Comprehensive studies on reliability of jointly operating fuel and electric power systems

Tatyana Dzyubina*, Gennady Kovalev

Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The paper places an emphasis on the fact that many publications on complex reliability assessment of electric power and fuel systems do not always substantiate the application of various methods. We address the "system", "nodal", and "estimation" approaches to assess the reliability of electric power systems, given reliable fuel supply to power plants. These approaches are accompanied by an analysis of their correspondence to the objectives and goals of the study, as well as an analysis of the validity of their application in terms of the obtained result accuracy, research time, complexity of search for and preparation of the input data and forms of their representation in a model. All the approaches were tested in case studies. The nodal and system approaches were tested on a conventional power system, while the estimation approach was tested on design diagrams of the gas and electric power systems of the Northwestern Federal District of the Russian Federation.**

***Index Terms* — fuel system, electricity system, complex research, power plant fuel supply, reliability indices.**

I. Nomenclature

$p(Q)$ – series of the fuel system operable state probability distributions.

i – power plant index.

p_i^F – fuel supply probability (supply coefficient) of the ith power plant.

p_i^G – operable state probability of each generator of the ith power plant.

p_i^{GF} – operable state probability of each generator of the ith power plant, considering the supply coefficient.

$P_n(m)$ – probability that m units of n are in operable state with the total power $\sum_{i=1}^{m} P_i$

n – the total number of units.

p, q – probabilities of operable and non-operable states of each of n units, .

$P^{F(G,L)}$ – unit capacity of a fuel system component (F), generator (G), or load (L) in an electricity system.

$P_i^{F(G,L,Gd,R)}$, $p_i^{F(G,L,Gd,R)}$ –outputs of the fuel system (F), available capacity (G), or load (L) in an electric power system, generalized (Gd) and resultant (R) outputs necessary to supply the load (megawatts) and related probabilities.

Q_i^F – output of the fuel system in tons of coal equivalent (tce) per year.

p'_i, q'_i – mean and root-mean-square deviation of the fuel system actual output (available capacity or load).

P', P'' – corrected probabilities of failure-free operation and idle time of units at power plants.

– upper and lower boundaries of the nodal reliability index of electricity supply to consumers - probabilities of electricity supply, given fuel system reliability.

p_i^{GSS}, p_i^{EPS} – nodal probabilities for shortage-free operation of gas and electric power systems.

II. Introduction

A comprehensive study of the electric power system adequacy suggests an assessment of whether or not the system (EPS) is provided with all kinds of resources, particularly with primary energy resources, i.e. fuel (gas, coal, fuel oil, etc.) for thermal power plants, water in reservoirs for hydroelectric power plants, and nuclear material for nuclear power plants.

Natural gas is the most relevant fuel of all the fuel types for thermal power plants due to its environmental compatibility, efficiency and availability. In some regional power systems, the coal share in the total amount of fuel currently accounts for 70-90% [1]. According to forecasts,

* Corresponding author.
E-mail: tvleo@isem.irk.ru

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in the Russian Federation, after 2030, the electricity generated from gas is expected to increase by 1.9 times [2], and in 2040 the share of gas in the world energy balance will reach 24% [3]. It is worth noting that gas, unlike other types of fuel, cannot be stored at power plants. Another point affecting the reliability of power systems is the liberalization of electricity markets. For example, market "refusals" to deliver fuel affect the operation of electric power system [4].

In this regard, it became necessary to study the reliability of integrated operation of gas systems (GSs) and electric power systems (EPSs).

The issues of integration (joint operation) of the electricity, gas and heat systems are addressed in [5-14]. The studies presented in [5-8] focus on the models [5, 7, 8] and methods [6] for solving problems of optimal energy flow for integrated electricity and natural gas systems for one or several time periods [7, 8]. In [9], the authors propose a distributed control system for such systems.

In [10], the authors present an integrated model to co-optimize the expansion of electrical energy storage, in combination with electrical and natural gas infrastructures to reliably supply electric loads at the least cost.

The proposed model is formulated as a two-stage stochastic optimization problem, in which investment decisions are made in the first stage, followed by a variety of operating conditions under different potential random scenarios.

