Assessment of Electric Power System Adequacy Considering Reliability of Gas Supply to Power Plants

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***Abstract*—The paper proves the need to make an integrated reliability analysis of gas supply and electric power systems when planning their expansion. The proposed methodological approach aims to assess the adequacy of electric power systems, considering reliable gas supply to power plants. Based on this systems approach, the reliability of gas supply system and adequacy of electric power system are analyzed for one of Russia's Federal Districts. An impact of gas constituent on the assessment of the electric power system adequacy was determined by calculations with and without regard to reliability of gas supply to electric power plants.**

***Index Terms* — gas supply system, electric power system, adequacy, assessment, reliability indices, mathematical modeling.**

I. Nomenclature

A. Model for reliability assessment of gas supply system(GSS)

$i \in R$ – nodes in the model network that correspond to the fields $(i \in R_1)$, consumers $(i \in R_2)$, underground storage $(i \in R_3)$, pipeline junction points $(i \in R_4)$.

$(i, j) \in U$ – edges connecting nodes i and j.

For each calculated field-node $i \in R_1$ we specify:

$q^o[x^o]$ – variation series of potential gas supply to the system.

x_i^o, X_i^o – current and maximum possible gas supply from fields to the system, t.c.e.

C_i^o – specific costs of gas production, RUR/t.c.e.

λ_i^o – coefficient considering gas consumption for auxiliaries, $\lambda_i^o < 1$.

For each calculated consumer-node $i \in R_2$ we set:

$M[x_i^I]$, $\sigma[x_i^I]$ – demand of household consumers for gas, represented by a mean value and mean square deviation of the normal law of distribution, t.c.e.

x_i^I, X_i^I – current and maximum possible demand for gas for consumer category I (household), t.c.e.

$X_i^{II(III)}$ – demand for gas for consumer category II (III) (industrial consumers, gas –fired boiler and electric power plants), t.c.e.

C_1, C_2 and C_3 – specific gas cost for consumer categories I, II, III, respectively, $C_1 << C_2 << C_3$, RUR/t.c.e.

x_{0i}, B_i – current and maximum volume of backup fuel, t.c.e.

C_{0i} – specific costs of backup fuel, RUR/t.c.e.

x_i^d – total gas shortage for all consumer-node categories, t.c.e.

y_{0i} – specific damage due to gas undersupply, RUR/t.c.e.

$\mathcal{P}_i^{GSS}$ – obtained reliability of meeting the demand or shortage-free gas supply to consumers.

For each underground gas storage (UGS) -node $i \in R_3$, we set:

$q^{st}[x_i^+], q^{st}[x_i^-]$ – variation series of potential gas withdrawal from UGS to the system or potential gas injection into UGS.

x_i^+, x_i^- – potential gas supply from UGS to the system or gas injection into UGS, t.c.e.

C_i^+, C_i^- – specific costs of gas withdrawal or injection, RUR/t.c.e.

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V_i – storage capacity, t.c.e.

S_i – gas reserve at the beginning of the considered period, t.c.e.

λ_i^+ – coefficient, considering gas storage losses, $\lambda_i^+ < 1$.

For each main gas pipeline $(i, j) \in U$ we set:

$q^{gp}[x_{ij}]$ – variation series of capacity.

x_{ij} – main gas pipeline capacity, t.c.e.

C_{ij} – specific costs of gas transportation from node i to node j, RUR/t.c.e.

λ_{ij} - coefficient considering gas transportation losses , $\lambda_{ij} < 1$.

B. Model for reliability assessment of electric power system (EPS)

x_i – generating capacity at the *i*-th node of EPS (MW).

z_{ij} – transfer capabilities of a tie between the EPS nodes *i* and *j* (MW).

y_i – values of electricity consumer load at the *i*-th EPS node (MW).

a_{ij} – given positive coefficients of specific power losses during transmission from node i to node j.

$\mathcal{P}_i^{\mathrm{EPS}}$ – probability of shortage-free operation of electricity consumers.

