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About the journal

Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction in a complex physical, technical, economic and social environment.

Energy systems research methodology is based on a system approach considering energy objects as systems with complicated structure and external ties, and includes the methods and technologies of system analysis. The system approach is also necessary to address complex energy issues and challenges.

Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems.

The journal welcomes papers on advances in power engineering and heat supply, energy efficiency and energy saving, renewable energy and clean fossil fuel generation, and other energy technological issues.

Energy Systems Research is also concerned with energy systems challenges related to the applications of information and communication technologies including intelligent control and cyber security, modern approaches of system analysis, modeling, forecasting, numerical computations and optimization.

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- Distributed energy systems
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PREFACE

Energy Systems Research Journal: What is it and why?

Nikolai Voropai

Nikolai Voropai is president of the Melentiev Energy Systems Institute SB RAS and Editor-in-chief of Energy Systems Research Journal

Dear Colleague,

This is the first Issue of new Journal – Energy Systems Research. It is an international peer-reviewed Journal addressing all the aspects of energy systems (electric, gas, oil, heat, and others), including their sustainable development, reliable and effective operation, smart control and management, integration and interaction in a complex physical, technical, economic and social environment. Generally, energy systems research methodology is based on a system approach considering complex energy objects (power, heat, gas, oil, etc., integrated energy objects) as systems with complicated, usually inhomogeneous, structure and external ties. It is important that a new system acquires the properties, which are not found in its components. The methods and technologies of system analysis should be used as the techniques for solving system problems in energy. Such system methodology is necessary to address complex energy issues and challenges.

These basic principles of the methodology for system energy research are intuitively obvious for the experts thoroughly investigating the sophisticated modern energy systems which are the most complex artificial objects man has ever created. Meanwhile, even the Ancient Greek Philosophers had the initial understanding of the system structure of the environment. According to the figurative definition by B.S.Fleishman [1], this was a naïve systemology. In the Middle Ages, in the epoch of physicalism being the philosophy of cognition, the system views of the Ancient Greeks were completely forgotten. An objective reason for the renaissance of the systemology, intensified use and expansion of the system views in various domains of knowledge was complication of technical objects generated by the technical revolution of the 20th century, their stronger interaction and mutual influence, as well as their impact on the environment and human health, and an increasing role of man as a link of control of these complex objects.

A.A.Bogdanov [2] and L. von Bertalanffy [3] made a considerable contribution to the revival and development of the methodology for systems studies. The research by R.L.Ackoff [4], W.R.Ashby [5], J.Klir [6], M.Mesarovic [7], I.V.Blauberg and E.G.Yudin [8], V.V.Druzhinin and D.S.Kontorov [9], N.N.Moiseyev [10], B.S.Fleishman [1], to name but a few, shaped modern ideas about the methodology of systems studies, and developed the methods and technologies for system analysis. Peak of the research into the development of the systems phylosophy and methods for systems analysis in a general theoretical context and for specific system problems in different areas was observed in the 1960s-1980s. At the same period, the International Institute for Applied Systems Analysis was founded in Wien, Austria. The goal of the Institute was to conduct systems studies on urgent global problems by international groups. In the 1990s-2000s, the intensity of elaboration of general theoretical fundamentals for the systems methodology somewhat decreased, however its successful application, adaptation and extension to specific areas of research continued. The latter is objectively conditioned, because at a general theoretical level the methods and approaches are normally very abstract and have to inevitably be specified in terms of concrete applications, which by no means diminishes the methodological and theoretical significance of such a specification.

An important area of application and expansion of the systems philosophy is energy represented by an aggregate of interrelated energy systems that constitute energy sector, and integrated energy systems. In the USSR, this trend was associated with the name of G.M.Krzhizhanovsky who headed the State Commission for Electrification of Russia (GOELRO) in the 1920s. In actuality, the electrification plan developed by this Commission was a program for the national economic development based on the electric power industry [11]. To develop the GOELRO plan, G.M.Krzhizhanovsky applied the so called comprehensive method rooted in the systems philosophy. In the 1930s, researchers in the USA devised a method for integrated energy resources planning that was also based on the methodology of systems approach, and further intensively applied in the energy system expansion planning [12 et al].

In the 1970s, L.A.Melentiev generalized and developed the comprehensive method of G.M.Krzhizhanovsky in the form of a methodology for systems studies in energy [13]. There were several objective reasons that encouraged the development of this methodology. Firstly, in the 1950s-1970s the USSR saw intensive energy development: the unique unified electric power, gas and oil systems of the country were established, and the nuclear energy and coal industries were created. There was a need for a methodology for planning the expansion and control of these complex energy objects. Secondly, this period was characterized by the emergence of rather powerful computers that were used to devise effective mathematical models for modeling, optimization and planning of the expansion and control of complex systems, including energy systems. Thirdly, creating the methodology of systems research in energy, L.A.Melentiev actively used general methodological trends in the systems philosophy and systems analysis for the research into the complex systems and problems.

It is worth noting that the comprehensive method by G.M.Krzhizhanovsky, the methodology of systems studies in energy by L.A.Melentiev and the method of integrated energy resources planning largely originated from the plan-based approach to the expansion and control of the operation of energy systems and energy sector as a whole. In the last decades of the last century, due to restructuring and reforming of energy industries on a market basis, many countries faced the need to revise and develop the systems philosophy by rationally combining market mechanisms and state regulation in the energy sector. A so-called holistic approach was proposed as an updated method for the integrated energy resource planning [14, 15, et al]. It was also necessary to specify and develop the methodology of systems studies in energy, which was related to the need to consider the increased uncertainty of external conditions; a great number of stakeholders involved in the process of expansion planning and control of energy systems, and their different, often contradictory, interests; considerably increased requirements of consumers to reliability and efficiency of energy supply, and quality of energy resources delivered to them [16, et al.].

