Energy Security and Critical Facilities of Energy Systems: Methodology and Practice of their Identification on the Example of Russia's Gas and Electric Power Industries

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***Abstract* — The paper is devoted to the identification of energy system facilities that are critical in terms of national and regional energy security. Levels of critical facilities of the industry are substantiated and an algorithm for their inclusion in the lists of federal or regional critical facilities is developed. A simulation mathematical model of gas industry and a model for estimating the adequacy of the electric power system of Russia are used to estimate the role of the facility in the system availability. The study involves modeling of the operation of Russia's power and gas industries for the desired time interval given the factors affecting the operation of the systems. The proposed approach has been tested in the conditions of Russia's gas industry and the Interconnected Power System of Siberia. The result of the research is a list of critical facilities of the gas industry at the federal level, which includes, along with the facilities of gas transportation network, the main compressor stations of gas fields and underground gas storage facilities, as well as critical facilities of the Interconnected Power System of Siberia.**

***Index Terms* — gas industry, electric power system, critical facility, sys-tem availability, adequacy, energy security.**

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I. Introduction

National energy development should meet energy security requirements. Broadly speaking, there are two major requirements. The first one is long-term deficit-free supply of the required types of fuel and energy resources (FER) to domestic consumers, and the fulfilment of the obligations to export Russian FER under normal operation of the energy sector. The second requirement implies providing the conditions for meeting the domestic demand for all the types of FER, and for FER export in case of emergencies in the energy sector. The emergencies in the energy sector mean partial or complete simultaneous failure of a limited number of facilities. It is also important to consider large-scale emergencies when energy facilities (or individual energy systems) in several areas or even federal regions have to operate under abnormal conditions, for example, under abnormally low temperatures or other large-scale external (with respect to the energy sector) impacts .

The second requirement necessitates well-grounded identification of critical facilities (CF) of the energy sector and of energy systems, i.e., identification of the facilities whose partial or complete failure can considerably reduce production capabilities of the energy systems or of the entire energy sector and result in shortage of relevant types of energy to be supplied to consumers. According to [1], CFs of the energy sector are the facilities whose partial or complete failure can result in inability to manage the economy of the Russian Federation, the economy of its entities or administrative-territorial units and in irreversible negative changes (destruction); or would pose a threat to population security. In terms of energy security, the identification of critical energy facility can be based on the following main negative consequences (in case of its considerable or complete failure): unacceptable losses suffered by consumers of final energy in case of undersupply of the required FER types.

The energy sector and energy systems in different periods may have different lists of critical facilities because the configuration of energy transmission systems, nodal loads of both consumers and producers change over time. Some facilities may lose their significance with time, whereas others more significant ones may emerge and their failure could be critical for production capabilities of the energy sector and energy systems of the country. An analysis of interrelated operation of energy systems within the energy sector allows finding out which CFs in the lists compiled for individual energy systems can be included in the list of CFs of the energy sector level. Negative consequences for consumers in case of a failure of a particular CF, given backup capabilities of the energy sector to reduce the negative consequences (FER interchangeability, diversification of their sources, etc.), can be a criterion for inclusion in such a list. Identification of critical facilities of the energy sector and compilation of their list make it possible to analyze and minimize the consequences due to different threats that may cause emergencies at the energy facilities, and to provide early preparation of CFs to operation under such conditions. It also allows concentration of material, financial and human resources to enhance the stability of the identified facilities operation and backup, when the resources are limited.

II. Present-day state of the critical facilities identification problem

This section presents a brief description of publications related to the issue. The focus of these publications is the identification of critical facilities in energy systems.

In [2, 3], the authors analyze a gas transport network to identify its critical units. The methodological approaches applied here are based on the topological network analysis with an accent on the issues of reliability and controllability. Such an analysis makes it possible to quantify the reliability of a gas transport network, and to estimate the role of each network component within various time intervals. As a case study, the authors present a real gas transport network in several EU countries. The paper presents the results of an analysis of such a critical infrastructure and shows the need to consider physical characteristics, such as limitations of the transmission capacity of gas pipelines. A special flow model was developed to estimate the aftereffects of negative external impacts on the gas supply to consumers. The vulnerability analysis is performed based on three aspects: global vulnerability analysis, demand robustness and critical pipeline analysis. The global analysis of vulnerability is performed considering possible disturbances at gas production and transportation facilities. The demand robustness analysis suggests assessing the ability of consumers to withstand external effects. In the critical analysis of gas pipelines, the authors address external factors affecting certain gas pipelines.