The authors of [11] propose a mixed-integer linear programming approach to security-constrained co-optimization of expansion planning of natural gas and electricity transmission systems. This approach simultaneously considers N-1 contingency in both natural gas system and electric power system.

Attention is drawn to the increased risk of emergency situations in the natural gas system, which threaten the security of the entire integrated energy system. A disadvantage of the study is limited consideration of unforeseen events by the level of N-1 contingency.

A broader consideration is given in [12, 13], where the authors discuss the operation of an integrated energy system consisting of electricity, gas and heat systems. The study in [12] addresses a unified fault identification and location method using big data analysis. Here, the concept of "fault" does not include the concept of "partial failure" as in the theory of reliability. In [13], the authors focus on the impact of a gas pipeline emergency on fuel supply to electricity and heat sources. They also raise, to some extent, the issues of reliability (security) of the integrated energy system. The study presented in [14] is similar in scope. It focuses on the influence of gas system on adequacy of an electric power system.

In Russia, there have been no studies on reliability of jointly operating gas and electricity systems.

A comprehensive analysis of the electric power system adequacy, given the reliability of a system of fuel delivery to power plants can be made by two methods [14]:

1) first, we assess the reliability of fuel system and then the consequences of its failures for the power system adequacy are taken into account;

2) the joint operation of gas and electric power systems is considered by simulating simultaneous failures in both systems based on stochastic modeling.

We have proposed and tested a system approach according to which the reliability of gas system and the adequacy of electric power system of the Northwest Federal District are analyzed [15–17]. The nodal approach was also mentioned here, although no studies on it were conducted.

In the studies based on the system approach, an all-round analysis of the reliability of jointly operating gas and electric power systems was carried out by the first method, i.e. in the beginning, the operation of gas system was modeled and its reliability was assessed, and then the operation of the power system was modeled, given the consequences of the gas system failures. For these purposes, we used the mathematical models to analyze the reliability of complex gas systems [18] and electric power systems [19].

The publications devoted to the assessment of power system adequacy in terms of reliability of gas systems, i.e. reliable gas delivery to gas-fired power plants, do not always explain the appropriateness of applying a particular method from the standpoint of the accuracy in presenting the technical and economic properties of the studied objects in the computational model [15–17]. Therefore, the novelty of this study lies in considering the methods with an analysis of their correspondence to the research objectives and aims, as well as with an analysis of their appropriateness in terms of time consumption to calculate reliability, complexity of input data preparation, availability of the necessary data and forms of their representation in a model. Special emphasis is put on partial failures [20, 21].

Additionally, we propose a wider problem statement: to address fuel supply to the plants operating not only on gas, but also on any other fuel (coal, fuel oil, etc.), i.e., we analyze the reliability of a fuel system (FS) in general and its effect on the electricity supply reliability. We have also put forward an estimation method to scrupulously consider the nodal and system approaches.

We have performed a comparative analysis of several methods to calculate the reliability of electricity system, taking account of the fuel system reliability.

The most universal representation of random values is their function or a distribution series in the most detailed form (with a sufficiently great number of steps). Therefore, all the models examined in this study are compared with this standard representation.

The paper focuses on various models and approaches ("nodal" (Section III), "systems" (Section IV) and "estimation" (Section V)) to allow for reliability when calculating and analyzing the adequacy of energy systems, and the methods for their evaluation.

III. Nodal approach

In the nodal approach, the reliability of fuel system is taken into account in the calculation of electric power system adequacy by considering the reliability depending on the equipment failure rate for the system directly supplying fuel to a certain EPS node.

The reliability analysis of fuel system is performed on the assumption that it operates independently of electric power system (sometimes, this is not true, but this issue is not addressed here). By analyzing the fuel system reliability, we find a series of probability distribution of its operable states, *p(Q)*. The latter is used to determine the main reliability indices of the system, including the probability of meeting consumer demand for fuel, or shortage-free supply, and the mean of actual output. Knowing them, it is possible to analyze the reliability of joint operation of energy system components. This can be done using two methods.

Method 1: The standard calculation suggests multiplication of the initial distribution series of operable state of the generating equipment of power plant operating on a certain fuel by the *p(Q)* series corresponding to it.