E_u – mean value of electricity undersupply to consumers, MWh.

π – coefficient of consumer provision with electricity.

q_i , $q_i^{/}$ – initial and corrected failure rates of equipment at gas-fired power plants, at node i.

p_i , $p_i^{/}$ – initial and corrected probabilities of failure-free operation of equipment at the gas-fired power plants, at node i.

II. Introduction

A comprehensive characterization of the electric power system reliability is impossible without estimation of the extent to which the electric power industry is provided with all types of resources: material, financial and labor.

The most important resources among the material ones are primary energy resources i.e. fuel for thermal power plants, water in reservoirs for hydropower plants, nuclear fuel for nuclear power plants. Moreover, because of rapid renewable energy development, nowadays, the problems of considering the electricity output unevenness at such plants become urgent.

According to [1], gas consumption in the world increases annually approximately by 1.4 percent and by 2040 natural gas will have dominated the world energy balance. This can be explained by several reasons: relative abundance of natural gas, its environmental advantages over the other fossil fuels, etc. Its share in the energy balance will rise from 21 percent in 2013 to 24 percent in 2040.

As for Russia, currently and in the future (until 2030) in certain regions thermal (condensing and cogeneration) power plants will use natural gas as a fuel. Its share in the total fuel volume makes up and will make up 70-90 percent for a long time [2]. By 2030 electricity production at gas – fired power plants will have increased by 1.92 times (against 2010) [3]. This will be associated with an increasing demand for heat and electricity with gas as the priority for environmental and economic reasons. It is also necessary to take into account the fact that the other fuel types (coal, heavy oil, etc.) can be stored at thermal power plants in considerable amounts, whereas gas is not stored at power plants. Consequently, large-scale emergencies in the main gas networks or failures in the distribution networks that supply gas to concrete thermal power plants can cause long-term interruptions of electricity supply to consumers.

The above information can serve as a ground for the need to jointly consider the reliable operation of gas supply and electric power systems.

The second point that makes the joint consideration of reliability of gas supply and electric power systems relevant is electricity market liberalization. The limitations and "market-related" refusals to supply fuel due to market liberalization also affect the electric power system operation [4].

Thus, the development of programs and strategies for planning the expansion and operation of energy systems in the coming period calls for a comprehensive approach to jointly analyze arbitrary events and processes in the gas supply and electric power systems. This will allow investigation of electric power system adequacy, considering expected and unexpected gas supply limitations which can overlap the potential failures of equipment in electric power systems under the conditions of a growing physical and functional interaction between gas supply and electricity supply systems. Thus, it will be possible to enhance the controllability of both systems, their reliability and efficiency.

The reliability assessment of electric power system, considering the reliability of gas supply system is a relevant issue at various stages of their expansion and operation. There can be problems in their control in the case the two systems have coinciding peak loads. This can cause a decline in the pressure in gas pipeline which will affect gas delivery to the generating units [5,6]. There are studies in which the interrelated operation of gas supply and electric power systems is modeled considering gas contracts [7]. The authors of [8,9] present the models applied to on-line planning the gas and electricity supply system operation. The models in the above sources consider on-line and short-term planning of the joint operation of the two systems. In this paper, we propose a methodology and a model for analyzing the reliability of the GSS and EPS joint operation for the long term, which involves analysis of reliability over a long time interval and viewing a variety of different operating conditions of these systems. The analysis reveals the weak (critical) places in each of the systems under consideration.

III. Problem Statement and Solving Methods

The analysis of existing models demonstrates that the electric power system adequacy, considering reliability of gas supply to power plants, can be modeled in different ways:

1) considering the effects of gas system failures on reliability of the electric power system, but modeling natural gas network separately from the electric power system;

2) modeling the joint operation of gas supply system and electric power system on the basis of stochastic simulation of failures simultaneously in both systems.

A comprehensive reliability analysis of the joint operation of gas and electricity supply systems is recommended for the application of the first method in the initial stage, i.e. first we model the operation of gas supply system and assess its reliability, and then the operation of electric power system is modeled considering the consequences of failures in gas supply systems.