In today's interpretation, the methodology of systems studies in energy includes the following fundamental principles:

- Study on the nature of the investigated energy systems, including an analysis of factors shaping the main objective trends in the evolution of these systems and extent to which they manifest themselves; and research into the main energy systems properties that are transformed as these systems develop. This principle is of paramount importance since the success of future investigations depends totally on the insight into the essence of the studied object, i.e. an individual energy system or their aggregate within energy sector, or integrated energy system, as well as external conditions for the expansion and operation of the object in question.

- Creation and updating of models and methods for the research into the energy systems and planning of their rational expansion and effective operation. The models of energy systems should be updated and improved regularly to adequately consider changing properties and trends in the development of these systems, and to take into account the external conditions for their development and operation, the impact of market mechanisms and state regulation, etc. The methods for the study of energy systems and planning of their expansion and operation should consider not only the specificity of the models but also the expansion planning conditions, i.e. a great number of criteria and constraints, a contradictory nature of interests of different stakeholders involved in the expansion and operation of energy systems, etc.
- Solving of crucial expansion and operation problems that face individual and integrated energy systems, and energy sector, including: the development of state concepts, strategies and programs for energy development and investment programs for the development of energy companies; the study of national and regional energy security, reliability, survivability and controllability of individual and integrated energy systems; the determination of control actions to ensure the required levels of reliability, survivability and controllability; the study on the problems of development and operation of interstate energy interconnections and energy markets; and many other important tasks.

Our Journal – Energy Systems Research - will provide readers with access to the results of the systems research into energy. I invite you to collaborate with our Journal.

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Strategy for Implementing Black Start and Islanded Operation Capabilities on Distribution System Level

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***Abstract* — Due to a change in load situation caused by the installation of decentralized generation plants accompanied by distinct advantages and disadvantages for grid operation, distribution system operators seek an advanced degree of supply autonomy. Embedded in an appropriate environment of controllable plants, storages and extended demand-side management using intelligent automation, local distribution systems can bear major faults of the transmission system, safeguard infrastructure in graded extent and facilitate supply restoration in the transmission system. Implementing capabilities of islanded operation, black start and crisis-resilience can be considered a comprehensive task concerning various areas of grid operation. Substantial fields of action are presented. Analysis has been conveyed in order to allow objectified contemplation. All considerations are based on factual data of a small distribution system operator (DSO).**

***Index Terms* — Black Start Capability, Islanded Operation Capability, Ancillary Services, Crisis Management**

I. Introduction

Due to the transition of the electric power supply into a decentralized system based on renewable energy sources, schedulable, demand-actuated feeding generating plants with high rated power that provide the backbone of a reliable electrical power supply and ensure sufficient power quality are decreasingly available. As a replacement for the conventional large power plants, on distribution network level smaller plants based on different generation technologies with low rated power each are installed. Public utility companies are increasingly becoming power plant operators and managers of owner-operated plants in their network area. DSO may turn the initial challenge to control those plants in a grid-conducive manner into the advantage of being able to cope with major faults in the superposed transport network through coordinated black start of suitable generating units, activate plants without black start capability, operate the distribution grid islanded and, finally resume the supply of loads. In case of a voltage collapse or a blackout, the grid is out of order and loads remain unsupplied. If the interruption of supply affects a larger network area, for example the transportation network level and lasts for a longer period of time, a crisis situation can arise, in which it is no longer possible to supply the population with electrical energy, heat energy, drinking water and as a consequence with other goods. This has a significant impact on society and the result is the emergence of national crises [1]. For that reason, on distribution grid level measures of network restoration are required in order to resume a stable network operation. Most commonly, network restoration of distribution networks is executed by renewed connection to the transmission network. Because of increased installation of decentralized plants, DSOs are interested in islanded operation capability and black start capability of their systems. In order to gain an understanding of the essential questions regarding grid operation in the event of a black start and islanded operation, initially elementary basics are outlined. Then, for a real distribution network, the characteristics of generation and consumption are drafted, which are challenges in the area of self-sufficiency. Finally, the theoretical basics and the findings of the analysis are used to derive a general approach for the systematic implementation of self-supply capability.

The ability of a plant to put itself into operation in absence of voltage of the grid and to operate stably in a low operating point as idling or to provide on-site power

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demand is referred to as black start capability. Thus, those plants independently attain an operational status in which they are ready for synchronization with the grid. Whether a particular plant is black start capable can be determined by thoroughly disconnecting it from the grid including all ancillary units. In volt-free state, operation of ancillary units for provision of on-site power is continued or restored. Now the plant will be started up and set to idle. In the next step, the plant is made ready for coupling to the grid by increasing the voltage to network level. As prolonged supply disruptions may occur in case of a major outages, black start capable plants have to be able to independently sustain this particular operating point [2].

Islanded operation capability of a plant requires the capability to permanently provide a stable supply of an independent (sub-) system, including voltage and frequency regulation. In comparison to black start capability the implementation of the island operation capability can be considered to be a comprehensive task, as the control of the plant generators have to provide active and reactive power throughout the entire design range of the grid. Further, requirements have to be met by the control systems, as significant voltage and frequency fluctuations can appear, causing protective tripping during normal network operation [2, 3].

