Status and Prospects of Integrated (Electric and Gas) Networks in Russia

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***Abstract* — The paper emphasizes the urgency of establishing integrated (electrical and gas) systems using gas-fired generators, which is explained by the progress in designs of the generators, the reduction in their cost, and the increasing use of renewable energy sources (RES). Solving methodological problems related to the functioning and reliability of integrated systems will make it possible to optimize the structure of energy systems of territories in the context of the growing importance of RES, and to improve the reliability of electricity supply to consumers. It is noted that the mathematical methods for coordinated control of integrated interconnected electrical and gas systems should adequately take into account the dynamics of the change in the amount of gas accumulated in the pipes. A brief review of the world publications on this problem is given, the successful Russian developments in this field are noted. Expansion of LNG consumption in some local areas is considered as one of the promising directions for the development of the gas economy in the changing energy situation. The paper proves the expediency of economic and technological research into the integrated system models in which the conversion of local electricity supply system to gas is considered as the only source for power generation. In conclusion, new reliability analysis and synthesis problems arising in the context of the creation of integrated systems, are listed.**

***Index Terms* — analysis and synthesis of reliability, gas fired generators, gas supply system, integrated systems, models with lumped parameters, power supply system, renewable energy sources.**

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I. Introduction: The Reasons For The Appearance Of Integrated Systems And The Prospects For Their Development

One of the main directions in rapidly developing "smart grid" technologies is the interaction between electric and gas systems and their coordinated control. A number of factors explain the growing urgency of the problem. The main of them are: the increase in the share of RES in the structure of electricity generation and the technical improvement in gas-fired generators for power generation on natural gas. Now we can definitely say that these factors are long-term and lead to revolutionary changes in the energy industry. The fixed assets of the energy industry are huge, therefore, even revolutionary changes cannot happen overnight: the processes of modernization and transition to new technologies are very inertial. However, these processes cannot be stopped, they determine the direction of the energy development vector in the coming decades. Given the inevitability of the changes, they (we) need to be prepared in advance.

Installations using renewable energy sources, primarily wind generators and solar panels, have undeniable advantages. They are relatively cheap, their negative impact on the environment is negligible compared to the traditional methods of energy production: hydrocarbon, nuclear, hydropower. Now solar generators or panels are successfully used as both a primary and an alternative energy source. The sites where batteries are installed are very different: private houses, cottages, offices, holiday homes, sanatoriums, small and medium-sized businesses. Solar panels allow the consumers not only to gain energy independence, but also to reduce or completely eliminate electricity costs. Batteries, as a back-up energy source, are extremely important in hospitals, medical centers and many other institutions, where the uninterrupted operation of the equipment is necessary. Batteries are especially valuable for the remote off-grid consumers in rural areas.

For many areas of the Planet, the advantages of wind generators are undeniable. In Denmark, for example, about 40 percent of all consumed energy is produced by windmill generators. There are cases where wind energy not only fully covered the electricity needs of this country, but also allowed the export of its surplus abroad.

The only significant drawback of these renewable energy sources is their dependence on weather conditions.

However, their combined use with gas- fired generators makes it possible to smoothen this flaw and more fully reveal the renewable energy advantages.

The modern market in Russia offers a wide choice of gas-fired generators (GFG) with a capacity of 2 - 500 kW, from different manufacturers. It is very easy to calculate the cost-effectiveness of the GFG. The production of 1 kWh of electricity requires 0.3 -0.4 m^3 of natural gas. At a cost of 5-6 rubles per 1m^3 of natural gas, this is 1.5-2.4 rubles. Electricity rates for most parts of the Russian Federation vary from 3 to 4 rubles / kWh, and in Moscow are about 6 rubles per kWh. The benefits of the GFG are obvious. In personal economy, small and medium-sized businesses, GFG should quickly payback itself. The advantages of GFG over diesel generators are obvious: the cost of 1 kWh of electricity generated by GFG is approximately 4 times lower.