The authors of [4] present a method for identification and ranking of the critical components and their sets in technical infrastructures. The criticality of a component or a set of components is defined as vulnerability of a system to a failure of a certain component or a set of components. The paper also considers the problem of numerous simultaneous failures with synergetic aftereffects that complicate the problem. The proposed method allows solving this problem. As a case study, the authors propose a method for analyzing the distribution system in a Swedish municipality.

In [5], the authors propose a complex model for estimating the impact of interdependence between electric and gas systems on the reliability of power supply to consumers. The gas network operating conditions are modeled using constraints on the basic unit operation. Constraints on gas delivery may cause changes in the electric power industry operation. The case studies conducted by the authors proved that.

The authors of [6, 7] analyze possible impacts on the integrated gas and power networks. Failures in the gas system are shown to be more risky for an integrated energy system than failures in the power system. Therefore, the authors paid attention to possible control actions aimed at minimizing the negative effect of failures in the gas system. This approach can also be used for the cases when power is generated by gas-fired power plants.

The research aimed at finding the methods to reveal critical (weak points, bottlenecks) places in electric power systems (EPSs) was started long ago. Here we present some papers published recently. In [8], the authors describe a technique for identification of critical damages in EPS by modeling failures of its components with Monte-Carlo method. In [9], the method proposed by the authors to identify weak points in power system, employs a cascading failure model for EPS vulnerability analysis. Following the analysis of a sequence of emergencies, the authors of [10] propose identifying the EPS weak points using two dominating (according to their opinion) vulnerability indicators: the difference between actual power flow and maximum allowable power flow limited by steady-state stability margin, and the minimum number of sequential critical EPS states that make manual control inefficient. In [11], the authors use Fault Chain Theory to determine the stability loss of EPS and its weak points. This paper offers a new indicator for vulnerability assessment to identify critical transmission lines and vulnerable EPS sections that contribute to rapid propagation of the system's failure. Complex Network Centrality theory is used for identification of key EPS nodes. The authors of [12] present an algorithm and results of applying this theory.

The analyzed papers focus mainly on technical aspects of the problem. Their authors propose methods for identifying CFs in energy systems and in gas networks. Thus, they assign different indices to different facilities of a system, to determine the system vulnerability in case of a failure of a given facility. In this study, we suggest accentuating the significance of the analyzed object for the system operability, and clarifying the level of criticality for consumers if a certain object fails. The second level task is to determine the most critical situations for consumers under various combinations of failures in the system facilities.

Considering the previously gained experience, and based on an analysis of the research conducted worldwide, we developed an algorithm for compiling lists of critical energy system facilities that play an important role in operability of energy systems. This algorithm is exemplified by Russia's gas industry.

In this paper, critical facilities are identified for the gas industry of Russia represented by the Unified Gas Supply System (UGSS), and for the Unified Power System (UPS) of the country.

III. An Algorithm for Compiling a List of Critical Facilities in the Energy System

Natural gas is currently the major fuel in the fuel and energy balance of the country. Its share in the boiler and furnace fuel in Russia accounts for 74%. In Russia's European part and in the Urals (where 88% of the RF population live), this share exceeds 90%, and in some RF entities, it is as high as 98-99%.

The Unified Power System of Russia is a powerful infrastructure of the country, which provides joint operation of energy industries within a single energy sector, and connects them directly to final energy consumers.

On this basis, at the first stage of the critical facility identification we will give detailed consideration to the Unified Gas Supply System and an electric power system of Russia, and on their example discuss the issues of:

- Developing an algorithm for the identification of CFs in a particular system;
- Building a procedure for assessment of negative consequences for the considered energy system due to partial or complete loss of the identified critical facility, in case of different emergencies;
- Assessing the contribution of specific CFs in providing the availability of a certain energy system in emergencies;
- Developing a list of measures to minimize negative consequences caused by lower availability of each CF identified for the considered energy system.
- Substantiating a list of invariant measures to minimize negative consequences caused by different emergencies at CFs identified in the considered energy system, given possible combinations of emergencies at different facilities.