II. Characteristics Of Islanded Microgrids (MG)

Subject of consideration is distribution grids comprising low voltage (LV) and medium voltage (MV) networks. Alike micro grids, within those systems and within subsystems loads, distributed generation (DG) units and energy storage systems (ESS) can be found, which can be controlled by the network operator [4, 5]. However, in contrast to MG, arbitrary distribution grids usually operate in grid connected mode, and islanded operation is possible in exceptional case only. Aim of MG is to self-sufficiently cover the electricity demand using own resources and to minimize dependence on the grid [6]. If required, power can be provided to or borrowed from the grid [7, 8]. As a consequence, in order to become capable of self-sufficient supply and islanded operation, distribution grids have to meet requirements of MG stipulated in the definition. Of particular importance is identification of optimal MG configuration. For proper design and reliable operation, information on expected load is required. Target of optimization algorithms is to determine cost minimal configuration of generating units as RES and storage systems to reliably supply the demand [9]. Control of MG occurs on the three levels of primary control, secondary control and tertiary control. Voltage control, current control and power sharing control are executed by primary control. Secondary control is responsible for adaptation of system frequency and voltage to nominal values in the aftermath of deviations observed as load changes. Energy management and optimization is dealt with on tertiary level [5, 10]. By means of integration of renewable energy sources in MG, life cycle cost as well as electricity cost can be reduced and system reliability can be increased [11, 12]. A large share of RES in total DG complicates frequency control due to imbalances resulting from RES variability [6, 11]. Control and management of MG is a complex task due to dynamic and uncontrollable behavior of its components. Electricity production of RES strongly depends on uncertain and volatile weather conditions. Consumption and storage are strongly influenced by the behavior of loads and consumers [6].

A. *Operation and Control of Micro Grids*

To obtain as much energy as possible from scarce resources and to reduce operating costs, MG are to be run at optimum operating point [13]. Unlike conventional power grid, operation of micro-grid requires control of a large number of small fluctuating DG units, ESS and consumers. Aside from optimization of energy exchange in MG and best possible utilization of RES in MG power quality and system efficiency are to be investigated. For control of a large number of devices within a MG in order to ensure reliable MG operation, intelligent automation technology is required. Application of conventional control concepts as stand-alone controllers for individual plants or centralized SCADA systems is limited, due to restrictions of communication, complexity of the control task and others. For that reason, artificial intelligence as (centralized) artificial neural networks (ANN) as well as decentralized control concepts are gaining importance. Multi- agent technology, which can be considered an advancement of artificial intelligence, is capable of fulfilling the desired control tasks. Multi-agent systems (MAS) consist of communicating, interacting agents, which are equipped with artificial intelligence and provide new opportunities in solving the desired control tasks [14–18].

Classification of MAS is possible according to the three basic concepts of centralized MAS, distributed MAS and hierarchical MAS. Centralized MAS feature a master-slave structure for control of the agents by a single control unit. Distributed MAS consist of communicating agents that share information and collaboratively coordinate their actions to solve the control problem. In hierarchical MAS, some agents are authorized to influence the behavior of other agents [19].

Control of the devices of a MG using MAS is implemented by representing each element of the MG by a dedicated, intelligent agent, which controls its actions by means of mathematical algorithms or artificial intelligence. The behavior of the agents as well as the scope of control tasks in the case of the micro grid connection to the network differ from the case of islanded operation [20]. In grid connected mode, proper scheduling or energy exchange between plants, storages and loads is a control task that can be optimized in terms of economic, ecological, supply engineering or other targets [21, 22]. Islanded MG operation requires the MAS to provide control of MG voltage, frequency and phase angle [20, 23]. It is expected that transition between grid connected mode and islanded operation is fulfilled rapidly and seamlessly [15].

B. Ancillary Services in Micro Grid

As MG may be operated in islanded mode, all ancillary services necessary for grid operation are to be rendered within the MG. Based on trading information of the MG members, a market for reserve capacity can be established. Objective of optimization is minimization of customers expense [24, 25]. Typical disturbances within MG requiring ancillary services are deviations of voltage amplitude and frequency, harmonics and inter-harmonics, voltage fluctuations and flickers caused by active power output and load reactive power. For analysis of power quality, approaches as Fourier Transform (FT), spectrum analysis, short time Fourier Transform (STFT), wavelet transform (WT), S-transform, Hilbert-Huang transform (HHT), Taylor-Fourier Transform (TFT) or an atomic decomposition algorithm may be applied [26–28].

C. Frequency control in islanded grid

During islanded operation, frequency control is of particular importance, which is why it is presented here separately from the other ancillary services. Today, in normal grid operation, frequency control is mainly provided by conventional power plants with rotating generators. The (local) level of MG requires both technical equipment for frequency regulation and market mechanisms for control of generation and load. In islanded grids, significant variations of frequency can occur due to imbalances of generation and consumption. Accordingly, both automatic generation control (AGC) and load-frequency control (LFC) can be considered necessary [29]. Obstacles to an integrated approach to frequency control in MG are real-time determination of fluctuating production and consumption [29]. Real-time pricing is regarded as a proper instrument for influencing the behavior of smart loads that are able to react flexibly to varying electricity prices due to frequency changes [30]. In case of market failure, immediate grid stabilization measures have to be held available as load prioritization [31]. For use of inverter-based renewable feeders for grid stabilization, consideration of their virtual inertia is promising [32].

D. Battery Management in Micro Grid

Power imbalance problems can be mitigated using ESS for storing excess production of RES by charging ESS on increased grid frequency and discharging on frequency drops [11]. Those ESS support MG by provision of a limited energy reservoir, which can absorb and release energy for integration of RES. Owing to their limited capacity, diligent management of state of charge (SOC) of ESS is an integral part of MG. Battery Energy Storage Systems (BESS) compensate for fluctuating generation in MG and thus support stability as well as maximization of power production. Proper dimensioning of storage and management of SOC are essential [33].

III. Analysis Of Structural Data Of The Distribution Network Under Consideration

Contemplation is based on structural data of a real distribution network from the year 2014, which included 660 generating plants with a gross rated power of 19.4 MW. Among those plants are 622 photovoltaic plants, 20 gas cogeneration plants, 9 biogas plants, 4 biomass plants, 2 wind power plants, 2 hydropower plants and one digester gas plant. Volatile plants as PV plants and wind power plants contribute 14.8 MW rated power and 76 percent of the gross rated power. The remaining capacity of 4.7 MW or 24 percent is attributed to demand-actuated plants, which form the basis for further considerations concerning black start and islanded operation capability of the distribution grid. As 2.1 MW of those plants are owner-operated plants, the DSO has immediate access to demand-actuated plants with 2.6 MW rated power, which can be controlled by the control center. Accordingly, the generation structure can be considered highly heterogeneous, which is exacerbated by the diversity of individual plants, especially regarding photovoltaic plants. Electricity generation within the distribution network is consequently limited seasonally and during the day depending on the availability of environmental factors as insolation and wind speed. For photovoltaic plants, an annual utilization degree of 12.8 percent corresponding to 1.100 annual full-load hours can be assumed. In Fig. 1, the prevalence of certain power intervals in percent of rated power of a photovoltaic plant within the distribution grid during one year is depicted in blue. The red line demonstrates the percentage of time during which a certain percentage of the rated power is produced.