With the GFG used as a source of electricity in addition to RES, particular requirements are imposed on the operation of gas system. Daily gas supply schedules are characterized by unevenness associated with life and production activities of consumers. Usually this is a decrease at night and a higher than average, but changing, level of flow in the daytime and evening time. Now these cyclic changes are superimposed with acyclic unevenness caused by the vagaries of the weather.

Extension of the GFG nomenclature, improvement in quality and cost reduction have triggered new tasks in the field of control of natural gas transmission and distribution systems. Without going into the history of the matter, let us dwell on a brief description of [1-6], where the authors propose approaches to solve these problems. Consideration is given to the operation of power system with external electricity sources, which, however, is insufficient to fully meet the demand of consumers. Electricity shortage is eliminated (or reduced) by GFG receiving gas from the gas system that has a network structure. To meet the electricity demand changing in the daily cycle, it is necessary to "fill the pipe" in advance, i.e. to create the required reserve of accumulated gas. Thus, the models of gas system control should take into account gas compressibility, dynamics of the accumulated gas change, and non-stationarity of the flow through the pipelines. In [1-5], the authors constructed such models, and proposed the methods for coordinated control of large-scale electric and gas systems for a daily cycle of operation. The most interesting question is how exactly to take into account the effect of flow non-stationarity. The gas-dynamic model should be on the one hand fairly accurate, on the other hand, it should be as simple as possible. It must not contain details that exert secondary influence on the processes under study.

The next section gives an overview of some of the latest publications on the joint control of power system that includes gas-fired generators supplied with gas from the gas distribution network. Of particular interest in these papers is the method to simulate dynamics of gas accumulated in pipes. Section III claims that in the power industry of the Russian Federation there are no examples of using gas-fired generators to peak shave the maximum electricity consumption, but the conditions when such a technical solution would be advisable arise very often.

Further, section IV discusses the possibility of using LNG in interconnected systems. At the beginning of the section, the state of the distribution of LNG technologies in the domestic industry is briefly described. There are good prospects for making a switch to LNG in the settlements in sparsely populated areas. Attention is drawn to the idea of local electrification with LNG as a primary or additional energy carrier.

The choice of the integrated systems parameters cannot be justified without an assessment of reliability indices of the options. The arising problems will constitute a new chapter of the applied theory of reliability. Section V lists some problems to be solved in the near future.

II. New Problems In Has Systems Modeling. Overview Of Publications

Since the dynamics of the accumulated gas is important for gas systems, the equations of the non-steady-state flow are used. On sufficiently good grounds, it is customary for this purpose to use the system of partial differential equations - a model with distributed parameters (DPM). It relates the operation parameters of the gas flow with the time and space variables t, x. The flow in the pipes is considered to be one-dimensional, i.e. the values of the parameters along the section with the coordinate x perpendicular to the axis of the pipe are the same. This model is a reference model. However, it is excessively complex to study the effect of gas accumulation in large-scale gas system. Therefore, the simpler models are constructed using ordinary differential equations for the functions of one variable-time t, i.e. lumped parameter model (LPM).

Such models are proposed, in particular, in [1-5]. The simplest equivalent of DPM is obtained by replacing the derivatives with respect to the spatial coordinate in the DPM by their finite difference analogues. Other more sophisticated models have also been developed. The methods for integrating the equations in [1-5] are illustrated by examples of calculations on model and real gas pipelines.

In [1], the task is to determine the gas system operating conditions optimal in the sense of minimum gas compression costs. In the paper, the authors give the results of modeling the chain, i.e. the system of successively connected elements: pipelines and compressors. The possibility of intermediate gas withdrawals is taken into account. Data on the operating conditions of Williams-Transco gas pipeline stretching from the state of Georgia to New York are presented. The dynamic non-stationary model is compared with the static one, the optimal control

— with the operating conditions obtained at a constant compression ratio of compressors.