From the standpoint of energy security, the following two types of facilities can be recognized as CFs of an energy system:

- Facilities whose failure may cause considerable undersupply of certain FERs countrywide (deficit in the relative amount δ_{total} and higher with respect to the total demand of the country for this type of FER). Such facilities can be considered as CFs of federal level;
- Facilities that are not included in the list of federal CFs according to this system, whereas their failure may cause considerable undersupply of certain FER at least in one region (deficit in the relative amount δ_{reg} and higher with respect to the total demand of the region for this type of FER). Such facilities can be considered as CFs of regional level.

For example, earlier, in [13], δtotal for the gas industry was taken equal to 5%. The value of 30% could be used as δreg as a first approximation. It should be kept in mind that these values are rather conventional and special studies are needed for their complex substantiation for each energy system.

An algorithm for compiling a list of CFs for the regional and federal levels is given in Fig. 1.

IV. Characteristic of the considered gas network and mathematical problem statement

Let us consider a real situation in the gas industry of Russia. In 2018, gas production in Russia accounted for 725 bcm (natural gas and associate gas of oil fields), the amount of gas imported from Middle Asian countries made up 8 bcm. Domestic consumption in the same year (including auxiliary gas consumption by gas industry) amounted to 490 bcm, gas export accounted for 244 bcm, including a bit more than 194 bcm to the non-FSU countries [14].

Existing territorial structure of Russia's gas system has

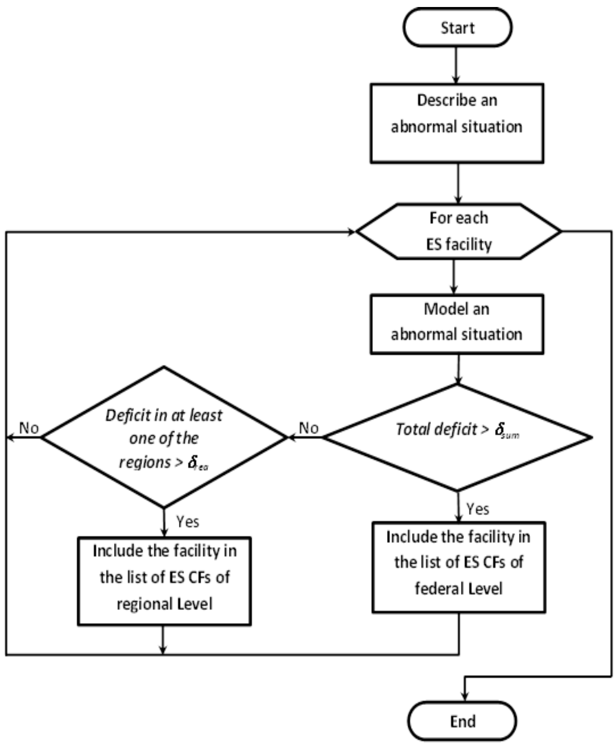

Fig. 1. An algorithm for compiling a list of CFs for the regional and federal levels of a particular energy system.

a number of notable drawbacks. The main domestic gas consumer, European part of the country, is located 2-2.5 thousand kilometers away from the gas production areas. More than 85% of Russian gas today is produced in the northern areas of Tyumen region (NATR). NATR gas is transported at long distances via multiple-line corridors with dramatic concentration of gas flows in one corridor. These corridors have a large number of intersections and joints. The lines within one corridor are sometimes located very close to one another. Today, there are more than 20 intersections of the main pipelines in Russia, which are potentially risky for the Unified Gas Supply System operation. Failure in some of them may reduce gas supply to domestic consumers throughout the country by 85% and lead to practically complete failure of gas export (subject to 50% reduction in gas supply to domestic consumers).

Previous studies [13, 15] showed critical facilities in Russia's gas system (20 intersections of the main pipelines). Meanwhile, the issue of including the remaining facilities of the gas industry in the list of critical from the standpoint of energy security was not considered. Along with a large number of intersections of the main pipelines at the nodal booster stations and outside them, the main compressor stations at the fields and underground gas storage facilities (UGSFs) are major facilities that ensure gas industry availability.