Onshore wind power plants feature an annual utilization degree of approximately 18.8 percent and 1.650 annual full-load hours. Consequently, photovoltaic plants and wind power plants may only be considered with their expected level of generating power for considerations

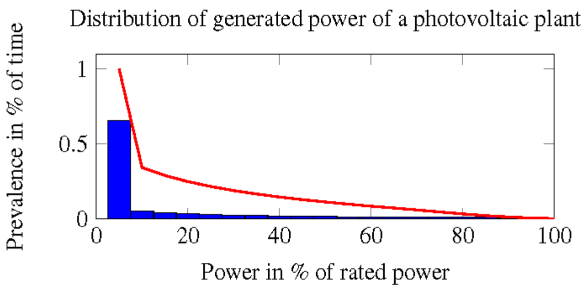

Figure 1. Distribution of generated power of a photovoltaic plant over time.

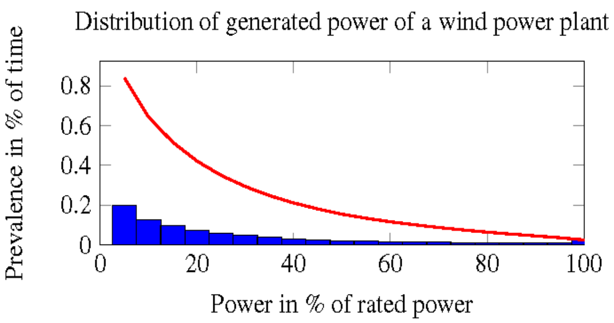

Figure 2. Distribution of generated power of a wind power plant over time.

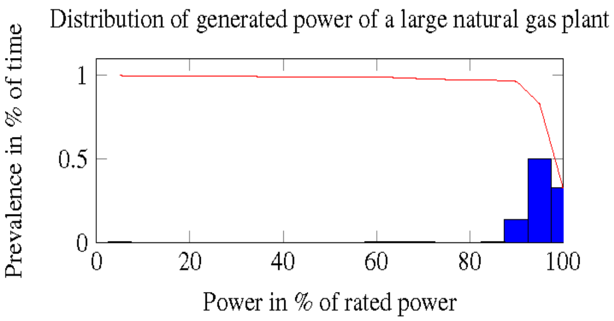

Figure 3. Distribution of generated power of a natural gas plant over time.

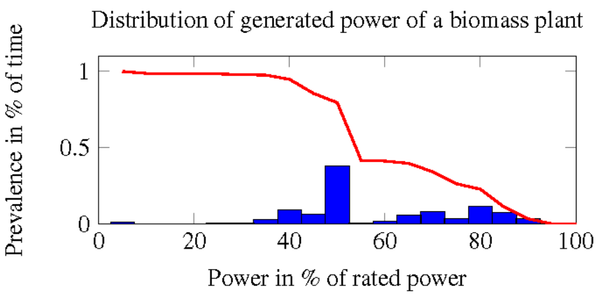

Figure 4. Distribution of generated power of a biomass plant over time.

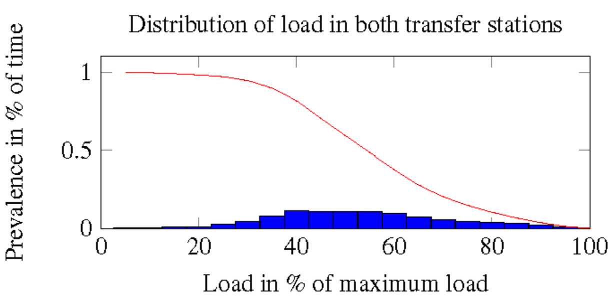

Figure 5. Load of the entire grid over time.

regarding islanded operation. In Fig. 2, the prevalence of certain power intervals in percent of rated power of a wind power plant within the distribution grid during one year is depicted in blue. The red line demonstrates the percentage of time during which a certain percentage of the rated power is produced.

A quite different behavior can be observed for plants based on plannable energy sources. In the distribution network under consideration, a natural gas combined heat and power plant (CHPP) exists with a rated power of 0.8 MW, which is used perennially in order to generate the largest possible amount of electrical energy (Fig. 3).

Accordingly, the prevalence of power intervals with high percentage of rated power is high in comparison to fluctuating plants. Furthermore, there are biomass CHPP based on wood pellets within the grid for supply of local heating networks. Those plants are operated on a seasonal basis, as thermal heat is required mainly during the heating period (Fig. 4).

