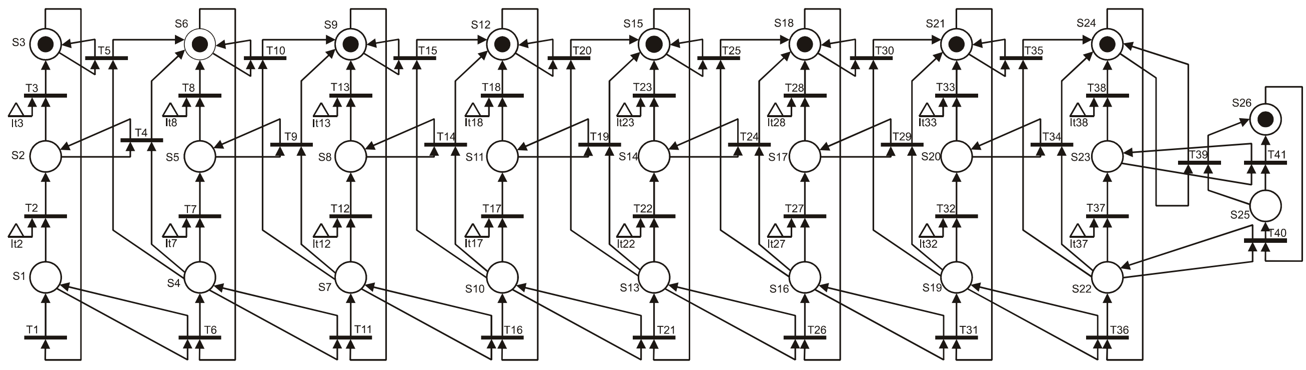

Fig. 7. Reliability model of a basic overhead pole-type station in the terms of extended Petri nets

$$\overline{\mu} = \frac{\overline{\lambda}_a \cdot (1-q)}{q}. \quad (11)$$

As obtained from the sample the mean performance fallibility is for the station: $q = 14.89 \cdot 10^{-6}$ and $\overline{\mu} = 1054.38 \frac{1}{a \cdot szt.}$.

On the basis of empirical data, a hypothesis was formulated regarding the exponential distribution of station repair time. Probability density function of the exponential distribution has the form [6–8]

$$f(t_a) = \lambda \cdot e^{-\lambda \cdot t_a}, \quad (12)$$

where λ - the parameter of the exponential distribution as equal to the inverse of the average value of the sample

$$\lambda = \frac{1}{\overline{t}_a}. \quad (13)$$

The designated value of the distribution parameter is $\lambda = 0.120$.

The probability density function of recovery time of MV/LV stations as obtained through simulation as well as its theoretical course, and the results of a verification of the hypothesis of distribution by means of λ Kolmogorov and χ^2 Pearson test of significance at a level α = 0.05, as shown in Fig. 8

A similar analysis was conducted for the time from the correct operation of the station to failure. In its results the following values as well as characteristics of reliability were obtained: the average time of correct operation of the station: $\overline{t}_{pr}$ = 168219 h, with a standard deviation of s = 83722 h, at a confidence interval for the mean of 148554 h < t_{pr} <187884 h. The resulting probability density distribution of the correct time of operation is a normal distribution with parameters: m = 168219 as well as σ = 83722. Probability density function of the normal distribution has the form [6–8]

$$f(t_{pr}) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot exp\left[-\frac{(t_{pr} - m)^2}{2 \cdot \sigma^2}\right]. \quad (14)$$

where m - expected value of a random variable t_{pr}, σ - standard deviation of a random variable t_{pr}.

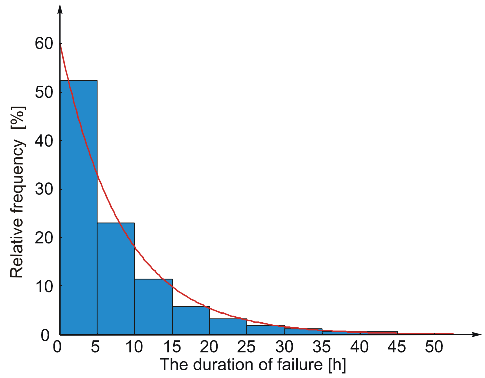

Fig. 8. The probability density function of the duration of the repair of a station was recorded as a result of a simulation using the extended Petri nets and its theoretical course (λ = 1,086 < λ_α = 1,358; χ^2 = 2,72 < χ^2_α = 3,33)

Parameters determined by the simulation, were also determined by analysing the empirical data from stations in service. The above data comes from 10 years of operation of more than six thousand MV / LV stations. In Table 2 are listed the station reliability parameters as obtained through simulation and the analysis of empirical data.