Method 2: With the supply coefficient used for estimation, we determine the fuel delivery probability for each i^{th} power plant (supply coefficient) p_i^F. In this case, the operable state probability of each generator p_i^G of the i^{th} power plant is calculated by the formula

$$p_i^{GF} = p_i^G \cdot p_i^F$$

This formula is used to build a corrected initial series by electricity generation to analyze the adequacy of EPS node, considering the fuel system reliability, i.e., the corrected values are applied in further calculations of the EPS reliability.

The results of the calculation by the nodal method were compared by a simplified test case yet considering all the essential factors affecting the integral reliability of power supply to consumers.

To calculate the distribution series for the fuel and electric power systems random states, we used the scheme of independent trails based on Bernoulli distribution [22]

$$P_n(m) = C_n^m p^m q^{n-m} \quad C_n^m = \frac{n!}{m!\,(n-m)!}$$

$$0! = 1;\ n! = 1 \cdot 2 \cdot \ldots \cdot n, \qquad (1)$$

where $q = 1 - p;\ m = 0, 1, 2, \ldots, n$.

In this notation: $P_n(m)$ is the probability that m units of n are in the operable state with the corresponding total power $\sum_{i=1}^{m} P_i$; p, q are probabilities of operable and non-operable states of each of n units, $p+q=1$; P_i is the unit capacity.

These distribution series can also be represented as a result of processing the statistical (reported) data on functioning of the corresponding equipment.

Table I. Fuel system distribution series.

No	Q_i^F, Mln TCE/YR	P_i^F, MW	p_i^F
1	0	0	$0.1 \cdot 10^{-9}$
2	7.656	100	$0.9 \cdot 10^{-8}$
3	15.312	200	$0.3645 \cdot 10^{-6}$
4	22.968	300	$0.8748 \cdot 10^{-5}$
5	30.624	400	$0.13778 \cdot 10^{-3}$
6	38.28	500	$0.5931 \cdot 10^{-2}$
7	45.936	600	$0.8787 \cdot 10^{-3}$
8	53.592	700	$0.574 \cdot 10^{-1}$
9	61.248	800	0.1937
10	68.904	900	0.3874
11	76.56	1000	0.3487

Note: The calculation correctness is confirmed by meeting the normalizing condition, i.e. the sum of probabilities of events equals 1.0.

Let us consider a fuel system represented by ten objects with an output of 100 MW each and with a 0.9 operable state probability of each object, i.e. $P^F = 100$, $n = 10$, $P^F = 0.9$, $q^F = 0.1$. Table 1 demonstrates the fuel supply random state distribution series calculated by the Bernoulli distribution (1). The system output is given as Q_i^F (tons of coal equivalent per year) and as P_i^F (megawatts).

The mean and the standard deviation of the actual fuel system output , are respectively equal to

$$M[P^F] = 852.32 \text{ MW};\ \sigma[P^F] = 300.92 \text{ MW}.$$

Table 2 presents the available capacity distribution series for the power plants comprising nine units with a 100 MW capacity, and with a 0.85 operable state probability, i.e.

$$P^G = 100,\ n = 9,\ P^G = 0{,}85,\ q^G = 0{,}15.$$

The mean and the standard deviation of the available capacity, respectively, equal

$$M[P^G] = 765.055 \text{ MW};\ \sigma[P^G] = 106.94 \text{ MW}.$$

Table 3 presents the distribution series of the load to be supplied. This series is regarded to be given.

The mean and the standard deviation of load are respectively equal to

$$M[P^L] = 477 \text{ MW},\ \sigma[P^L] = 229.28 \text{ MW}.$$

The connection diagram of the studied object is sequential in terms of reliability, therefore it can be

Table 2. Power plant available capacity distribution series.