In [2], the operating conditions are calculated based on the same model as in [1]. The model is applied however to a network of complex circuit-free configuration (tree-like type). Together with the criterion of minimum energy costs, the criterion of maximum satisfaction of the consumer's demand is considered. The calculation results are given for two examples: a simple system of three gas pipelines with a single junction point and an industrial system that supplies gas to 8 consumers from one source and includes 5 compressors (the operator is Tennessee gas pipeline company). The research shows how much the solution depends on the optimization criterion.

In [3], the methods of operative influence on the operating conditions of interconnected electric and gas systems varied and their influence on cost indicators was investigated. The test energy system (IEEE RTS96) considered as an example includes: the electricity system that contains 24 consumers, several power generators, including 4 gas fired generators; the gas system that contains 24 pipelines and 5 compressors (gas pumping units). The optimization criterion takes into account the costs of fuel gas and the cost of electricity supplied to the electricity system from other sources. Various strategies of operational impact on gas system operating conditions are considered.

In [4], the authors investigate the same problem as in [3]. In fact, to simulate a non-stationary flow through the system, each pipeline is divided into several (a small number) parts, and this partition serves as the basis for approximation based on finite differences of partial derivatives with respect to a spatial variable. Dynamic and static flow models are compared. It is shown that the latter can lead to technologically unrealizable solutions. The comparison of solutions considering and not considering the non-stationary nature of the flow in the daily cycle demonstrated that when peak consumption is considered the shortage is substantially reduced. It should be noted that the models of gas pumping units in [1-4] do not reflect all technological limitations.

In [5], the authors consider the joint operation (with the interaction of operating conditions) of the electric system and gas system in the State of Illinois. This is a complex industrial structure: the electric system contains 2522 lines, 1,908 nodes, 870 consumers, 225 power generators (including 153 gas fired generators); the gas system contains 215 pipelines, 157 nodes, 12 compressor stations and 4 sources. Strategies for uncoordinated and coordinated control of the electric and gas systems are explored. The study shows that in the case of coordinated control both players can win: the electric system - due to a more complete satisfaction of the demand for energy, and the gas system - due to the increase in gas sales. The research presented in [5] expands our understanding of the practical possibilities of the modeling tools used.

The literature review [6] contains a representative list of publications addressing the dynamics of gas flows for the period up to 2014.

Researchers in Russia also conduct studies on operative control of large gas systems with non-stationary flow [7-10]. In [10], in particular, the authors show how these studies make it possible to justify the measures enabling the enhancement of the gas system survivability. The LPM developed and used in [7-10] has the same capabilities as the models presented in [1-5].

The above brief and incomplete analysis of comparatively new (within the scope of the general direction of "smart grid") research on coordinated control of electric and gas systems shows that these studies are of an applied nature and open a new page in the operational control of large energy systems. It is difficult to find analogues to the technological problems considered in the above publications (primarily [5]), as well as in the other publications on the same topic, in the Russian energy sector.

The assortment of gas-fired generators at the market is wide and the prices are affordable. It would appear that nothing hinders their use for power generation during the daily maximum and in peak situations, as is done in the state of Illinois. There is however no evidence of such precedents. It is to be hoped that the trends in the world energy development will reach Russia and in the future the coordinated development of electric and gas systems and their operative control will become widespread.

III. The Relationship Between Electric And Gas Systems

There is certainly mutual influence of these systems on one another at the present time. In the largest mega-metropolis of the country, in Moscow, about 80% of the incoming gas is used to produce heat and electricity. Demand for electricity significantly changes daily, weekly and annually. These fluctuations affect first of all the unevenness of gas consumption, i.e. non-stationarity of gas system operating conditions. However, this relationship does not find a formal reflection in the interaction of services that perform operational control of the systems. Moscow is not the only example.

Fig. 1 shows a diagram of gas flow rate (in thousand m^3 / h) through one of the gas distribution stations (GDS) of Perm. The main consumer of this gas distribution system is a combined heat and power plant (CHP). The curve has a clearly expressed cyclic character. Hourly flow rate ranges from 96 to 150 thousand m^3 / h. The trends in increasing and decreasing average daily flow are also noticeable due to changing weather conditions. Fig. 2 illustrates the graphs of a daily change in consumption for 4 days in December. Gas consumption of CHP can go with some shift in time from the demand graphs for heat and electricity, but clearly depends on them.

