UDC 621.311.1 DOI:10.30724/1998-9903-2019-21-3-4-59-67

SELECTION OF OPTIONS FOR RECONSTRUCTION OF POWER SUPPLY SYSTEM BASED ON THE FUZZY SETS THEORY AND THE CRITERIA OF DECISION-MAKING THEORY

A.V. Malafeev, A.I. Yuldasheva

Nosov Magnitogorsk State Technical University, Magnitogorsk, Russia
ORCID: http://orcid.org/0000-0003-1471-9764, malapheev_av@mail.ru
ORCID: https://orcid.org/0000-0002-1403-4434, alinayuldasheva1@gmail.com

Abstract: *The article proposes a method for selecting options for reconstruction of power supply system based on the criteria of decision-making theory. The reconstruction process is considered as a sequential game with two players: active and passive. The probability of possible states of the system is determined basing on the fuzzy sets theory. The main criterion for the choice of reconstruction option is the value of damage from the power supply interruption. The application of the proposed method is considered on the example of a large metallurgical enterprise.*

Keywords: *power supply system, fuzzy sets theory, decision-making theory, game flow chart, Bayes criterion, probable damage.*

For citation: Malafeev A.V., Iuldasheva A.I. Selection of options for the reconstruction of the power supply system based on the fuzzy sets theory and the criteria of decision-making theory. *Proceedings of the higher educational institutions. ENERGY SECTOR PROBLEMS*. 2019; 21 (3-4):59-67. (In Russ). doi:10.30724/1998-9903-2019-21-3-4-59-67.

Introduction

The increasing complexity of technology and consolidation of production has led to the need to apply various mathematical calculations for solving management problems. One of the issues that require application of a rather complex mathematical apparatus is planning of development and reconstruction of power systems in general, networks of main and territorial grid companies, and power supply systems of large industrial enterprises. The latter are characterized by a radical change in the scheme with complete replacement of equipment of any segment of electrical networks when replacing large energy-intensive technological equipment or introducing a new technological process (in particular, for metallurgical enterprises it is steelmaking and finishing of steel in electric arc furnaces, construction of new energy-intensive plants for flue gas cleaning, etc.). At the same time, during the process of construction and commissioning of new facilities, the terms of financing may change, the actually purchased equipment may not be as planned, there may be schematic changes, the actual load will differ from the design. This indicates the uncertainty in a number of factors; no statistical information is available, especially when introducing new technologies. The most convenient approach to accounting for such uncertainty is application of the fuzzy sets theory, which is quite a powerful strategic tool for managing complex systems. As noted in [1], in practice it is constantly necessary to make decisions in the context of incomplete information, and, since the mathematical apparatus of the fuzzy sets theory allows us to model human reasoning, the technologies and algorithms developed within this theory are universal in their applicability. Also the theory of fuzzy sets has found application for solving various problems in the field of energy: for making decisions in managing the reconstruction of power facilities; in determining the strategy for restoring power supply after an accident; when diagnosing damage in networks, etc. [2]. In work [2] it is concluded that the use of fuzzy sets when choosing options for reconstruction power output schemes of power stations makes it possible to formalize this operation having information uncertainty and with inconsistent rules and criteria. In [3] an algorithm for solving multi-criteria optimization problems with uncertain information is presented on the example of choosing the optimal variant of efficiency increasing of overhead power lines operating in extreme environmental conditions. It is concluded that when making decisions, an integrated approach is needed to formulate and apply principles for evaluating the efficiency of investments in reconstruction projects (such as the domination principle, Pareto-optimal alternatives, formation of complex indicators, selection of the main indicator and transition of the rest to the category of restrictions, selection of non-dominant alternatives, additive convolution). In [4], the application of the fuzzy sets theory to assess production risks for an industrial power supply system was demonstrated. In [5], an algorithm was developed for selecting the optimal parameters of power supply systems, which allows one to solve planning problems in a multi-criteria formulation taking into account several uncertain factors. Discounted undersupply of electricity to consumers due to potential outages and net present value were taken as the criteria for efficiency and reliability. In addition, the work substantiates a rational set of uncertain factors and a method for obtaining additional information, which increases the efficiency of taking into account the uncertainty of the initial information in SES optimization problems and solving them using statistical methods, in particular, the Bayes criterion. The method of multi-criteria analysis of the models for development of power supply systems under conditions of uncertainty, presented in article [6], makes it possible to exclude subjectivity connected with the choice of the most probable value of power consumption and consider many options from the predicted range. A system of criteria for evaluating development models has been developed, which shows economical, technical, and architectural and town planning aspects (total discounted costs, technical losses of electricity, undersupply of electricity, length of transmission lines) and their mathematical models have been developed taking into account the information uncertainty. To assess the effectiveness of investment programs for reconstruction, the use of reliability models based on homogeneous Markov chains, which, however, requires detailed information on the results of reconstruction, is proposed in [7]. The work [8] is devoted to evaluating risks of a secure nature when planning the development of distributed generation taking into account uncertainty in load, generation, energy prices. In [9], a method is proposed for assessing such a risk during cascade development of an accident under conditions of extensive use in distribution networks of block-modular substations and other modern equipment based on the theory of D-S evidence. The use of method of sequential equivalence to assess the reliability is considered in [10].