Apart from electricity production, load situation and grid structure are also relevant. The distribution network under consideration is supplied with electric energy from the adjacent 110 kV transmission network via two transfer stations (electrical substations). From there, energy is distributed on medium voltage level (20 kV) to secondary substations or mains connections on medium voltage level. In total, the distribution network includes 220 secondary substations in a grid area with large spatial expansion. Approximately 20.000 people and diverse commercial customers are supplied. Within the observation period of one year, an average load of 6.4 MW was drawn from the superimposed HV grid with a standard deviation of 2.2 MW. A maximum load of 12.6 MW was observed as well as a minimum load of 0.0 MW. Analysis is based on 15-minute load measurement in the transfer stations. As all amounts of electrical energy, which are fed into the MV grid, lower the load in the transfer stations, effective load within the grid exceeds the measured values. Due to the circumstance that most plants within the MV grid are renewable plants and feature 15-minute measurement of the fed-in electricity, refined approximation of the load situation is possible. With an average generation of 5.3 MW, average load is 11.7 MW. Maximum load was 20.3 MW and minimum load 1.7 MW. However, due to a lack of measured data with sufficient temporal resolution, especially for numerous small photovoltaic plants, effective gross electricity consumption within the distribution grid can only be estimated containing error. In Fig 5 the data on power obtained from the superimposed transmission grid in certain power intervals in percent of maximum power consumption within the distribution grid during one year are shown in blue. The red line demonstrates the percentage of time during which a certain percentage of maximum power is consumed.

IV. Network Restoration Strategy On Distribution Level

Well-known strategies for network restoration on transmission system level can be applied to distribution grids in a modified manner. In general, network restoration strategies describe a logical structure of separate principles in form of a decision tree, which is repeatedly run through until network operation and supply of all loads are successfully restored. In the event of a blackout, a loop is entered and for all zones of the grid, all plants and all loads defined measures are executed as exemplarily visualized in Fig. 6 [34].

V. Structure Of Analyzed Distribution Grid

The medium-voltage distribution network under consideration is connected to the superimposed high-voltage level by two transfer stations. According to the network plan containing all transfer stations, substations and lines as visualized in Fig. 7, the distribution grid can be subdivided into 11 areas. Subdivision is carried out in a way that the respective segments form an independent unit each without modification of the network structure, switching is possible with little effort and there are at least two connections to the rest of the network. Another

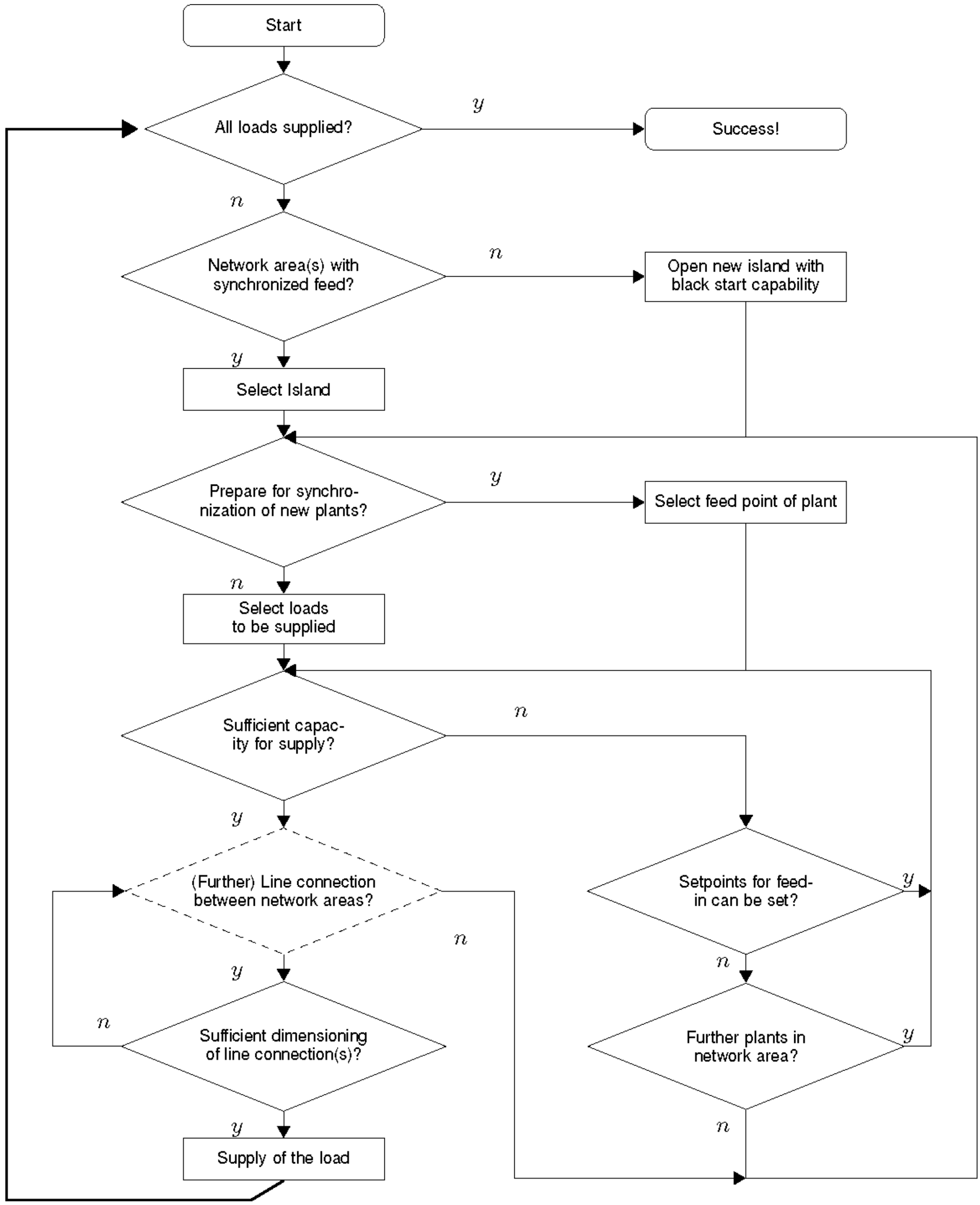

Figure 6. Generic network restoration strategy [34].