The proposed methodological approach is a “systems” one. All energy nodes of the electric power system are connected with one another by the joint operation, and mutually assist each other in the emergency (shortage) conditions. This approach should reflect the interaction between the operation of gas supply system and operation of electric power system, and the principles of modeling these systems should be coordinated:

1. Both reliability of gas supply and reliability of electricity supply should be modeled for the same time periods (year, season, quarter, month, etc.).

2. When setting the input data, it is necessary to consider seasonal indices of the equipment failure rate (when this statistic is available).

3. The reliability assessment of gas supply and electric power systems should be based on the mathematical methods of probabilistic modeling with the same accuracy.

4. Aggregation of gas supply and electric power systems should have the same level. Electric power plants should be considered as gas consumers. Topography of gas supply and electricity supply systems should coincide in a general case.

We propose a comprehensive reliability analysis of the integrated system (gas supply and electric power systems) on the basis of the systems approach, where the resultant data from the model for reliability assessment of gas supply system are transferred as input data to the model for reliability assessment of electric power system. Thus, the following sequence of actions is suggested:

1. Reliability assessment of gas supply to thermal power plants. To this end, we apply the model for reliability analysis of a large-scale gas supply system [10]. This analysis should provide such nodal reliability indices of gas supply as probabilities of shortage-free gas supply to consumers.

2. Reliability assessment of electricity supply to consumers. For this purpose, we use the model of reliability analysis of a large-scale electric power system [11]. When setting the failure-rate data for gas-fired thermal power plants it is necessary to take into account additional probability of failure of these plants due to unreliable operation of gas supply system. This should be done by considering the results of gas supply system reliability assessment.

We will consider in more detail the models for the assessment of gas supply and electric power system reliability, which are applied in the systems approach.

In the model for reliability analysis of a large-scale gas supply system, the object of research is represented by a multi-node gas supply system that embraces fields and other gas sources, underground gas storages (UGS) and gas consumption nodes (with consumer categories), which are connected through the system of main gas pipelines [10].

The model takes into account the probabilistic nature of demand of household consumers for gas; capacities of main gas pipelines, volume of gas supply to the system from fields, volume of gas withdrawal to the system or gas injection into the underground gas storages. The three last factors depend on the condition of the respective equipment and should be determined, considering its emergency and planned shutdowns.

Demand of household consumers (category 1) is approximated by the normal law of distribution, the other random values can be approximated by the other laws of distribution.

The rest of the parameters, such as the initial gas reserve in the underground gas storage, volume of backup fuel at consumption nodes and demand of industry, boiler and power plants (categories II and III) are set deterministically.

The maximum calculation time interval is one season of the year (winter or summer). This is connected with the fact that under relatively short-term disturbances in the system by virtue of inertia the underground gas storages cannot often switch from withdrawal mode to injection mode, and therefore the underground gas storages operate as gas sources in winter time and as gas consumers in summer time.

Conceptually, the model makes it possible to determine: the distribution law of gas imbalances at consumption nodes, main reliability indices, functions of gas flow distribution along the main gas pipeline, operation of fields and underground gas storages. The model takes into account the given demand for gas, gas supply from fields to the system, gas withdrawal from underground gas storages to the system and gas injection into underground gas storages, underground gas storage reserves, capacities of main gas pipelines, gas consumption for auxiliaries at fields, gas storage losses in the underground storages, gas transportation losses in the main gas pipelines, and fuel interchangeability.

An algorithm for gas supply system reliability assessment includes:

1. *Probabilistic block.* Here we apply the method of statistical trials (Monte Carlo method) based on which the variation series set for a given calculation time interval are used to statistically simulate random states of the demand of household consumers for gas x_i^I, possible gas supply to the system from fields x_i^o and underground storage x_i^+ (or injection into the underground gas storage x_i^-), and capacity of the main gas pipeline x_{ij}, $(i,j) \in U$, $i \in R$

2. *Block for calculation of system operating conditions.* Here we apply the method for optimization of flow distribution in gas transmission systems (a modified Busacker-Gowen algorithm) which makes it possible to consider the first law of Kirchhoff; respective constraints on capacity of pipelines, fields, gas storages; gas supply to consumers, which should not exceed the calculated demand; gas losses in the stages of production, storage, and transmission; and fuel interchangeability.