When comparing options for reconstruction of the factory electrical network in case of production expansion, taking into account the damage from a power failure, uncertain (or partially uncertain) values include the following:

1) Deviation of actual load increase from the design value;
2) Nature of the emergency;
3) Disconnection time, taking into account finding the damage location.

This paper considers the first of these factors.

Methods for selecting options for reconstruction of power supply system

Large-scale reconstruction is accompanied, as a rule, by a stepwise commissioning of production facilities and individual sections of power supply system. During the process of commissioning of new and reconstructed facilities, it may become necessary to adjust decisions on implementation of the next stage. In this regard, it is necessary to consider the task of planning in such conditions as dynamic one. We represent this process as a sequential game [11] with participation of two players: an organization performing a complex of reconstruction works (active player A), and “nature” (passive player P).

The action of “nature” is determined by deviation of actual load of the object from the design, the change in electricity prices in comparison with the forecast, the possibility of emergencies of various types and various time of their liquidation. Depending on the current situation, it is possible to take various decisions on further reconstruction, and therefore it is advisable to consider the reconstruction process as a game in mixed strategies, the number of moves in which is 2N (N is the number of stages). The probability of one or another state of "nature" (player P move) will be determined on the basis of the fuzzy sets theory, considering the actual load resulting from reconstruction of power supply system as a one-sided fuzzy number. For this we will use numbers with membership function specified by the Cauchy curve parametrized at a level of 0,5 [12]. In this case, it has the following form:

$$\mu(P) = \frac{1}{1+\left(\frac{P-P_{bn}}{P_{av}-P_{bn}}\right)^2}, \tag{1}$$

where P is actual load as a result of reconstruction; P_{bn} is boundary value of load corresponding to the right boundary of the fuzzy interval core; as a boundary value we will take the design value of the calculated load; P_{av} is load corresponding to a 10 % excess of the actual load over the design value (an error of 10% corresponds to the definition of design loads by the method of design factors which is now used in design practice (see, for example, [12]); $P_{av} = 1{,}1P_{bn}$.

It is necessary to minimize the loss of player A. We will accept the damage from violation of reliability of power supply during implementation of any option as the player A loss. Then the role of payment function will be played by player A loss after the next move.

The structure of the game graph for two stages of reconstruction is shown in Fig. 1.

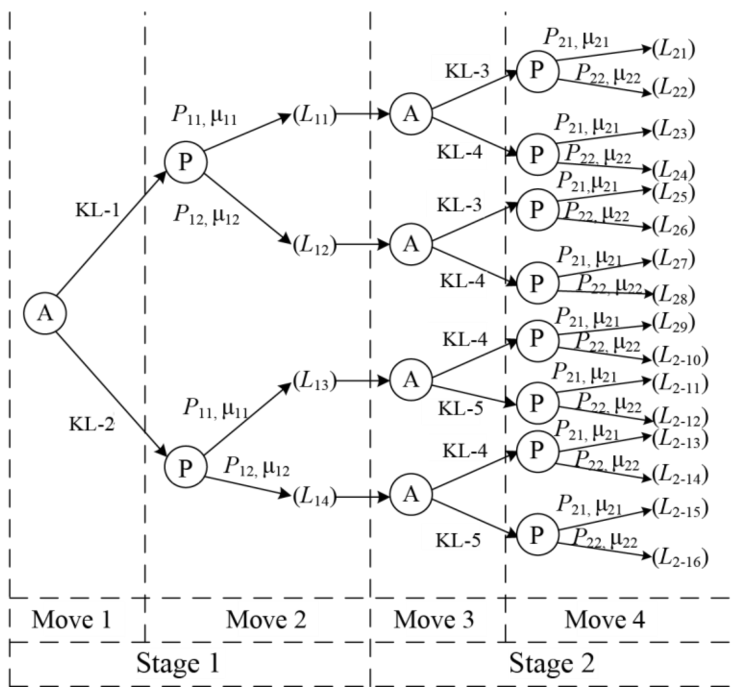

Fig. 1. General view of the game graph, corresponding to two-stages reconstruction of power supply system