Currently, 22 UGSFs are in operation in Russia's gas transport system, 5 UGSFs of Gazprom Group operate outside Russia (3 in Belorussia, 1 in Armenia and 1 in Germany), 7 UGSFs (where Gazprom Group is a co-investor) are operated in the gas network of European countries. All those UGSFs are taken into account in a specially developed Gas Flow Model (within Oil and Gas of Russia software) [13, 15, 17] that allows an analysis of all the aspects of both the Unified Gas Supply System of Russia and Gas Transport Systems (GTS) of European countries that are technologically connected to it. The computational model contains 382 nodes, including the above UGSFs, 28 gas sources (in the model they are main compressor stations (CS)), 64 gas consumers, 268 nodal CS, and 628 arcs representing main pipeline corridors and individual main pipelines, and branches to distribution networks.

Mathematically considered related GTS is represented as a network changing in time. The nodes of this network have businesses of production, processing and consuming material flows serving as connections between the businesses. To estimate the system state after a disturbance, the minimum consumers' energy resource deficit at minimum costs of its delivery serves as an optimum flow distribution criterion.

Change in the system's facilities condition requires that the flow distribution problem be solved for the maximum energy carrier supply to the consumer, i.e., in this case, the model is formalized as a maximum flow problem [18, 19]. Calculation graph is completed with two fictitious nodes: O is an aggregate source, *S* is a total sink. Additional sections are introduced to connect node *O* with all the sources and all the consumers with node *S*. Mathematically, the problem has the form:

$$\max f \tag{1}$$

subject to:

$$\sum_{i\in N_j^+} x_{ij} - \sum_{i\in N_j^-} x_{ji} = \begin{cases} -f, & j=O \\ 0, & j\neq O,S \\ f, & j=S \end{cases} \tag{2}$$

$$0 \le x_{ij} \le d_{ij}, \text{ for all } (i, j) \tag{3}$$

Here N_j^+ is a subset of arcs 'entering' node *j*; N_j^- is a subset of arcs 'leaving' node *j*; *f* is a value of total flow in the network; x_{ij} is a flow over the arc (*i, j*); d_{ij} is constraints on flow in the arc (*i, j*).

Problem (1)-(3) on the maximum flow in the general case does not have a unique solution. The next step is solving the problem on maximum flow at minimum costs, i.e., minimization of the cost functional:

$$\sum_{(i,j)} C_{ij} x_{ij} \to \min \tag{4}$$

where C_{ij} is price or specific costs of the energy resource transportation.

A complex approach to solving the problems stated for the entire process chain of UGSS makes it possible to obtain an aggregate estimate of production capabilities of the entire system under extreme conditions. The solutions will be the determined potential for meeting the gas demand and possible gas undersupply to consumption nodes in case of an abnormal situation. These results can be used for compiling a list of facilities whose failure can cause potential gas deficit in the network. Let us rank this list based on the relative amount of gas deficit in the network. By excluding the facilities whose loss will lead to lower potential gas deficit in the network than the previously assigned value, e.g., 5%, we can get a list of CFs for the gas industry. This list should also be ranked based on the extent of impact on the network operability.

V. Results of studies on the gas industry

Relevant studies were performed using the above model of Russia's gas industry. Input conditions for the calculations are an average day of maximum gas consumption based on statistical data on gas consumption by region as of January 2018. Network operation on such a day can be considered to be at its maximum with respect to the average annual load. Total gas flow in the network on such a day, given gas export, made up around 2250 mcm. The results of the studies show that the potential gas deficit for consumers will be observed in case of a failure of 441 facilities of the Russian gas industry (242 nodes and 199 arcs of a network calculation graph). A threshold of the potential gas deficit (δ_{total} of 5% of the total gas demand) was exceeded by 61 facilities, with one facility failed. These facilities should be put on the CF list of federal level.

These facilities include 25 arcs between nodal compressor stations and 36 nodes that include 30 nodal compressor stations, five main compressor stations of large gas fields, and one UGSF. The calculated values of relative gas deficit in the network in case of failure of specific nodes and arcs that are ranked based on the gas deficit decrease are given in Table 1 (the actual names of the facilities are replaced by conventional numbers).

Data in Table 1 show that in case of shutdown of each of the first eight gas industry facilities from the list of CFs of federal level, relative gas deficit in the system can be around 20% of the total demand. Shutdown of each of subsequent 15 facilities may limit gas flow in the system by about 10-16%. Failure of all the other facilities from the CF list may cause 5-9% relative gas deficit in the system.