The calculation of optimal conditions implies the determination of gas production volumes at each field (source); volumes of backup fuel supply to consumers; supplied gas volumes which consist of the gas supply volumes to all categories of consumers at each node, $x_i^s = x_i^I + X_i^{II} + X_i^{III}$; gas volumes at gas injection into or withdrawal from the underground gas storage; gas flows along the respective gas pipelines.

Formalized statement of the problem of calculation of optimal conditions has the following form

$$\sum_{i \in R_1} C_i^o x_i^o + \sum_{i \in R_1} C_{0i} x_{0i} + \sum_{i \in R_3} C_i x_i + \sum_{(i,j) \in U} C_{ij} x_{ij} + \sum_{i \in R_2} y_{0i} x_i^d \to min \qquad (1)$$

subject to

$$\sum_j \lambda_{ji} x_{ji} - \sum_j x_{ij} + \lambda_i^o x_i^o = 0,$$
$$0 \le x_i^o \le X_i^o, \qquad i \in R_1 \qquad (2)$$
$$\sum_j \lambda_{ji} x_{ji} - \sum_j x_{ij} + x_{0i} - x_i^s = 0,$$

where
$$x_i^s = x_i^I + X_i^{II} + X_i^{III} - x_i^d,$$
$$0 \le x_i^{I(II,III)} \le X_i^{I(II,III)},$$
$$0 \le x_{0i} \le B_i,$$
$$0 \le x_i^d \le x_i^I + X_i^{II} + X_i^{III}, \qquad i \in R_2 \qquad (3)$$
$$\sum_j \lambda_{ji} x_{ji} - \sum_j x_{ij} + \lambda_i^+ x_i = 0,$$
$$0 \le x_i^+ \le min\{X_i^+, S_i\},$$
$$0 \le x_i^- \le min\{X_i^-, V_i - S_i\}, i \in R_3 \qquad (4)$$
$$\sum_j \lambda_{ji} x_{ji} - \sum_j x_{ij} = 0 \quad , \quad i \in R_4 \qquad (5)$$
$$0 \le x_{ij} \le X_{ij}, \qquad (i,j) \in U. \qquad (6)$$

The minimum cost of gas supply to consumers is considered as a criterion. This criterion ensures the fulfillment of the condition of maximum gas delivery to consumers at a minimum cost, which corresponds to the real conditions of gas distribution.

Equality constraints represent gas balances at the corresponding nodes and the remaining constraints are set as two-sided inequalities. Gas storage losses are taken into account only at gas withdrawal from underground storage, and gas pipeline losses are considered once at the end of the pipeline.

3. *Block for calculation of the gas system reliability indices*. Here we apply the probability theory methods: the addition and multiplication theorems of probability of various events and methods for calculation of distribution functions of gas imbalances which are used to determine the main reliability indices:

– reliability of gas supply to consumers as a probability of satisfaction of the demand for gas or shortage-free gas supply to consumers $\mathcal{P}_i^{GSS}$;

– a mean value of gas undersupply*;*

– a coefficient of relative provision of consumers with gas, etc.

Model of electric power system reliability assessment [11] as well as the model of gas supply system reliability assessment is based on the method of statistical trials and also consists of three main computational blocks.

The problem is solved by the method of simulation modeling of electric power system operation during the calculation period (year, quarter, month). The variation series of capacities of units at nodes and transmission lines in ties are calculated by their known failure rates. The generation function is represented by a binomial expression. The state of loads and capacity of equipment are simulated by the Monte-Carlo method. The calculated conditions are optimized by the method of interior points [12], where the functional is represented by one of the principles of minimization and distribution of capacity shortage among nodes. The principle is selected considering power losses in lines and damages due to electricity undersupply at nodes [11].