Here KL-1 ... KL-5 are elements of the strategy being implemented – the input sections of the power supply system; P_{11}, P_{12} and P_{21}, P_{22} are possible load values of the reconstructed segment at the first and second stages, respectively, with probabilities p_{11}, p_{12}, p_{21}, p_{22}. D_{11} ... D_{14} are loss values corresponding to implementation of two options (construction KL-1 or KL-2) of the first stage, when load is P_{11} or P_{12}; D_{21} ... $D_{2\text{-}16}$ are similar values for subsequent construction of KL-3 or KL-4 and load P_{21} (P_{22}). As loss D, we will use the reduced costs, taking into account the damage.

As a decision criterion, we take the Bayes criterion, which allows one to operate with subjective probabilities of the states of nature. As probabilities, we will use the values of membership function (MF) from expression (1). In this case, the loss at the i-th stage of reconstruction will be determined as follows:

$$L_{is(i)} = \sum_{i=1}^{N} \mu_{ia(i)} D_{is(i)a(i)}, \tag{2}$$

where $s(i)$ is number of the selected strategy; $a(i)$ is the state of nature at the i-th stage; $\mu_{ia(i)}$ is MF value for the state $a(i)$; $D_{is(i)a(i)}$ is loss, which includes investments, reduced to one year, and damage from power supply interruption when implementing strategy s $s(i)$ and state of nature $a(i)$.

When taking into account the degree of confidence of player A to the accepted distribution, the Hodge-Lehmann criterion can be used, which is a combination of Bayesian and Wald criteria. The expression for loss in this case will be the following:

$$L_{is(i)} = \lambda \sum_{i=1}^{N} \mu_{ia(i)} D_{is(i)a(i)} + (1-\lambda) \max_{1 \le i \le N} \left(D_{is(i)a(i)} \right), \tag{3}$$

where $\lambda \in [0;1]$ is degree of confidence.

In the absence of any preferences (for λ=0) we obtain the Wald criterion:

$$L_{is(i)} = \max_{1 \le i \le N} \left(D_{is(i)a(i)} \right). \tag{4}$$

When using any of the specified criteria, the final version of the reconstruction will be selected by the criterion of minimum loss $\min L_{Ns(N)}$ at the last stage.

Practical implementation

As an example, the reconstruction of a large metallurgical enterprise is considered. It is planned to construct aspiration units, for power supply of which the construction of a new 110/10 kV PS-11 substation is envisaged. PS load will be S_1= 80 MVA. It is planned to carry out external power supply of PS-11 110kV from PS-60 and central electric station (CES); to provide more reliable power supply, construction of additional lines from substations is planned – 30, 62, 85.

Variants of PS-11 connection diagrams are shown in fig. 2

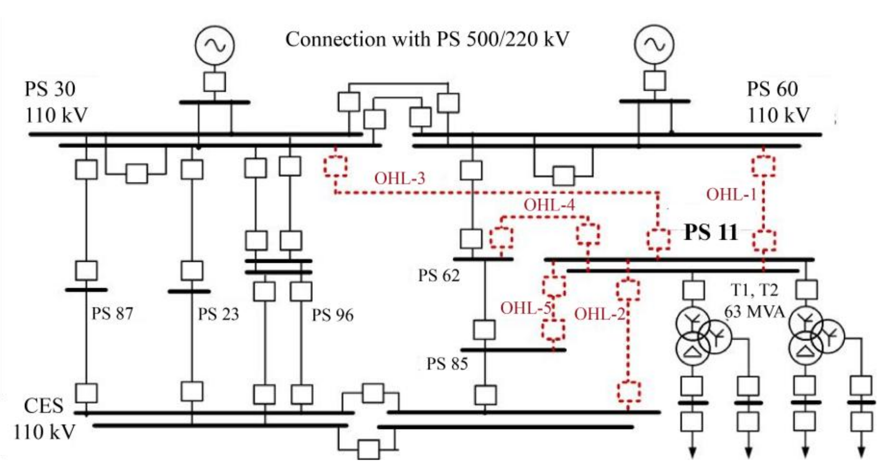

Fig. 2. Possible variants for PS-11 connection

For the proposed circuit solutions, a game graph is constructed (Fig. 3).