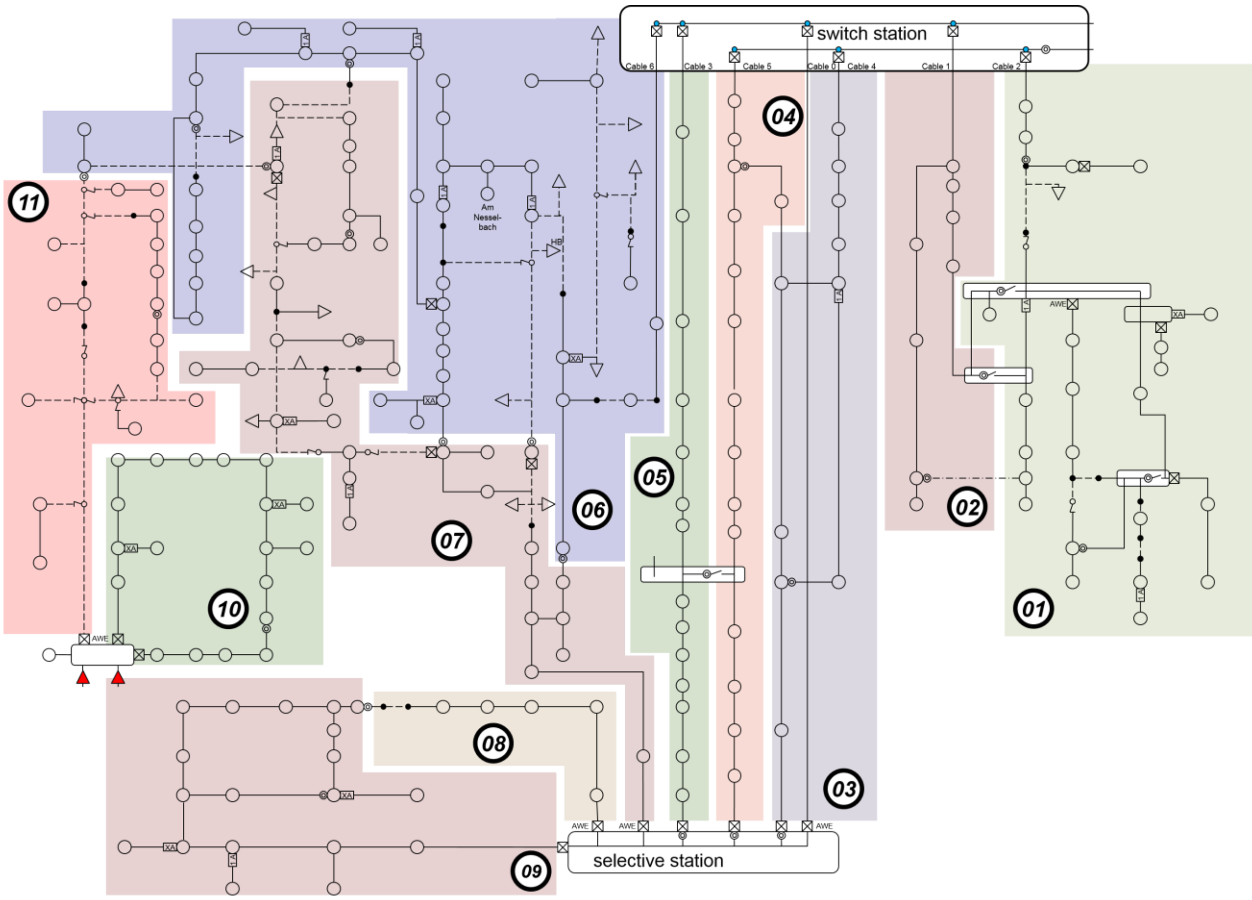

Figure 7. Grid structure and segmentation into 11 network areas.

criterion is that each segment can directly be supplied by at least one transfer station. Hence, those areas can be isolated from failures in other areas by switching in the transfer stations. Those areas can be considered independent islands, which have to be equipped with suitable storage, controllable plants and an individual concept for demand-side management in order to enable islanded operation. The next criterion for subdivision of the grid in the depicted 11 segments is the circumstance that currently switches for connection of the sub-stations to the MV grid are manual switches. In order to reduce the effort for upgrading, the switches in all substations, initially only the switches in the switch stations, have to be renewed.

In the rural distribution grid under consideration, the network areas show diverging properties regarding load structure, generation capacity, critical infrastructure and equipment. The transfer station switching cabinet supplying 9 of the 11 network areas via 7 lines is extremely important. It supplies the urban areas of the distribution grid, which exhibits relatively high load density. The second transfer station is located in a sparsely inhabited, remote network area with low load density. Altogether the network is meshed and the n − 1 criterion is broadly respected. Several stubs supply remote settlements and facilities.

For the individual grid segments, analysis of basic parameters of load and generation was carried out. While it was possible to attribute plants to particular substations, the assessment of load parameters within the grid segments was imprecise, as only large industrial consumers feature 15-minute measurement of consumption. As no data on the allocation of individual consumers to network nodes and thus to grid segments could be obtained, it was only possible to estimate the load by evaluating the maximum value pointers of the substations with reference to maximum load of the grid. Data on load and generation within the individual grid segments in megawatts (MW) are presented in Table 1.

According to the data, network area 1 can be considered the distribution grid's powerhouse, as it includes 9.6 MW generation capacity, representing 49 percent of the total installed capacity. As large industrial customers are situated there, network area 1 also accounts for 18 percent of overall load. Moreover, it is the only area where rated generation power exceeds the demand, and the rated generation power of the plannable plants is almost equal to the demand. Thus, segment 1 is selected to serve as starting a point for network restoration and islanded operation considerations. In addition, the rated power of controllable plants exceeds the average load and achieves

Table 1. Estimated data on load in the grid segments (i) for maximum load $P_{L,max}$, average load $P_{L,av}$ as well as on rated power of generating plants P_G, controllable plants P_{GC} and uncontrollable plants P_{GU}.