1. *Probabilistic block.* The assessment is based on the method of random events. In this block we perform the k-fold modeling of electric power system parameters (until the required accuracy is reached), such as: x_i – generating capacity at the i-th node of electric power system z_{ij} – transfer capabilities of the tie between nodes i and j of the electric power system, y_i – values of electricity consumer loads at the i-th node of electric power system.

2. *Block for calculation of system operating conditions*. To assess power shortage of the k-th state of the electric power system, $k = 1, \dots, K$, it is necessary to find:

$$\sum_{i=1}^{n} y_i \to max, \tag{7}$$

considering balance constraints

$$x_i - y_i + \sum_{j=1}^{n}(1 - a_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} = 0, \; i = 1,...,n,$$

$$i \neq j, \tag{8}$$

and linear inequality constraints on variables

$$y_i \leq \bar{y}_i^k, \; i = 1, \dots, n, \tag{9}$$

$$x_i \leq \bar{x}_i^k, \; i = 1, \dots, n, \tag{10}$$

$$z_{ij} \leq \bar{z}_{ij}^{k}, \quad i = 1, \dots, n, \; j = 1, \dots, n, \; i \neq j, \tag{11}$$

$$y_i \geq 0, \; x_i \geq 0, \; z_{ij} \geq 0, \; i = 1, \dots, n,$$

$$j = 1, \dots, n, \; i \neq j. \tag{12}$$

3. *Block for calculation of the electric power system reliability indices.* The assessment of electric power system reliability provides the following reliability indices:

– probability of shortage-free operation of electricity consumers $\mathcal{P}_i^{\mathrm{EPS}}$;

– a mean value of electricity undersupply to consumers E_u;

– a coefficient of consumer provision with electricity π, etc.

To implement the systems approach, the nodal gas supply reliability indices (probabilities of shortage-free gas supply to consumers $\mathcal{P}_i^{\mathrm{GSS}}$) are applied in the second stage to assess the electric power system reliability. To this end, knowing the equipment failure rate q_i at the gas-fired power plants of a given node i, we calculate the values $p_i = 1 - q_i$, which are then multiplied by the corresponding nodal reliability indices of gas supply system $\mathcal{P}_i^{\mathrm{GSS}}$, *i.e.* $p_i^{/} = p_i \cdot \mathcal{P}_i^{\mathrm{GSS}}$. In the end, the adjusted equipment failure rates at power plants $q_i^{/} = 1 - p_i^{/}$ are calculated. Thus, we obtain input data for the mathematical model of adequacy assessment of the electric power system, considering provision of these plants with gas.

IV. A CASE STUDY OF EPS ADEQUACY ASSESSMENT CONSIDERING RELIABILITY OF GAS SUPPLY TO POWER PLANTS

The experimental studies on the suggested system approach to the assessment of electric power system adequacy, considering the reliability of gas supply to thermal power plants were conducted for the scheme of energy system in one of Russia's Federal District (RFD). The share of generating capacity in RFD energy system using gas as a primary energy resource exceeds 70 percent [13] of the total generating capacity. Figure 1 presents the calculated schemes of the gas supply system and electric power system in RFD, dotted line is used to demonstrate the functional interaction between these systems.

The reliability of gas supply to consumers and power plants was assessed for one month (January, as the most intensive month in terms of energy consumption). All data on gas supply and electric power systems are given for 2015. The initial data on demand for gas for the RFD consumers, its export to the FSU and non-FSU countries, and the data on the upper constraints on gas production and transportation and other indices to be used in calculations on the mathematical models were prepared considering an average scenario of economic development.