Table 1. Calculated relative gas deficits in the networks on the maximum gas consumption day of january 2018 in case of failure of facilities referred to federal critical facilities of UGSS

CF ordinal number in the ranked list	Facility type	Gas deficit due to CF failure, %
1, 2, 3, 4	Node	21
5, 6, 7	Arc	21
8	Node	19
9, 13, 14	Arc	16
10_a^*, 11, 12, 15	Node	16
16	Arc	12
17, 18, 19, 22, 23	Node	10
20 ,21	Arc	10
24	Node	9
25, 26, 28_a	Node	8
27	Arc	8
29, 31, 33, 35, 37, 39, 41	Arc	7
30_a, 32, 34, 36, 38, 40	Node	7
42, 48, 50	Arc	6
43_a, 44_a, 45, 46_b^{**}, 47, 49, 51	Node	6
52, 55, 56, 59, 60	Arc	5
53, 54, 57, 58, 61	Node	5

* - a node belongs to production facilities, i.e., to gas compressor stations at the gas fields;

** - a node belongs to underground gas storage facilities.

VI. Statement of the problem on identification and ranking of critical facilities of power system, and solving technique

Electric power system is a complex technological infrastructure characterized by a number of specific features to be considered when identifying its critical facilities:

- Operation of EPS varies within a year depending on power consumption and capacity utilization, which depend on the season. While identifying CFs, it is necessary to analyze all of them, as the facility significance can be revealed not only when power consumption is maximum. Moreover, the maximum power consumption in different areas may fall both on different days and on different months;
- Considering the consumption, it is advisable to take into account scheduled maintenances of energy equipment, since the maintenances render additional impact on the system operation, i.e., on the possible power shortage and electricity undersupply in case of an analyzed facility failure;
- Apart from the failure of the analyzed EPS facility within the calculated period, any other equipment in operation may fail, thus aggravating the situation.

According to the above said, to identify and rank the EPS CFs, it is advisable to use a model simulating EPS operation during a year taking into account all the factors that impact on the power shortage and electricity undersupply. A model for estimating the EPS adequacy is advisable to be taken as a basis for such a model [20]. This model simulates multiple operating conditions of EPS within a year using Monte-Carlo method in terms of scheduled and emergency maintenances, regular and random load fluctuations. The model consists of three computational blocks:

1. A block for developing the computed EPS states;
2. A block for identifying power shortages for the developed EPS states; Mathematical statement of this problem is as follows [5]:

Estimating the power deficit of the th EPS state, $k = 1, \ldots, N$ find

Table 2. Characteristics of reliability zones in ips of siberia

Node #	Node name	Annual load maximum MW	Available capacity MW	Own reserve	
				MW	% of P_{max}^H
1	Omsk EPS	1782	1479	-303	-17
2	Novosibirsk EPS	2690	2730	40	1.49
3	Tomsk EPS	1302	918	-384	-29.49
4	Altay EPS	1884	1444	-440	-23.35
5	Kemerovo EPS	4535	5028	493	10.87
6	Krasnoyarsk EPS	6235	12006	5771	92.56
7	Khakassia EPS	2155	5430	3275	151.97
8	Tyva EPS	152	40	-112	-74.01
9	Irkutsk EPS	7570	12550	4980	65.79
10	Bodaibo load center	90	20	-70	-77.78
11	Buryatia EPS	945	898	-47	-4.97
12	Trans-Baikalia EPS	1260	1156	-104	-8.25
	IPS of Siberia	30225[1]	43699	13474	44.58

* - a node belongs to production facilities, i.e., to gas compressor stations at the gas fields;