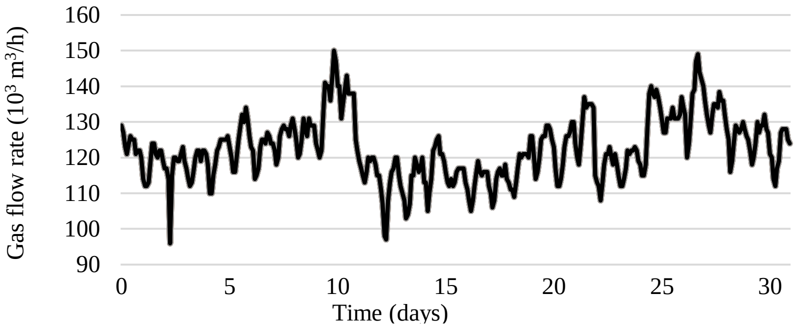

Figure 1. Gas flow rate through GDS-1 in city of Perm in December 2003.

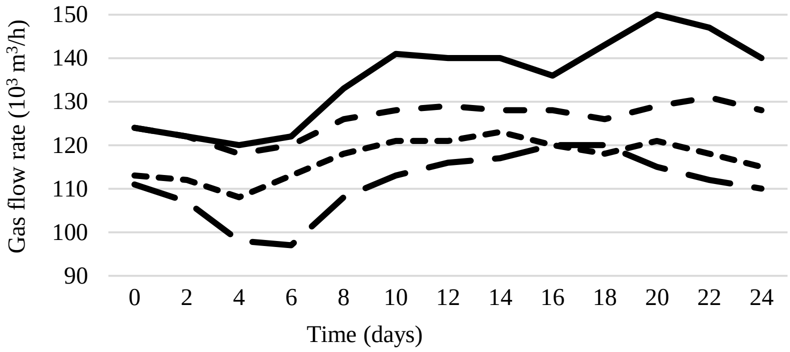

Figure 2. Daily chart of gas supply through GDS-1 in Perm for 10, 11, 23, 13 December (from top to bottom).

Thus, the interdependence of the electric and gas system operating conditions is beyond doubt. It is also clear that it will increase as the share of renewable energy in the balance of electricity production increases. This indicates the feasibility of developing models of integrated systems. The models allow assessing the technological and economic effects of measures aimed at organizing and improving such systems, finding the optimal options for their structure, and preparing regulations for their management.

IV. Prospects For Liquefied Natural Gas In Integrated Systems

Liquefied natural gas (LNG) plays an increasing role in the global energy sector. The technologies for liquefaction, transport, regasification are developing rapidly, production volumes are growing and the scope of application is expanding. However, the Russian gas industry is sluggish to adopt the technological innovations. In fact, the participation of Gazprom in the Sakhalin II project was limited to the use of foreign equipment and technologies. It practically did not lead to the implementation of new large-scale projects and did not give an impetus to the development of domestic technologies.

The so-called independent (read independent of Gazprom) producers, primarily NOVATEK, were more susceptible to innovation. The Sabetta project for the construction of gas liquefaction plant on the shore of the Ob Bay and the gas export through the seas of the Arctic Ocean to the world markets is being successfully implemented: the construction of the first production line has actually been completed. Four tankers of the Arctic class (data of January 2018) transport Yamal gas to the world markets. Other smaller LNG projects are also being implemented. In 2017 Gazprom announced the development of such a project within the program for conversion to gas in the Russian regions. The project provides for the construction of a mini LNG plant with a capacity of 40 thousand tons per year in the Bolsheselsky district of the Yaroslavl region. This will allow the region to switch to gas, as well as implement the programs for converting automobile transport to gas engine fuel. The use of LNG halves the cost per kilometer of vehicle mileage. The consumer to be converted to gas is, in particular, the Breitovsky district, the only area in the region which is not supplied with gas. It is located near the village of Bolshoye Selo, where a liquefaction plant will be built. It is planned to convert more than 80 black-oil-fuel-fired boiler plants to LNG.