No	P_i^G, MW	p_i^G
1	0	$0.3842 \cdot 10^{-7}$
2	100	$0.196 \cdot 10^{-5}$
3	200	$0.444 \cdot 10^{-4}$
4	300	$0.5876 \cdot 10^{-3}$
5	400	$0.4994 \cdot 10^{-2}$
6	500	$0.283 \cdot 10^{-1}$
7	600	0.10692
8	700	0.25969
9	800	0.3679
10	900	0.23163

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

Table 3. Load distribution series

No	P_i^G, MW	p_i^G
1	100	0.105
2	200	0.11
3	300	0.115
4	400	0.12
5	500	0.125
6	600	0.13
7	700	0.145
8	800	0.15

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

presented as follows (Fig. 1).

Fuel system → Electric power system → Load

Fig. 1. Diagram of fuel system connection to electric power system and to load.

Normally, the power supply reliability is determined for a uniquely set output of each of the systems included in the diagram (fuel system, electric power system, load), and for the probability of providing this efficiency. Here, consideration is given to the distribution series for various outputs and the probabilities related to them, which corresponds better to real operation conditions of the systems, because this is how the electric power system partial failures and the load undersupply are considered.

The fuel system available capacity is assumed to be larger than the power system available capacity, considering the redundancy (1000>900>800) required.

Based on the data from Fig. 1 and Tables 1 and 2, we should obtain a generalized fuel system and electricity system series and multiply it by the load series. The resultant series can be used to determine the power supply reliability indices for the investigated scheme.

The generalized distribution series characterizes possibilities for the joint operation of fuel and electricity systems, considering their individual reliability of operation.

The formation of the generalized distribution series requires a technological analysis of the complex object at issue. Naturally, the main link here is electricity system.

Table 4. Load distribution series

No	P_i^{Gd}, MW	p_i^{Gd}
1	0	$0/382955\cdot10^{-7}$
2	100	$0/194855\cdot10^{-5}$
3	200	$0/445049\cdot10^{-4}$
4	300	$0.593439\cdot10^{-3}$
5	400	$0.663965\cdot10^{-2}$
6	500	$0.298266\cdot10^{-1}$
7	600	0.11212877
8	700	0.2916282
9	800	0.3877872
10	900	0.1713499

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

Table 5. Load supply distribution series

No	P_i^{Gd}, MW	p_i^{Gd}
1	0	0.0918451
2	100	0.105
3	200	0.1099997
4	300	0.1149946
5	400	0.1199232
6	500	0.1243209
7	600	0.1255264
8	700	0.1238744
9	800	0.0845157

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

Therefore, when composing (multiplying) the distribution series for the outputs of fuel and electric power systems, the generalized output values are taken from the relation $P^{Gd} = \min(P^{Gd}, P^L)$, i.e. the minimum values are selected according to the scheme in Fig. 1.

The results of this analysis are used to form the final generalized series presented in Table 4.

The multiplication of the generalized distribution series for the outputs of joint operation of fuel and electricity systems (Tab. 4) with the load distribution series (Tab. 3) provides the resultant distribution series for this load supply (Tab. 5). This series allows obtaining exact ("standard") reliability indices. The values of the output used to supply the load are determined according to the technological features of a system from the $P^R = \min(P^{Gd}, P^L)$ relation. The probabilities of each of the load supply random states show the extent to which this load is provided by the system, Fig. 1.

According to Table 5, the variable load is supplied with a probability of 0.9081549 equal to the sum of probabilities of supplying all the loads. Consequently, a denial in supply will occur at probability

$$P_1^R = 0.0918451 = 1.0 - 0.9081549 \qquad (2)$$

Below is the calculation using the fuel supply coefficient p^F of each generator in the system and the operable state probability p^G with the values assumed in the previous calculation (p^G= 0.85 ; p^F = 0.9). We assume that given the fuel supply to generators, their operable state probability has the value

$$p^{GF} = p^G \cdot p^F = 0.85 \cdot 0.9 = 0.765$$

Table 6. Available generating capacity, distribution series

No	P_i^{GF}, MW	p_i^{GF}
1	0	$0.21\cdot10^{-5}$
2	100	$0.612\cdot10^{-4}$
3	200	$0.82319\cdot10^{-3}$
4	300	$0.633294\cdot10^{-2}$
5	400	$0.309238\cdot10^{-1}$
6	500	0.10067804
7	600	0.21849862
8	700	0.30483716
9	800	0.2480856
10	900	0.0897331

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

To calculate the distribution series for random values of the available generating capacity, we used the Bernoulli distribution (1). Table 6 presents the generalized series.