** - a node belongs to UGS facilities.

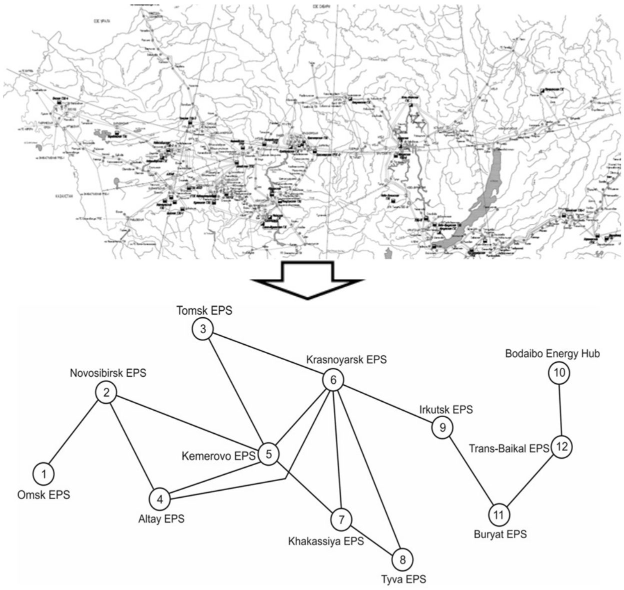

Fig. 2. Level of modeling the IPS of Siberia for CF identification.

$$\sum_{i=1}^{n} y_i \to \max \qquad (5)$$

Subject to the balance constraints

$$x_i - y_i + \sum_{j=1}^{n}(1 - z_{ji}a_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} = 0,\ i = 1, \ldots, n,\ i \neq j \qquad (6)$$

and linear inequality constraints on variables

$$y_i \le \bar{y}_i^k,\ i = 1, \ldots, n, \qquad (7)$$

$$x_i \le \bar{x}_i^k,\ i = 1, \ldots, n, \qquad (8)$$

$$z_{ij} \le \bar{z}_{ij}^k,\ i = 1, \ldots, n,\ j = 1, \ldots, n,\ i \neq j, \qquad (9)$$

$$y_i \ge 0,\ x_i \ge 0,\ z_{ij} \ge 0,\ i = 1, \ldots, n,\ j = 1, \ldots, n,\ i \neq j, \qquad (10)$$

where: x_i – available power at node i, $\bar{x}_i^k$ – available generating capacity at node i , y_i - load covered at node i , $\bar{y}_i^k$ - load at node i, z_{ij} , – power flow from node i to node j, $\bar{z}_{ij}^k$ – transfer capability of a power line between nodes i and j , a_{ij} specified positive coefficients of specific power losses at its transmission from node i to node j, $i \neq j$, $i = 1, \ldots, n$, $i \neq j$, $k = 1, \ldots, N$.

3. A block for computing the mathematical expectations of electricity undersupply and power shortage.

To identify and rank the EPS CFs, the following procedure is proposed:

1. Compile a list of EPS facilities to determine the mathematical expectation of power shortage and mathematical expectation of electricity undersupply in case of their failure. This can be done in several ways:
   - by sequential search of power plants and transmission lines within one facility;
   - by sequential search of EPS facilities assigned by experts.
2. Assess the adequacy of all the selected options for sequential search depending on the method selected at the first step.
3. Determine the mathematical expectations of power shortage and electricity undersupply for each option. The assessment can be made for any a priory specified time interval, namely, for a year, month, day, and hour.
4. Rank the results obtained.
5. Identify the facilities with the highest impact on the mathematical expectation of power shortage and electricity undersupply.
6. Identify and rank the EPS CF.

VII. Experimental studies on EPS CF identification

The process of EPS CF identification is demonstrated by the example of Interconnected Power System of Siberia. The interconnected Power System of Siberia (IPS of Siberia) is a large power interconnection within The Unified Power System of Russia. The IPS of Siberia includes large thermal and hydro power plants (TPP, HPP) and 220 and 500 kV transmission lines (TL). A schematic

Table 3. Transfer capabilities of inter-zone ties of IPS of Siberia.

Tie No.	Connected power systems	Transfer capability of a tie, MW
1	1. Omsk – 2. Novosibirsk	1305
2	2. Novosibirsk – 4. Altay	1440
3	2. Novosibirsk – 5. Kemerovo	950
4	3. Tomsk – 5. Kemerovo	1170
5	3. Tomsk – 6. Krasnoyarsk	780
6	4. Altay – 5. Kemerovo	950
7	4. Altay – 6. Krasnoyarsk	850
8	5. Kemerovo-6. Krasnoyarsk	1560
9	5. Kemerovo-7. Khakassia	1650
10	6. Krasnoyarsk-7. Khakassia	3400
11	6. Krasnoyarsk-8. Tyva	135
12	6. Krasnoyarsk-9. Irkutsk	3630
13	7. Khakassiya. Tyva	135
14	9. Irkutsk-11. Buryatia	885
15	10. Bodaibo load center – 11. Buryatia	66
16	11. Buryatia -12. Trans-Baikalia	410

* - a node belongs to production facilities, i.e., to gas compressor stations at the gas fields;

** - a node belongs to UGS facilities.

Table 4. Power plants of ips of siberia that were disconnected in the course of studies.