i	$P_{L,max}$	$P_{L,av}$	P_G	P_{GC}	P_{GU}	$P_{GC}/P_{L,max}$	$P_G/P_{L,max}$
1	3.7	2.1	9.6	3.3	6.3	0.9	2.6
2	1.2	0.7	0.8	0	0.8	0.0	0.7
3	1.5	0.8	0.2	0.1	0.1	0.1	0.1
4	1.7	1.0	0.2	0	0.2	0.0	0.1
5	1.3	0.8	0.6	0	0.6	0.0	0.5
6	3	1.7	1.7	0	1.7	0.0	0.6
7	2.5	1.4	2.4	0.5	1.9	0.2	1.0
8	0.2	0.1	0.3	0.1	0.2	0.5	1.5
9	1.7	1.0	0.7	0.4	0.3	0.2	0.4
10	1.7	1.0	1.8	0.2	1.6	0.1	1.1
11	1.3	0.7	1.1	0.3	0.8	0.2	0.8
	20.3	**11.7**	**19.4**	**4.9**	**14.5**	**0.2**	**1.0**

approximately the maximum load. Moreover, the large industrial customers have emergency power plants available, so the capacity of plannable and unplannable plants can be used for network restoration. If grid segments 1 and 8 are neglected, there are no significant plannable generation facilities in most of the segments for maintaining islanded operation.

VI. Sequence Of Measures For Implementation Of Islanded Operation

Subsequently a strategy for structuring the activities in preparation of the implementation of islanded operation is developed. With due regard to the sequence of measures, DSO can determine islanded operation scenarios, understand the possibilities associated with the existing infrastructure as well as advisable expansion. Furthermore, assessment of economic matters enables DSO to safeguard investment decisions and to determine a reasonable order of implementation.

A. Identification of loads

All loads connected to the distribution grid have to be registered as well as attributed to a particular network area and network node. Characteristic features of the load as maximum and average of power rating are to be recorded as well as information on behavior and controllability. Association of loads to network areas and nodes can determine information on load parameters for the network areas and nodes determined by summarization. Thus, it becomes evident at which point in the network what load can be expected and what supply is required.

B. Determination of supply interruption durations

As all considerations on islanded operation are particularly related to the provision of electrical energy from scarce re- sources, a limitation of the supply interruption duration and development of supply scenarios appear to be reasonable. Those durations in combination with the load required determine the amount of energy to be provided. Some supply interruption durations are outlined to exemplify. Minimum supply interruption duration in Germany can be estimated at 12 minutes or 0.2 hours according to typical annual supply interruption duration per customer in the year 2014 [35]. A further, longer supply interruption duration correlates to the duration of a typical supply interruption per customer in Germany in the year 2014 of approximately one hour. Further intervals of 3, 6, 12, 24 and 48 hours. A period of ten days or 240 hours is assumed as the worst case interruption duration scenario, introduced as a crisis scenario by the German government [36].

C. Load Prioritization

As a next step, different supply scenarios in case of supply interruption are drafted. Regarding their importance for the supply of the population, the facilities can be arranged in the order of their significance.

Minimum supply scenario: only facilities essential for public services of general interest are supplied. These are the facilities of water supply, sewage treatment, health care (especially hospitals), retirement homes, public shelters, fire stations, police stations and facilities of utilities.

+ Other facilities of public interest: another scenario going beyond the minimum supply scenario includes the supply to additional facilities of public interest. Those are the facilities of food supply, food production, production and supply of energy sources, and other important supplies, including agricultural enterprises, farms or greenhouses, food-processing plants such as butchers and bakeries, warehousing facilities and petrol stations.

+ Maintenance of basic functions in private residential units: exceeding the aforementioned supply scenarios, domestic appliances such as room heating facilities, refrigerators, freezers, emergency lighting and further safety-relevant devices are supplied. Thus, it is ensured that the population is not obliged to leave their dwellings in crises.

+ Shortened supply of usual demand: most domestic appliances can be supplied, however appliances with high power consumption should be avoided.

Maximum supply scenario: all customers and loads are supplied as usual without any restrictions. This scenario corresponds to the maximum load that can be observed in the network, including special cases such as electric storage heaters.

D. Registration of available generating plants

At the next step, the available generation structure has to be captured by associating all plants to network areas and nodes. Realistic plans for capacity extension are to be included. Additionally, an overview of the distribution of the plants in the network area is made, and it becomes obvious where centers of power generation are located. Further evaluation requires information on the behavior of the plants as maximum-, minimum- and average feed-in power as well as standard deviation. Moreover, information on the plant type and its feed-in characteristics appears to be significant. Feed-in behavior is controllable for conventional plants based on storable energy sources or fluctuating for renewable plants, which are influenced by external circumstances. Type and costs of required combustibles as well as magnitude of storage provide important information for plant operation in the event of a crisis. Details about the type of the electric machine or the generator, whether it is a synchronous machine or an asynchronous machine and how great the control capacity is, allow an assessment of the contribution to regulatory activities in islanded operation. Additional information regarding islanded operation and black start capabilities of the plants in general should also be collected. Finally, the preparation of information on the controllability of the plant, its connection to the control center, and on the plant operator is recommended.

E. Prioritization of plants

After collecting data on the plants, prioritization regarding requirements of islanded operation takes place. Dimensions of prioritization are black start capability, islanded operation capability, predictability and controllability, range of combustibles and rated power.

F. Calculation of missing plannable capacities

By contrasting juxtaposition of determined supply scenarios and identified generation plants, the status quo of self-supply is acquired. Thus, it becomes evident which additional capacities are needed to cover different supply scenarios. For all scenarios, missing capacities are to be outlined individually.