The main technical characteristics of aggregate pipelines

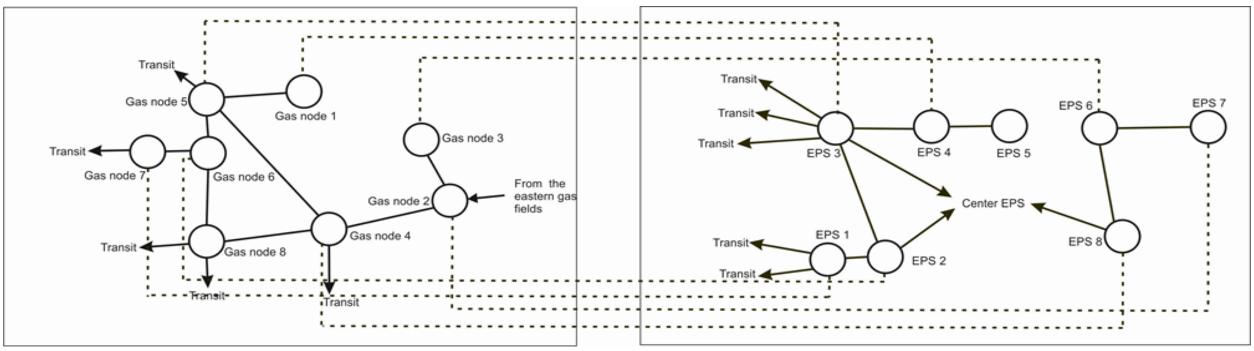

Figure 1. Calculated schemes of gas supply system (a) and electric power system (b) in RFD.

Table 1. Technical indices of aggregate pipelines of gas supply system in RFD.

N	Name	Lines: number/ diameter, mm^2	Capacity, billion m^3/year	Length of the pipeline, km
1	Gas nodes 2 – 4	4/1420 2/1220	210	550
2	Gas nodes 2 – 3	1/1420	30	508
3	Gas nodes 4 – 8	4/1420 2/1220	210	539
4	Gas nodes 4 –5	1/1420 2/1220 1/1020	104	639
5	Gas nodes 8 –6	2/1220 1/1020	22	180
6	Gas nodes 6 – 7	1/1020	9	259
7	Gas nodes 6 – 5	1/1020 1/720	13	304
8	Gas nodes 5 – 1	1/720	4	523

Table 2. Annual gas consumption at nodes in RFD gas supply system.

N	Node name	Export and transit, billion m^3/year	Demand, billion m^3/year	Total, billion m^3/year
1	Gas node 1	0	0.6	0.6
2	Gas node 2	0	7.0	7
3	Gas node 3	0	1.7	1.7
4	Gas node 4	0	7.3	7.3
5	Gas node 5	50	19.5	69.5
6	Gas node 6	0	3.5	3.5
7	Gas node 7	2.5	1.4	3.9
8	Gas node 8	45	4.6	49.6
	Total	97.5	45.9	143.4

Table 3. Gas sources.

N	Source name	Flow, billion m^3/year
1	From the eastern gas fields	132
2	The internal gas field	12

Table 4. Characteristics of underground gas storages.

N	Node name	Upper constraint, billion m3/year
1	The underground gas storages № 1	0.25
2	The underground gas storages № 2	1.1

Table 5. Failure rate of gas pipelines.

Diameter, mm	1420	1220	1020	720
Intensity of failures, 1/(103km/year)	0.15	0.25	0.39	0.54

Table 6. Reliability indices of GSS in RFD.

N	Node	Probability of shortage-free gas supply to consumers
1	Gas node 1	0.935208
2	Gas node 2	0.997083
3	Gas node 3	0.997083
4	Gas node 4	0.994958
5	Gas node 5	0.969208
6	Gas node 6	0.994958
7	Gas node 7	0.977292
8	Gas node 8	0.994958

Table 7. Characteristics of EPS ties in NWFD.

N	Connected nodes	Transfer capability of transmission line in direct and reverse directions, MW	Failure rate, km	Length km
1	EPS 1 – EPS 2	360	0.00195	242
2	EPS 2 – EPS 3	360	0.00195	92
3	EPS 3 – EPS 4	360 135	0.00195 0.00272	300 134
4	EPS 4 – EPS 5	360	0.00195	81
5	EPS 6 – EPS 7	135	0.00272	210
6	EPS 6 – EPS 8	135	0.00272	152

and natural gas consumption by the RFD entities are presented in Tables 1 and 2, respectively.