Node #	Node name	Power plant	Available capacity of PP, GW
1	Omsk EPS	TPP 5	0.73
2	Novosibirsk EPS	TPP 5	1.20
3	Tomsk EPS	JSC SHK	0.43
4	Altay EPS	Biysk TPP	0.51
5	Kemerovo EPS	Tom-Usinsk TPP	1.34
6	Krasnoyarsk EPS	Krasnoyarsk HPP	5.76
7	Khakassia EPS	Sayano-Shushenskoye HPP	5.33
8	Tyva EPS	Kyzyl TPP	0.17
9	Irkutsk EPS	Bratsk HPP	4.22
10	Bodaibo load center	Mamakan HPP	0.09
11	Buryatia EPS	Gusinoozersk TPP	1.16
12	Trans-Baikal EPS	Kharanorsk TPP	0.67

diagram of IPS of Siberia [5] and a transformed model of the IPS of Siberia for identification of its CFs is given in Fig. 2.

Division of the IPS of Siberia into reliability zones is done according to the division into the RF entities. The exception is the Bodaibo load center which formally belongs to the Irkutsk region but in fact is connected to the power system of the Republic of Buryatia (RB).

The reliability zone characteristics in the calculation model of IPS of Siberia are given in Table 2.

Transmission capacities of inter-zone ties in the calculation model of the IPS of Siberia are given in Table 2.

Transmission capacities of inter-zone ties in the calculation model of the IPS of Siberia are given in Table 3. To identify critical facilities in the IPS of Siberia, at the first stage we select (in an expert way) a number of power plants in the reliability zones and TL in the inter-zone ties whose loss will be modeled in the course of the studies. As reliability zone is a concentrated hub without constraints on the transfer capability, the largest power plants in each zone will make the highest contribution to the mathematical expectations of electricity undersupply and power shortage. Therefore, in the first stage of the experiment, we will sequentially disconnect the largest power plants in each zone. Characteristics of the disconnected power plants are given in Table 4.

Reliability zones of the IPS of Siberia were clustered following the principle of dividing the Russian Federation into entities, with the exception of Bodaibo energy system that administratively belongs to Irkutsk region but is actually connected to Buryat energy system.

As is seen from Table 5, in terms of power supply to consumers, only Mamakan HPP in Bodaibo load center can be referred to as the CFs of the IPS of Siberia. In the other reliability zones, the failure of the largest power plant did not result in higher electricity undersupply ei-ther in this zone or in the IPS of Siberia, i.e., the IPS of Siberia has sufficient generating capacity backup to meet the power demand in case of a failure of the largest power plants at each node of the considered system.

Similar failures were modeled at transmission lines of all the inter-zone ties of the IPS of Siberia. A series of calculations were performed with step-by-step disconnection of the largest line in each inter-zone tie. The transmission lines disconnected during the experiment are given in Table 6.

After a number of calculations, the values of mathematical expectation of electricity undersupply in the IPS due to a 'failure' of the indicated TL were obtained. The re-sults are given in Table 7.

As is seen from Table 7, the mathematical expectation of electricity undersupply in the IPS of Siberia changed negligibly. The values are high only in the case of failure of the largest TLs in the inter-zone ties Omsk-Novosibirsk, Bodaibo-Buryatia and Buryatia - Trans-Baikalia. As to the required power production of 663 billion kWh in the

Table 5. Effect due to disconnection of electric power plants in the reliability zones of IPS of Siberia.