As noted above, the choice of final version of reconstruction is carried out based on the criterion of minimum total loss according to the accepted criterion (Bayes, Hodge-Lehmann, Wald) $\min L_{is}$ at the last stage. In this case, the damage, as a component of the loss, is determined as follows:

$$Y_{is} = y_0 T_R \Delta P_{is}, \tag{5}$$

where y_0 is specific damage from undersupply of consumer electricity, determined by the time of interruption and the nature of production, rub./kW·h (for enterprises of ferrous metallurgy y_0 =18.3 rub./kW·h [14]); T_R is recovery time; ΔP_{is} is power, unsupplied to the consumer due to a power failure, taking into account the MF value μ_{ij} when working with this value of P_{is} ($\Delta P_{is} = |P_1 - P_{is}| p_{is}$, where P_1=64 MW is design load).

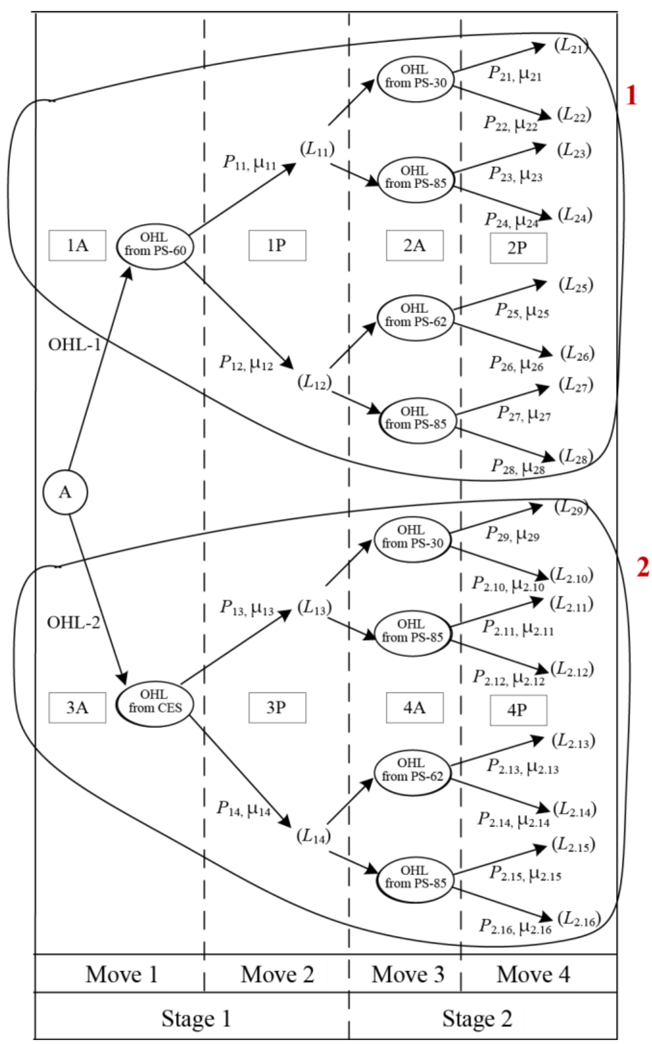

Fig. 3. The game graph corresponding to the construction of PS-11

For the proposed schemes, we estimated the capital investments *K*, and using the KATRAN software [15, 16], the reliability indicators (failure rate parameter ω and recovery time T_R) were calculated. The results are presented in Table. 1. In all considered options, we adopt construction of 110 kV power lines on metal poles using ASU-400 wires. Construction of 1 km of these wires will cost 0.55 million rub./km [17], its failure rate is ω = 0.0128 1/year per 1 km [17].

To correctly compare the obtained values, the capital investments were taken into account (the values are given in Table 1) in each of the reconstruction projects. Thus, the loss, which is reduced cost, taking into account damage Y_{is} , will be determined as follows:

$$L_{is} = Y_{is} + K_{is}E_N \tag{6}$$

where E_N is capital investment efficiency ratio $K_{is}\left(E_N = 0.12\right)$.