Natural gas is delivered to the gas supply system in RFD from the sources presented

in Table 3. The Table also shows the amount of gas supplied per year.

The reliability assessment of RFD gas supply system took into account the operation of underground gas storages. The data on the underground storages are presented in Table 4.

The main gas pipeline failure rate indices presented in Table 5 were taken from [14] and averaged by year.

As a result of the reliability assessment of the gas supply system in RFD, we obtained the nodal reliability indices, i.e. the probabilities of shortage-free gas supply to consumers (Table 6). The indices are quite high, and at five nodes out of eight they exceed the value 0.99. The lowest reliability indices are at gas nodes 1, 5, 7. These nodes are the most remote from gas sources and although there are underground gas storages at gas node 5, they make an insignificant impact on the indices.

The key characteristics of the calculated scheme of EPS in RFD are presented in Tables 7 and 8.

The EPS reliability in RFD was assessed in the studies both with and without regard to reliability of gas supply to power plants. The calculation results are demonstrated in Table 9 and Figures 2, 3.

The obtained results (Table 9 and Figures 2–3) demonstrate that on the supposition of absolutely reliable gas supply to power plants, the adequacy indices of electric power system correspond to the regulatory requirement in Russia $\mathcal{P}^{EPS}$ = 0.996 and even exceed this value. EPS 4 is an exception: its calculated reliability index was somewhat lower than the standard value and made up 0.992859.

Table 8. Characteristics of EPS nodes in RFD.

N	Node	Available capacity, MW	Absolute load maximum, MW
1	EPS 1	434	396
2	EPS 2	203	726
3	EPS 3	10158	7928
4	EPS 4	949	1540
5	EPS 5	3678	2628
6	EPS 6	1654	1361
7	EPS 7	2249	1600
8	EPS 8	1339	2552

Table 9. Indices of EPS adequacy in RFD.

Node	Indices of EPS adequacy without regard to GSS reliability		Indices of EPS adequacy with regard to GSS reliability	
	$\mathcal{P}_i^{\mathrm{EPS}}$	E_u	$\mathcal{P}_i^{\mathrm{EPS}}$	E_u
EPS 1	0.998555	64.1	0.997259	123.9
EPS 2	0.999944	1.3	0.999944	1.3
EPS 3	0.999944	10,2	0.999944	10.2
EPS 4	0.992859	524,3	0.987581	672.8
EPS 5	0.997770	84,4	0.997763	85.3
EPS 6	0.999944	2.5	0.999944	2.5
EPS 7	0.998984	57.8	0.998982	62.5
EPS 8	0.999999	0	0.999999	0

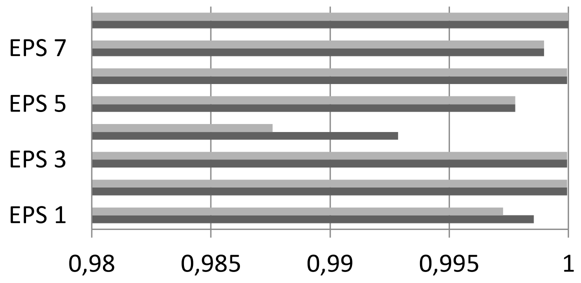

Figure 2. Probability of failure-free operation.

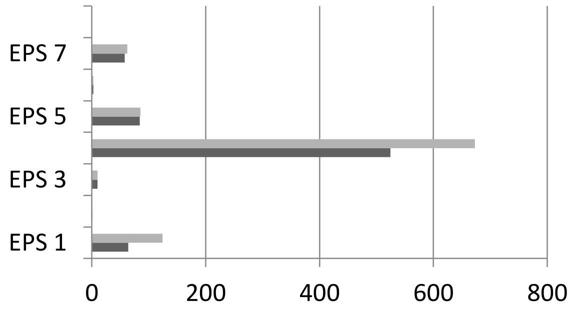

Figure 3. The mean value of electricity undersupply.