This project can serve as a basis for one more option of the integrated network. We are talking about the use of LNG as a fuel not only for boiler plants, but also for gas-fired generators that provide electricity to communities in the sparsely populated areas. This eliminates the need to build distribution electric network, which is especially important for scarcely populated areas, with considerable distances between settlements.

It should be assumed that such a revolutionary approach to the electrification of territories will not only reduce the cost of operating electric system facilities, but also increase the reliability of electricity supply, since the system will not contain power lines that are most prone to natural impact. The concept of local electrification, of course, must be studied comprehensively. There is a high probability that it will be needed to solve the problems of energy supply to the vast territories of Eastern Siberia and the Far East. The advantages of such solutions for the regions with conservation areas are also evident. In Russia, there are 103 reserves and hunting areas. Their preservation is the responsibility of the present and future generations. The implementation of the proposed idea of integrated systems will make it easier for us to fulfill this responsibility.

In this connection, we make one more important remark. The plans for the expansion of electric and gas systems have never taken into account the mutual influence of these systems to the proper degree. This resulted in miscalculations when choosing the structure and power of both systems. The energy structure of the Moscow region can be considered as an example. When developing the energy strategy of the city for the period until 2025, JSC Promgaz recommended a 43 percent reduction in the planned gas consumption. The reason is as follows: the electricity generated by the Moscow CHP plants was transmitted in large quantities to the adjacent areas of the Moscow region and even to more remote areas. What does this mean? Gas is burned in the metropolis area for the needs of consumers located outside it, in less urbanized areas. At the same time, large industrial enterprises in the city are being massively liquidated. It is impossible not to notice the absurdity of the situation. This can only be explained by inertia of human thinking.

It is also likely that those who now with skepticism perceive the concept of local energy sector, will be surprised that in the past the ideas of centralization led to the proliferation of monsters of hydroelectric power, hydrocarbon and nuclear power, and the wiring enough to wrap around the planet, which is harmful for human health.

V. Relevant Tasks Of Analysis And Synthesis Of Reliability Of Integrated Systems

1. Build a model for assessing the reliability of electric system whose control is coordinated with the operation of gas generators. Introduce reliability indices, estimate the indices depending on the principles of electric system and gas system control coordination.

2. Build models for assessing the reliability of local power system for consumer, for an option of a combined use of electricity, RES and gas generators (a special case - RES and gas generator).

3. Construct a model for choosing rational parameters of technological components of the system, including the capacity of energy (electricity and heat) sorage systems and the capacity of LNG storage for the option of combined use of electricity, RES and gas generators.

4. Develop methods for drawing up optimal maintenance schedules for the equipment of integrated systems.

5. Make recommendations to justify the strategy of converting a territory to gas (dividing the settlements to be converted into groups by types of supply: network gas, local gas supply with liquefied petroleum gases (propane, butane), local gas supply with LNG).

6. Compare the options of electricity supply on a multicriteria basis (within the unified energy system, local electricity supply with gas generators using LNG, etc.).

VI. Conclusion

1. The use of gas generators for energy supply to the settlements and territories has good prospects for energy in the 21st century.

2. It is advisable to coordinate the expansion planning and operational control of integrated (electric and gas) systems.

3. Modeling of operating conditions of the integrated systems should take into account the dynamics of changes in the gas accumulated in pipes. To solve the emerging problems, mathematical and software support is developed.

4. Modern technologies for liquefaction and regasification of natural gas ensure the competitiveness of an autonomous shift to LNG in the remote settlements.

5. Investigation of the integrated power systems using gas-fired generators will allow expanding the scope of intelligent networks [12, 13] and, possibly, will make adjustments to long-term energy development plans [14].

6. It is expedient to conduct a comprehensive study into the problems of autonomous electrification of settlements and territories.

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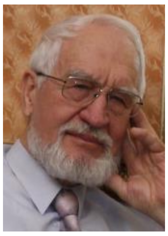

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