Table 1

PS-11 connectivity options and the corresponding investments and reliability indicators

Strategy	Constructed lines	Total length, km	Total capital investments, mln rub.	ω, 1/year	T_R, year
1	PS-60 – PS-11	5.2	2.86	0.000010	0.003948
	PS-60 – PS-11; PS-30 – PS-11	11.5	6.33	0.080650	0.000801
	PS-60 – PS-11; PS-85 – PS-11	12.3	5.45	0.060170	0.000801
	PS-60 – PS-11; PS-62 – PS-11	9.9	6.77	0.090890	0.000801
2	CES – PS-11	2.8	1.54	0.000005	0.003256
	CES – PS-11; PS-30 – PS-11	9.1	5.01	0.080645	0.000768
	CES – PS-11; PS-85 – PS-11	9.9	4.13	0.060165	0.000768
	CES – PS-11; PS-62 – PS-11	7.5	5.45	0.090885	0.000768

The results of loss calculation are shown in Table 2.

Table 2

The results of total loss calculation from the game graph

Strategy	Description of move	Load P_{ia}		MF value μ_{is}	Loss D_{is}, mln rub.	Total loss at P_{i1}	Total loss at P_{i2}
1	1A: Construction of OHL-1 (from PS-60) 1P: Load growth		P_{11}=1,2P_1	0,2	10,064	10,064	34,364
			P_{12}=1,05P_1	0,8	34,364		
	2A: Construction of OHL-3, 4, 5 (from PS-30, 62, 85) 2P: Load growth	From PS-30	P_{21}=1,15P_1	0,31	3,667	13,731	38,031
			P_{22}=1,3P_1	0,1	1,828	11,892	36,192
		From PS-85	P_{23}=1,1P_1	0,5	5,173	15,237	39,537
			P_{24}=0,85P_1	–	–	–	–
		From PS-62	P_{25}=1P_1	–	–	–	–
			P_{26}=0,9P_2	–	–	–	–
		From PS-85	P_{27}=0,8P_1	–	–	–	–
			P_{28}=1,2P_1	0,06	1,331	11,395	35,695
2	3A: Construction of OHL-2 (from CES) 3P: Load growth		P_{13}=1,2P_1	0,2	8,201	8,201	4,527
			P_{14}=1,3P_1	0,1	4,527		
	4A: Construction of OHL-3, 4, 5(from PS-30, 62, 85) 4P: Load growth	From PS-30	P_{29}=1,1P_1	0,5	4,933	13,134	9,46
			$P_{2.10}$=1P_1	–	–	–	–
		From PS-85	$P_{2.11}$=0,8P_1	–	–	–	–
			$P_{2.12}$=1,15P_1	0,31	3,283	11,484	7,81
		From PS-62	$P_{2.13}$=1P_1	–	–	–	–
			$P_{2.14}$=1,3P_1	0,1	1,678	9,879	**6,205**
		From PS-85	$P_{2.15}$=1,1P_1	0,2	2,492	10,693	7,019
			$P_{2.16}$=0,95P_1	–	–	–	–

As follows from Table 2, the best strategy, characterized by least loss, is construction of an overhead line from CES, and at the second stage from PS-62.

Conclusions

The article presents an improved method for selecting options for multi-stage reconstruction of the power supply system based on the game theory approaches, which differs from the existing methods of taking into account the probabilities of possible states of an object as a result of implementation of each stage.

It is proposed to determine the probability of possible states of an object on the basis of fuzzy sets theory using numbers with the membership function defined by the Cauchy curve. The reconstruction process is represented as a sequential game involving an active player (the service responsible for planning reconstruction work) and a passive player (“nature”), which allows one to take into account all possible changes in external factors and combinations of decisions taken at each stage. The value of costs was chosen as the main criterion for selection of reconstruction option, taking into account the damage caused by loss of the power supply reliability. It is proposed to choose it based on the criterion of the minimum loss at the last stage. The technique allows correction of the adopted strategy based on the results of the implementation of any of the stages.

As an example, we considered two stages of reconstruction of power supply system of a large metallurgical enterprise during construction of a new energy-intensive consumer. The calculations based on the game graph, allowed us to choose the option characterized by the lowest loss value.

References

1. Konysheva LK, Nazarov DM. *Osnovy teorii nechetkih mnozhestv*. Sankt Petersburg: Piter, 2011. (In Russ).

2. Kovalenko IV, Tremyasov VA. Application of the theory of fuzzy sets in the problem of reconstruction options selection for the main power distribution schemes of power plants. *Proceedings of the higher educational institutions. ENERGY SECTOR PROBLEMS.* 2004; 5-6:26-32. (In Russ).