Given reliability of gas supply to power plants, though the gas–based generation share in RFD exceeds 70 percent, the reliability indices of electricity supply in EPS of RFD changed negligibly. This fact confirms that the EPS existing in RFD is highly balanced and characterized by the essential provision with gas. The high adequacy is also determined by the maneuvering potential, mutual assistance of EPSs included in RFD for reliable electricity supply to consumers. On the other hand, the GSS unreliability increases electricity undersupply almost by 30 percent (see Table 9: 958.5 MWh/744.6 MWh = 1.29), and in some power systems, such as EPS 4 and EPS 8, the influence of GSS reliability on EPS reliability is rather evident, which proves the urgency of reliability studies on joint operation of GSS and EPS when solving the problems of design and expansion of the considered systems.

V. Conclusion

1. The paper proves the need for the consistent reliability analysis of gas supply and electric power systems.
2. The systems methodological approach to the joint analysis of random events and processes in gas supply and electric power systems is described. The models applied to the proposed approach are briefly characterized.
3. The reliability analysis of gas supply system and the electric power system in a Russia's Federal District is performed within the systems approach with and without regard to reliability of gas supply to power plants.

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References

[1] *World energy outlook.* International Energy Agency, 2015.
[2] *Energy strategy of Russia until 2030.* Decree № 1715 of RF Government, 2009. (in Russian)
[3] V. Bushuev, V. Kalamanov, *World energy–2050 (White paper).* Energia, Moscow, 2011. (in Russian)
[4] S. Pikin, A. Shkolnikov, "Emergency in Perm: impact on the market", Gosgortehnadzor of RF. Available: http://www.gosnadzor.ru Accessed: 26 March 2017. (in Russian)
[5] P.A. Fedora, "Reliability review of North American gas/electric system interdependency", *in Proc. 37th An-nu. Hawaii Int. Conf. System Sciences*, 2004.
[6] C. Correa-Posada, C. Sanchez-Martin, "Security-constrained optimal power and natural-gas flow", *IEEE Transactions on Power Systems*, Vol. 29, No. 4, 2014, DOI: 10.1109/TPWRS.2014.2299714.
[7] C. Sahin, Z. Li, M. Shahidehpour, I. Erkmen, "Impact of natural gas system on risk-constrained midterm hydrothermal scheduling", *IEEE Trans. Power Syst.*, Vol. 26, No. 2, pp. 520–531, 2011, DOI: 10.1109/TPWRS.2010.2052838.
[8] C. Correa-Posada, P. Sanchez-Martin, "Stochastic contingency analysis for the unit commitment with natural gas constraints", *in Proc. IEEE PowerTech*,

Grenoble, 16-20 June 2013, DOI: 10.1109/PTC.2013.6652219.

[9] M. Urbina, Z. Li, “A combined model for analyzing the interdependency of electrical and gas systems”, *in Proc. 39th IEEE North Amer. PowerSymp.* pp. 468–472, 2007, DOI: 10.1109/NAPS.2007.4402351.

[10] N. Ilkevich, T. Dzyubina, Z. Kalinina, *Multilevel modeling of gas supply system expansion*, Novosibirsk: Nauka, 2014. (in Russian)

[11] G. Kovalev, L. Lebedeva, D. Krupenev, “Models and methods for estimation and optimization of electric power system reliability”, *Reliability: theory and applications*, Vol.12, No. 2, pp. 92-105, 2011.

[12] I. Dikin, “Iterative solution of problems of linear quadratic programming” *in Proc. Soviet Math, Dokl. 8.3*, pp 674–675, 1967. (in Russian)

[13] *The scheme and program for the development of Russia’s Unified energy system for 2014–2020.* Order of the Ministry of Energy of Russia of August 1, No. 495, 2014. (in Russian)

[14] I. Gostinin, A. Viryasov, M. Semenova, “Analysis of emergency situations in the linear part of main gas pipelines”, *Engineering bulletin of Don*, No.2, 2014. (in Russian)

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