The multiplication of the series presented in Table 6 by the load series (Tab. 3) provides the resultant load supply distribution series (Table 7).

As seen from Table 7, the load is supplied with a probability of 0.9999979 equal to the sum of probabilities of supplying all the non-zero loads. Therefore, a denial in supply will occur at probability

$$P_1^R = 0.0000021 = 1.0 - 0.9999979 \quad (3)$$

Comparing the results based on Table 5 (standard distribution series, expression (2)) and Table 7 (distribution series based on fuel supply coefficient, expression (3)), we can conclude that there is an essential error, when the technique presented in Table 6 is used. Therefore, this technique can hardly be recommended, despite the simplification in calculations.

Even less exact results will be obtained, if, the means of the outputs of the indicated electric system components are used instead of the distribution series for the states of fuel system, electric power system and load. Thus, the means for the systems outputs calculated from the data in Tables 1, 2, and 3 equal

$$M[P^F] = 852.32 \text{ MW}; M[P^G] = 765.055 \text{ MW};$$
$$M[P^L] = 477 \text{ MW}.$$

The presented means allow us to conclude that the load will be supplied absolutely reliably at a probability of 1.0. However, this is not true. Even for our test case, the obtained standard deviation values provide a variance of random values such that even at their minimal values, the load will be supplied unreliably.

Based on the conducted study, we can conclude that, to calculate the reliability of EPS load supply, the calculations should rely on the technological features of the addressed systems, the block diagram of their connections, and avoid (for the calculation effort reduction) various ways to unreasonably simplify the initial scheme, its parameters, and calculation techniques.

IV. System approach

In the system approach, the calculation of the adequacy of electricity system nodes takes into account the fuel system reliability calculated for the entire fuel system, i.e. firstly, we estimate the reliability of a fuel system (the probabilities of shortage-free fuel supply to consumers are calculated, which implies estimating the reliability of fuel delivery to power plants operating on a given fuel).

When analyzing the reliability of the electricity supply to consumers in electric power system, the fuel system reliability can be taken into account by two methods.

Method 1. Correction of the generating equipment failure rate [15, 16].

The reliability indices calculated for fuel supply to consumers by node p_i^F are taken into account before calculating the generating capacity distribution series. First, we recalculate the failure rates of the generating equipment q_i^G for power plants of the given node i that operate on a given fuel.To this end, we calculate the probabilities of failure-free operation of the equipment of power plants operating on a given fuel, $p_i^G = 1 - q_i^G$. These probabilities are then multiplied by the corresponding fuel system nodal reliability indices p_i^F, i.e. $p_i' = p_i^G \cdot p_i^F$. Further, the corrected equipment failure rates for the power plants $q'_i = 1 - p_i'$ are calculated, and, based on them, the distribution series of generating capacity, or of operable state of units at power plants are calculated.

Method 2. Correction of the generating capacity distribution series.

The reliability indices calculated for the fuel supply to consumers by node i (probabilities of shortage-free fuel supply to consumers, p_i^F) are taken into account after calculating the distribution series of generating capacity or operable state of the units at power plants, by multiplying the calculated series by the corresponding series $(1 - p_i^F p_i^F)$.

Thus, by using these two methods, we obtain the input data for a mathematical model to estimate the EPS adequacy, given the reliability of fuel supply to these power plants.

In the system approach, the methods were compared to consider the fuel system reliability for a conventional power system: the system contains 5 units, (n = 5), each with a capacity of 800 MW and with the same failure rate = 0.03. The probability of the fuel system shortage-free operation equals $p^F = 0.9$.

According to Method 1 (correction of the generating equipment failure rate), we recalculate the power plant

Table 7. Load supply distribution series, considering table 6

No	P_i^R, MW	p_i^R
1	0	$0.21 \cdot 10^{-5}$
2	100	0.10505
3	200	0.110636
4	300	0.119138
5	400	0.136139
6	500	0.163017
7	600	0.176407
8	700	0.13891
9	800	0.05066673

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

Table 8. Distribution series for generating equipment operable state, considering fuel system operation, method 1.