3. Shevchenko NJ, Lebedeva JV, Havronichev SV. The algorithm for choice ofoptimal variant reconstruction of overhead power trasmission lines of 110–220 kV. *Modern problems of science and education*. 2013; 5. (In Russ).

4. Malafeev AV, Yuldasheva AI. The fuzzy sets theory usage for production risk assessment for the mode control of industrial power supply systems. *Electrical energy industry through the eyes of young people: proceedings of VI Intern. scientific and technical conference, Nov 9–13 2015; Ivanovo, Russia.* Ivanovo: IGEU im. V.I. Lenina, 2015; V.2. pp. 294-297.

5. Metelkov AA. Razrabotka metodiki planirovaniya sistem elektrosnabzheniya rajonov s maloj plotnost'yu nagruzok s uchetom neopredelennosti iskhodnoj informacii [dissertation]. Moscow; 2004. Available at: https://search.rsl.ru/ru/record/01002663331. Accessed: 21 Apr 2019. (In Russ).

Литература

1. Конышева Л.К., Назаров Д.М. Основы теории нечетких множеств. СПб: Питер, 2011. 192 с.

2. Коваленко И.В., Тремясов В.А. Применение теории нечетких множеств при выборе варианта реконструкции главных схем выдачи мощности электростанций // Известия высших учебных заведений. ПРОБЛЕМЫ ЭНЕРГЕТИКИ. 2004. № 5-6. С. 26-32.

3. Шевченко Н.Ю., Лебедева Ю.В., Хавроничев С.В. Алгоритм выбора оптимального варианта реконструкции воздушных линий электропередачи напряжением 110–220 кВ // Современные проблемы науки и образования. 2013. № 5.

4. Малафеев А.В., Юлдашева А.И. Использование теории нечетких множеств для оценки производственных рисков при управлении режимами промышленной системы электроснабжения // Электроэнергетика глазами молодежи: труды VI Междунар. науч.-техн. конф.; 9–13 ноября 2015 г., г. Иваново. В 2 т. 2Т. Иваново: ИГЭУ им. В.И. Ленина, 2015. С. 294-297.

5. Метельков А.А. Разработка методики планирования систем электроснабжения районов с малой плотностью нагрузок с учетом неопределенности исходной информации: Дис. ... канд. техн. наук. Москва; 2004. Доступно по: https://search.rsl.ru/ru/record/01002663331. Ссылка активна на 24 апреля 2019.

6. Семенова Л.А. Многокритериальный анализ

6. Semenova LA. Multi-criteria analysis of power systems development models in the face of uncertainty. *Cherepovets State University Bulletin*. 2016; 4:39-46. (In Russ).

7. Abdullazyanov EY, Vasiliev YA, Galiev IF. Enterprises power supplying schemes reliability models for investments efficiency. *Proceedings of the higher educational institutions. ENERGY SECTOR PROBLEMS*. 2009; 3:67-74. (In Russ).

8. Abapour S, Zare K, Mohammadi-ivatloo B. Evaluation of technical risks in distribution network along with distributed generation based on active management. *IET Generation, Transmission & Distribution.* 2014; 8(4):609-618. doi: 10.1049/iet-gtd.2013.0666.

9. Cunbin L, Gefu Q, Tingting Y. Operational Risk Assessment of Distribution Network Equipment Based on Rough Set and D-S Evidence Theory. *Journal of Applied Mathematics.* 2013. Article ID 263905. 7 p. http://dx.doi.org/10.1155/2013/263905.

10. Yuldasheva AI, Malafeev AV. Accounting the reliability index at planning the mode of industrial power supply system with own electric power stations. *Electrotechnical Systems and Complexes.* 2015; 3(28):36-40. (In Russ).

11. Duplyakin VM. *Teoriya igr*. Samara: Izd-vo Samar. aerokosm. un-ta, 2011. (In Russ).

12. Koroteev MV. Linguistic variables of economic indicators. *Audit and financial analysis*. 2012; 2:5. (In Russ).

13. Kudrin BI, Zhilin BV, Oshurkov MG. *Elektrosnabzhenie*. Rostov-on-Don: Feniks, 2018. (In Russ).

14. Nepomnyashchy VA. *Ekonomicheskie poteri ot narusheniya elektrosnabzheniya*. Moscow: MPEI, 2010. (In Russ).

15. Igumenschev VA, Malafeev AV, Panova EA, et al. *Kompleks avtomatizirovannogo rezhimnogo analiza KATRAN 9.0*. Svidetel'stvo o gosudarstvennoj registracii programmy dlya EVM RUS №2015662725. 30.11.2015. Byul. «Programmy dlya EVM, bazy dannyh, TIMS» №12. Available at: https://elibrary.ru /item.asp?id=35632066. Accessed: 20 Apr 2019.