Node	Node name	Math. expect. of electricity undersupply without power plants disconnection, kWh	Math. expect. of electricity undersupply after power plants disconnection, kWh	Math. expect. of electricity undersupply in the reliability zone where power plants were disconnected, kWh
1	Omsk EPS	3	29	0
2	Novosibirsk EPS	0	30	0
3	Tomsk EPS	0	26	0
4	Altay EPS	0	23	0
5	Kemerovo EPS	0	20	0
6	Krasnoyarsk EPS	0	23	0
7	Khakassia EPS	0	32	0
8	Tyva EPS	0	24	0
9	Irkutsk EPS	0	32	0
10	Bodaibo load center	0	401	358
11	Buryatia EPS	0	30	0
12	Trans-Baikalia EPS	24	30	27
System		27		

Table 6. A list of disconnected transmission lines.

Connected EPSs		Substation at TL start	Substation at TL end	TL voltage, kV
EPS name	EPS name			
Omsk	Novosibirsk	Tavrichesckaya	Barabinsk	500
Novosibirsk	Altay	Zarya	Altay	500
Novosibirsk	Kemerovo	Zarya	Yurga	500
Tomsk	Kemerovo	Tomsk	Novo-Anzhersk	500
Tomsk	Krasnoyarsk	Tomsk	Itat	500
Altay	Kemerovo	Barnaul	Novokuznetsk	500
Altay	Krasnoyarsk	Altay	Itat	500
Kemerovo	Krasnoyarsk	Novo-Anzhersk	Nazarovo TPP	500
Kemerovo	Khakassia	Novokuznetsk	Sayano-Shushenskoye HPP	500
Krasnoyarsk	Khakassia	Abakan	Itat	500
Krasnoyarsk	Tyva	Ergaki	Turan	220
Krasnoyarsk	Irkutsk	Kamala	Taishet	500
Khakassiya	Tyva	Abaza	Ak-Dovurak	220
Irkutsk	Buryatia	Klyuchi	Gusinoozersk TPP	500
Bodaibo	Buryatia	Taksimo	Mamakan	220
Buryatia	Trans-Baikalia	Gusinoozersk TPP	Petrovsk-Zabaikalsky	220

Table 7. Mathematical expectation of electricity undersupply in the IPS of Siberia due to a failure of TL in the inter-zone ties, kWh/ power demand ratio, % (node numbers corre-spond to their numbers in the previous Tables).

Node	2	4	5	6	7	8	9	11	12
1	3027 /0.45	-	-	-	-	-	-	-	-
2	-	29 /0	32 /0	-	-	-	-	-	-
3	-	-	22 /0	31 /0	-	-	-	-	-
4	-	-	40 /0	46 /0	-	-	-	-	-
5	-	-	-	24 /0	33 /0	-	-	-	-
6	-	-	-	-	28 /0	46 /0	35 /0	-	-
7	-	-	-	-	-	42 /0	-	-	-
9	-	-	-	-	-	-	-	47 /0	-
10	-	-	-	-	-	-	-	602 /0	-
11	-	-	-	-	-	-	-	-	295 /0

entire IPS, the 'failure' of the above TLs does not lead to considerable changes. Locally, however, for the reliability zones connected by the above given TL, their 'failure' can result in considerable elec-tricity undersupply.

Thus, the analysis of the IPS of Siberia in terms of critical facilities from the energy security perspective re-vealed that in the present-day contexts, Mamakan HPP and 500 kV Tavricheskaya-Barabinsk TL; 220 kV Taksi-mo-Mamakan TL; and 220 kV Gusinoozersk TPP - Pe-trovsk-Zabaikalsky TL could be referred to as CFs of EPS of regional level.

VIII. Conclusion

This paper has demonstrated the examples of imple-menting the approaches to the identification of critical facilities of energy systems in Russia's gas and electric power industries. A list of CFs has been developed for the gas industry. As to the power industry, an analysis of the situation in the IPS of Siberia has shown that the IPS of Siberia has sufficiently high reserves both in terms of generating capacities, and in terms of networks. Howev-er, the studies have revealed a number of CFs that have to be paid special attention to while planning the expansion of the IPS of Siberia.

The facilities identified during the studies should be paid thorough attention to in order to provide the sur-vivability of the gas industry, the entire energy industry and, subsequently, energy security of the country and its regions. Organizational measures should be taken to prevent emergencies, primarily at those facilities. The strategic objectives of developing the industries analyzed may include identification of directions and ways for re-ducing the significance of relevant CF in the potential ES availability. After gaining the experience in identifying the CFs in the gas and energy industries, the studies could be extended to identifythe CFs in other energy systems, and in the energy sector as a whole.

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