No	Number of units in operation	Capacity P^1, MW	Probability, p_i^1
1	0	0	$0.3303837 \cdot 10^{-4}$
2	1	800	$0.\ 113553 \cdot 10^{-2}$
3	2	1600	$0,\ 156113 \cdot 10^{-1}$
4	3	2400	0.10731247
5	4	3200	0.36883379
6	5	4000	0.50707386

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

Table 9. Distribution series of the generating equipment operable state, disregarding fuel system operation.

No	Number of units in operation	Capacity P^1, MW	Probability, p_i^1
1	0	0	$0.243 \cdot 10^{-7}$
2	1	800	$0.39285 \cdot 10^{-5}$
3	2	1600	$0.254043 \cdot 10^{-3}$
4	3	2400	$0.8214057 \cdot 10^{-2}$
5	4	3200	0.1327939215
6	5	4000	0.8587340257

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

Table 10. Distribution series for the generating equipment operable state, considering fuel system operation, method 2.

No	Number of units in operation	Capacity P^2, MW	Probability, p_i^2
1	0	0	0,1
2	1	800	$0{,}353565 \cdot 10^{-5}$
3	2	1600	$0{,}228639 \cdot 10^{-3}$
4	3	2400	$0{,}7392651 \cdot 10^{-2}$
5	4	3200	0,119514529
6	5	4000	0,772860623

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

generating equipment failure rate, given the fuel system reliability. For this purpose, we calculate the initial and the corrected probabilities for the failure-free operation

$$p^G = 1 - q^G \; 1 - 0.03;$$
$$p' = p^G \cdot p^F = 0.97 \cdot 0.9 = 0.873$$

The corrected equipment failure rate will equal

$$q' = 1 - p' = 1 - 0.873 = 0.127$$

Let us calculate a new distribution series of the power plant operable state with the corrected equipment failure rate by the Bernoulli distribution (1). Table 8 presents the obtained distribution series for the generating equipment operable state, considering the probability of the fuel system shortage-free operation.

Based on this distribution series, we calculated the mean and the standard deviation for the actual output: $M[P^1]$ = 3492 MW, and $\sigma[P^1]$ = MW, respectively.

According to Method 2 (correction of the generating capacity distribution series), we calculate the distribution series of the power plant operable state, based on the scheme of independent trials with the Bernoulli distribution (1).

Then, $n = 5$, $q = 0.03$, $p = 1 - q = 0.97$, $m = 0, 1, 2, \ldots, 5$. Table 9 presents the calculated distribution series for the generating equipment operable state.

Based on the distribution series, we calculated the mean and the standard deviation of the actual output: $M[P^2]$ = 3492 MW and $\sigma[P^2]$ = 1199.46 MW, respectively.

A comparison of the calculation results for the two methods of considering the fuel system reliability to estimate the electricity system adequacy (Tables 8 and 10) indicates that the first method (that takes into account the system specificity more precisely) demonstrates the real (although smaller) reliability, than the second, simplified method. The means of the outcomes are equal; the standard deviations are less in the first case, which indicates to a greater data homogeneity. We can conclude that the first method, considering the process technology, is more preferable.

V. Estimation approach

To estimate the interval of the power system nodal adequacy indices, namely, the lower and upper boundaries of the probability for shortage-free power supply to consumers, we, first, analyze the fuel system reliability. Thus, we calculate the reliability indices for fuel supply to consumers at all nodes , namely, the probability of shortage-free fuel supply to consumers p_i^F, $i = \overline{1, I}$, where I is the number of estimated consumer-nodes in the system. Similarly, we can calculate the EPS nodal reliability indices, i.e., the probabilities of the shortage-free power supply to consumers at an absolute reliability of fuel system (or disregarding the unreliable fuel system operation) – p_i^G. Then, the probability of power supply to consumers,