Conclusions

The simulation method for evaluating the reliability of power stations as described in terms of Petri nets allows for the description of the distributions of the basic functions of reliability, as well as to designate the mean values of coefficients, such as: the intensity of failure, the intensity of renewal, unreliability coefficient, or reliability coefficient. It is a very convenient method to use.

Table 2. Comparison of the reliability indicators and features of station as obtained through simulation and analysis of empirical data

No.	Parameter or characteristic of reliability	Simulation using the extended Petri nets	Calculations based on empirical data
1.	The mean duration of failure $\overline{t}_a$ [h]	$\overline{t}_a$ = 8,31 h	$\overline{t}_a$ = 8,51 h
2.	The standard deviation for $\overline{t}_a$ [h]	s = 7,36 h	s = 11,21 h
3.	Confidence interval for mean $\overline{t}_a$ [h]	7,15 h < t_a < 9,47 h	7,93 h < t_a < 9,10 h
4.	The intensity of failure [1 / (a · pcs.)]	λ_a = 0,0157 1/(a·szt.)	λ_a = 0,0144 1/(a·szt.)
5.	Reliability coefficient	$q = 14{,}89 \cdot 10^{-6}$	$q = 13{,}99 \cdot 10^{-6}$
6.	Intensity of renewal [1/(a·pcs.))	$\overline{\mu}$ = 1054,38 1/(a·szt.)	$\overline{\mu}$ = 1029,29 1/(a·szt.)
7.	Probability density distribution of the duration of failure	Exponential distribution λ = 0,120	Exponential distribution λ = 0,117
8.	The average time of correct operation $\overline{t}_{pr}$ [h]	$\overline{t}_{pr}$ = 168219	$\overline{t}_{pr}$ = 175488
9.	The standard deviation for $\overline{t}_{pr}$ [h]	s = 83 722 h	s = 85 269 h
10.	Confidence interval for mean $\overline{t}_{pr}$ [h]	148554 h < t_{pr} < 187884 h	171047 h < t_{pr} < 179931 h
11.	Probability density distribution of the duration of failure	Normal distribution m = 168219 oraz σ=83722	Normal distribution m = 175488 oraz σ=85269

As demonstrated by the analysis presented in this article, the parameters obtained by simulation are only slightly different from data obtained by calculations made on the basis of empirical data. Taking into consideration, that such data is not always available as well as the fact, that often an analysis is undertaken of the reliability of systems in design, it should be noted, that simulations undertaken using extended Petri nets are a very good and accurate tool for reliability analysis. In addition to the analysis presented in the article, the author also conducted simulations of complex processes in power stations with overt or hidden reserves as well as in selected parts of a medium voltage network. Also in these cases, the effectiveness of algorithms based on Petri networks has been confirmed.

The modelling of more complex systems using classical Petri nets is often associated with an excessive complexity of a pattern in network simulation. This is the main reason for the introduction of an expanded network of higher order in recent years. One type of such networks are coloured Petri nets. They allow for a more concise and easier to interpret simulation of even large systems. Coloured Petri nets extend the model by introducing to it the value assigned to the markers.

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The article presents the results of a verification of the suitability of a method based on extended Petri nets to determine the indicators as well as the reliability characteristics of power stations. The author presented the theoretical basis of extended Petri nets. He conducted simulation of a station failure, using a program based on the rules of a Petri net, and a reliability analysis based on empirical data from service stations. He made a comparison of the coefficients and the properties of reliability obtained by both methods , yielding similar results. Based on the analysis, the author concluded that Petri nets are a very convenient and accurate tool to perform reliability analysis of complex power systems. Ill. 8, bibl. 9, tabl. 2 (in English; abstracts in English and Lithuanian).

A. L. Chojnacki. Išplėstų Petri tinklų naudojimas vidutinės įtampos pastočių patikimumo analizei // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 5(121). – P. 17–22.

Pateikiami išplėstais Petri tinklais besiremiančio metodo elektros energijos pastočių patikimumo rodikliams ir charakteristikoms nustatyti naudingumo verifikavimo rezultatai. Išdėstyti teoriniai išplėstų Petri tinklų pagrindai. Naudojant Petri tinklų terminais pagrįstą programą, parengta stoties avaringumo imitacija ir remiantis pastotės eksploatacijos empiriniais duomenimis, atlikta patikimumo analizė. Abiem metodais gauti panašūs patikimumo rodikliai ir charakteristikos. Remiantis atlikta analize, daroma išvada, kad Petri tinklai yra labai patogus ir tikslus būdas sudėtingų elektros energijos sistemų patikimumo analizei atlikti. Il. 8, bibl. 9, lent. 2 (anglų kalba; santraukos anglų ir lietuvių k.).