16. Malafeev AV. Algoritm rascheta strukturnoj nadezhnosti sistem elektrosnabzheniya krupnyh promyshlennyh predpriyatij na osnove metoda posledovatel'nogo ekvivalentirovaniya. *Proceedings of the Russian Academy of Sciences. Power Engineering*. 2016; 4:62-72. (In Russ).

17. RUCABEL.RU [Internet]. Available at: http://www.rucabel.ru/asu/cabel_asu_400_93.html. Accessed: 20 Nov 2018.

моделей развития систем электроснабжения в условиях неопределенности // Вестник Череповецкого государственного университета. 2016. № 4. С. 39-46.

7. Абдуллазянов Э.Ю., Васильев Ю.А., Галиев И.Ф. Модели надежности схем электроснабжения предприятий // Известия высших учебных заведениий. ПРОБЛЕМЫ ЭНЕРГЕТИКИ. 2009. №5-6. С. 67-74.

8. Abapour S., Zare K., Mohammadi-ivatloo B. Evaluation of technical risks in distribution network along with distributed generation based on active management // IET Generation, Transmission & Distribution. 2014. Vol. 8. Iss. 4. P. 609-618.

9. Cunbin L., Gefu. Q., Tingting Y. Operational Risk Assessment of Distribution Network Equipment Based on Rough Set and D-S Evidence Theory // Journal of Applied Mathematics. Volume 2013. Article ID 263905. 7 p.

10. Юлдашева А.И., Малафеев А.В. Учет показателей надежности при планировании режима промышленной системы электроснабжения с собственными электростанциями // Электротехнические системы и комплексы. 2015. №3(28). С. 36-40.

11. Дуплякин В. М. Теория игр. Самара: Изд-во Самар. аэрокосм. ун-та, 2011. 191 с.

12. Коротеев М.В. Лингвистические переменные экономических показателей // Аудит и финансовый анализ. 2012. № 2. С 5.

13. Кудрин Б.И., Жилин Б.В., Ошурков М.Г. Электроснабжение. Ростов-на-Дону: Феникс, 2018. 382 с.

14. Непомнящий В.А. Экономические потери от нарушения электроснабжения. М: МЭИ, 2010. 187 с.

15. Игуменщев В.А., Малафеев А.В., Панова Е.А., и др. Комплекс автоматизированного режимного анализа КАТРАН 9.0. Свидетельство о государственной регистрации программы для ЭВМ № 2015662725. 30.11.2015. Официальный бюллетень «Программы для ЭВМ, базы данных, ТИМС» №12. Доступно по: https://elibrary.ru/item.asp?id=35632066. Дата обращения: 20 апреля 2019.

16. Малафеев А.В. Алгоритм расчета структурной надежности систем электроснабжения крупных промышленных предприятий на основе метода последовательного эквивалентирования // Известия РАН. Энергетика. 2016. №4. С. 62-72.

17. RUCABEL.RU [Электронный ресурс]. Доступно по: http://www.rucabel.ru/asu/cabel_asu_400_93.html. Ссылка активна на 20 ноября 2018.

18. РД 34.20.574. Указания по применению показателей надежности элементов энергосистем и

18. RD 34.20.574. Ukazaniya po primeneniyu pokazatelej nadezhnosti elementov energosistem i raboty energoblokov s paroturbinnymi ustanovkami [Internet]. Available at: http://www.xjob.ru/РД_34.20.574. Accessed: 20 Oct 2018.

работы энергоблоков с паротурбинными установками [Электронный ресурс]. Доступно по: http://www.xjob.ru/ РД_34.20.574. Ссылка активна на: 20 октября 2018.

Authors of the publication

Aleksei V. Malafeev – Department of Industrial electric power supply, Nosov Magnitogorsk State Technical University.

Alina I. Iuldasheva – Department of Industrial electric power supply, Nosov Magnitogorsk State Technical University.

Received ***December 29, 2018***