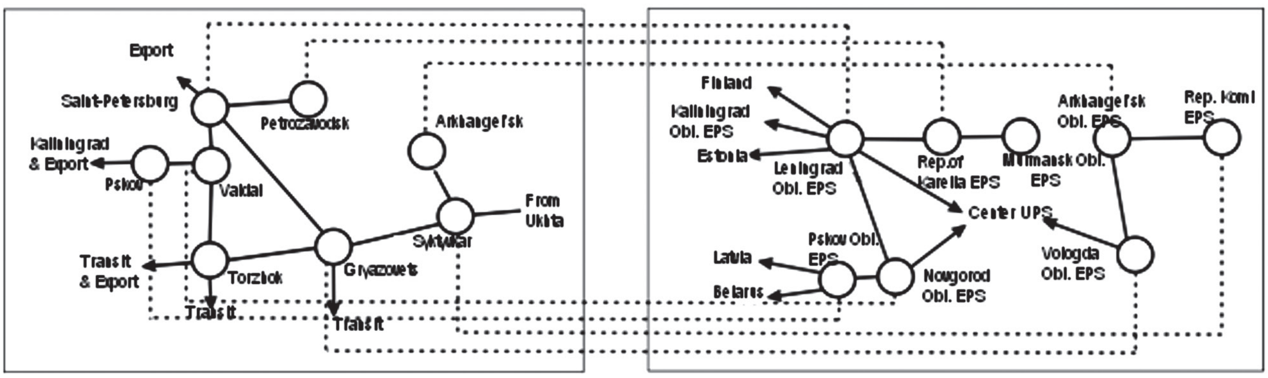

Fig. 2. Design diagrams for the NWFD gas system (a) and electric power system (b) with functional connections.

Table 11. Reliability indices of gas system in NWFD.

No	Node	Probability of shortage-free gas supply to consumers
1	Petrozavodsk	0.935208
2	Syktyvkar	0.997083
3	Arkhangelsk	0.997083
4	Gryazovets	0.994958
5	Saint-Petersburg	0.969208
6	Valdai	0.994958
7	Pskov	0.977292
8	Torzhok	0.994958

Note: The normalizing condition is met: $\Sigma p_i = 1.0$.

Table 12. Nwfd eps adequacy indices.

No	Node	Probability for shortage-free operation power consumers p_i^{EPS}	
		Disregarding Gas system reliability ($p_i^{GSS} = 1$)	Considering gas system reliability (system approach)
1	Republic of Karelia EPS	0.992859	0.987581
2	Komi Republic EPS	0.998984	0.998982
3	Arkhangelsk Region EPS	0.999944	0.999944
4	Vologda Region EPS	0.999999	0.999999
5	Leningrad Region EPS	0.999944	0.999944
6	Novgorod Region EPS	0.999944	0.999944
7	Pskov Region EPS	0.998555	0.997259
8	Murmansk Region EPS	0.997770	0.997763

given reliability of fuel system p_i^{GF}, is calculated as $p_i^{GF} = p_i^G \cdot p_i^F = P_i'$ This value can be considered as the lower boundary P_i' of the nodal reliability index of the power supply to consumers p_i^{GF}. Indeed, the EPS nodal reliability index, given the fuel system operation, will be above the lower boundary due to the manifestation of the system mutual-aid effect in the EPS. The upper boundary of the nodal index will be at $p_i^F = 1$, i.e., we believe that the fuel system is absolutely reliable, or its reliability is not considered in the analysis of the EPS reliability, $p_i^{GF} = 1\ p_i^F = P_i'$. Obviously, the probability of power supply to consumers, given the fuel system reliability, will be within a range from the lower boundary P_i' to the upper boundary P_i'', i.e. $P_i' \le p_i^{GF} \le P_i''$.

The interval estimation of the EPS nodal adequacy indices was tested for the energy system of the Northwestern Federal District (NWFD) [15, 17]. The fuel system is represented by a gas transmission system. The NWFD power system was selected because the share of the NWFD power system generating capacity using gas as a primary energy resource accounts for about 70% of the total generating capacity [23].

Fig. 2 presents the design diagrams of the NWFD gas and electric power systems. The dashed line marks the functional connections of the given systems.

To estimate the reliability of gas and electric power systems, we developed and used the mathematical models [15, 18, 19]. Based on the reliability estimation for the NWFD gas system, we obtained the reliability indices of gas supply to consumers by node. Table 11 presents the probabilities of meeting the consumer demand for gas or shortage-free gas supply [16].

We also estimated the NWFD power system reliability, both with and without consideration of the reliability of gas supply to power plants, and calculated the probabilities of shortage-free power supply to consumers (p_i^{EPS}) by node

Table 13. NWFD eps adequacy indices

No	Nodes in systems			Probabilities of shortage-free power supply to consumers		
	Gas system	p_i^{GSS} (from Table 11)	EPS	disregarding gas system reliability ($p_i^{GSS} = 1$), $P_i'' = p_i^{EPS}$ (upper boundary)	considering gas system reliability (nodal approach) $P_i' = p_i^{GSS} \bullet p_i^{EPS}$ (lower boundary)	considering gas system reliability (system approach)
1	Petrozavodsk	0.935208	Republic of Karelia EPS	0.992859	0.92852968	0.987581
2	Syktyvkar	0.997083	Komi Republic EPS	0.998984	0.996069964	0.998982
3	Arkhangelsk	0.997083	Arkhangelsk Oblast EPS	0.999944	0.997027163	0.999944
4	Gryazovets	0.994958	Vologda Oblast EPS	0.999999	0.994957005	0.999999
5	Saint-Petersburg	0.969208	Leningrad Oblast EPS	0.999944	0.969153724	0.999944
6	Valdai	0.994958	Novgorod Oblast EPS	0.999944	0.994902282	0.999944
7	Pskov	0.977292	Pskov Oblast EPS	0.998555	0.975879813	0.997259
8	Torzhok	0.994958	Murmansk Oblast EPS[1]	0.997770	0.997770	0.997763

[1] No connection to gas system

[16]. Table 12 presents the results.

To calculate the lower boundary of the nodal reliability indices for power supply to NWFD consumers, we superimposed the fuel system nodes on electricity system nodes. Table 13 presents the results. Thus, for example, the lower boundary for the Republic of Karelia EPS node (which corresponds to the Petrozavodsk node in the fuel system scheme) was obtained as follows:

$$P_i' = p_i^{GSS} \cdot p_i^{EPS} = 0.935208 \cdot 0.992759 = 0.92852968$$

An analysis of the calculation results confirms the theoretical assumption that the probability of power supply to consumers (considering the gas system reliability), calculated as $P_i' = p_i^{GSS} \cdot p_i^{EPS}$, is the lower boundary of the nodal reliability index for power supply to consumers (the next-to-last column in Table 13).

The nodal EPS reliability indices (considering the gas system operation) calculated according to the system approach (the last column in Table 13), appeared above the lower boundary due to the mutual-aid system effect of the power system operation.

The nodal and system approaches calculate the EPS reliability based on the point or discrete reliability index obtained as one certain number, which can lead to errors when making a decision. The estimation approach provides an interval estimation of the index, which is more objective and reduces calculation errors to minimum.

VI. Conclusions

1. We have proposed several methodological approaches (nodal, system, and estimation) to estimate the adequacy of an energy system, considering the reliability of fuel systems, i.e. reliable supply of a given fuel to power plants.

2. All the approaches were tested in case studies. The nodal and the system approaches were tested using a conventional electric power system. The estimation approach was tested using the design diagrams of gas and electric power systems of the Northwestern Federal District.

3. The reliability of energy system load supply should be calculated with respect to the technological features of the systems at issue and the block diagram of their connections.

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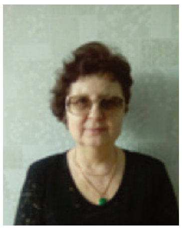
Gennady Kovalev graduated from Kalinin Polytechnic Institute. He is leading researcher of ESI SB RAS, Doctor of Engineering, Professor. His scientific interests include reliability of electric power systems (EPS), optimization of EPS reliability in the stages of design and expansion planning, diagnostics of power equipment.



Tatyana Dzyubina graduated from Irkutsk Polytechnic Institute. She has worked at ESI SB RAS, since 1976. She is a senior researcher, PhD in engineering. Her scientific interests are connected with mathematical modeling of reliability of large energy systems, the issues of calculation of natural gas prices and tariffs.