G. Estimation of generation capacity expansion

Since required additional capacities for coverage of all supply scenarios are transparent, a target structure of generating plants can be elaborated. The most obvious case of implementing the required capacities in terms of conventional power stations is not optimal from a macroeconomic point of view. As a result, large overcapacities in all distribution networks would appear. For the best possible use of scarce financial resources and energy resources as well as taking into account the probability of different fault scenarios, a guideline for capacity expansion is drafted. At the first step, following the cellular approach, the missing capacities for different scenarios are distributed to network areas and nodes if possible. Subsequently the capacities have to be distributed to different generating technologies and types of power stations. For missing capacities, predictable well-controllable technologies with black start and islanded operation capabilities based on storable regional energy carriers can be recommended to cover minimum supply. If the required combustibles can be produced sustainably on site or in the area of the distribution grid, permanent operation of these plants is possible in principle. Additional capacities for supply of other facilities of public interest should be implemented as predictable island-operable well-controllable technologies based on storable regional energy carriers and other energy carriers such as natural gas. For maintenance of basic functions in private residential units both centralized and decentralized CHPPs based on various fuels are saliently suitable, in particular due to the possible sectoral coupling between electrical energy supply and heat supply. If sustainably producible regional resources are available, these should be used preferably. Supplementary fluctuating regenerative generation technologies and CHPP based on fossil fuels can be used. Shortened supply of usual demand can be met by combining CHPP, centralized and decentralized renewable generating plants. Compared to the supply of basic domestic needs, the orientation of plant structure is more decentralized, volatile and characterized by regenerative plants. Decentralized renewable plants with fluctuating generation and generation peaks coincident with demand peaks are recommended to cover maximum supply. These are in particular photovoltaic systems for demands during daytime. After assignment of required capacities to plant types, the possibilities of expansion on site of existing plants, for example for biogas plants and biomass power plants, should be examined. Enhancement of capacities of biogas plants by installation of additional natural gas CHPP is advisable in many cases, provided the connection to a natural gas network is possible.

H. Estimation of storage capacity demand

Expansion and integration of fluctuating plants into the distribution system generate the need for short- and mid-term storage for grid stabilization. Storage, especially of electrical energy, has a balancing role with regard to short-term self-supply on the distribution grid. Two positive properties can be achieved by adequate distribution of storages. On the one hand, storages, provided a sufficient state of charge at the time of the query, allow for an extension of self-supply time range. By their ability to predictably and controllably provide electrical energy, they extend the available feed-in capacity and thus the possibilities of self-supply. Likewise, an adequate limitation of the generating capacities, in particular of plannable generation facilities based on fossil or non-renewable regenerative energy sources, is possible by adequate sizing of the storage facilities. On the other hand, energy storage allows the integration of fluctuating producers into concepts for the black start and islanded operation capabilities of the distribution grid. Rated power of storage devices has to be adjusted to the rated power of the fluctuating generators. The capacity of the storage units should be adjusted to the intended time range of different supply scenarios as well as the rated power required to supplement the plannable generators in different supply scenarios. In addition to design matters, an operational strategy for the storages optimized regarding the needs of islanded operation and energy management has to be provided. Seasonal and weather-related requirements have to be taken into account and, beyond considerations of maximizing yields, possible capacity planning is made in the case of self-supply as a function of forecasts for production and demand. With increasing scope of supply in order to meet customer-specific needs or to provide regular supply, the volatility of the demand for electrical energy rises. Moreover, the desire for integration of fluctuating regenerative plants into supply of the loads increases. Correspondingly, the storage requirements are shifted into the areas of the bridging power as well as the uninterrupted voltage supply. The upper limit of total required rated power of storage is determined based on the nominal rated power of fluctuating generators, if greater than maximum load. The lower limit of required rated power storage depends on average power output of fluctuating producers. By multiplying the duration of the worst-case interruption scenario by the difference between minimum load and possible predictable self-generation as well as a factor of ensured storage charge level the lower limit of the required storage capacity is calculated. The upper limit of required storage capacity is determined by multiplying the duration of the worst-case interruption scenario by the difference between maximum load and possible predictable self-production based on sustainably regionally viable energy carriers. Subsequent to elaboration of storage capacity and rated power in total, the power ratings have to be assigned to network areas. After that, for different supply scenarios suitable storage technologies have to be identified.

- Storage technologies with decoupling of power and capacity as well as minimum self-discharge are suitable for provision of power and capacity required to maintain minimum supply. Those are, for example, Redox-flow storage and power-to-gas applications.
- Central large-scale storage with low self-discharge for the additional supply to the institutions relevant to the community.
- Decentralized storages and home storages to maintain the basic functions in private residential units, support reduced fluctuating supply of regular demands, like (Li-Ion) battery storage, and enable electric vehicle to charge in both directions.
- Central buffers with high rated power and short-term focus for collection and provision of energy from fluctuating regenerative generators in the context of maximum supply.

I. Reconcilement of storage capacity and generation capacity expansion

In order to avoid unreasonable overcapacities, expansion scenarios for generating plants and demand of storage facilities are to be coordinated, and a suitable design for the entire plant structure is to be defined.

J. Analysis of distribution grid structure

Analysis of the distribution grid with regard to the expected power flows in different supply scenarios aims to find out whether extreme load scenarios amongst grid areas can be endured by the existing equipment. Considering different switching states and supply scenarios, critical transmission lines and network areas can thus be determined. Expected load indications are included in strategic network planning and derivation of equipment to be fostered or upgraded. Moreover, equipment necessary for implementation of black start and islanded operation has to be determined. In particular, the following areas may be considered relevant. Electrical machines in generating plants have to be enabled to contribute to frequency regulation or hold control of energy reserve. Inverters of PV plants ought to be retrofitted to communication-capable systems with aptitude of remote control as well as active and reactive power feed-in. At least, the feed behavior of the PV plants should be controllable by varying the predefined frequency range for feed-in or by remote control. Adjustable transformers in local network stations can be considered necessary to maintain required tolerance bands of voltage during reversed load flow or load flows amongst network areas. Re-equipment of electrical measuring instruments is necessary to capture the data relevant for grid operation at a suitable temporal resolution. Collection of the requirements for a network control room intended for the monitoring and control of the equipment, generators, storages and consumers under operating conditions of black start and islanded operation should be developed. It is also necessary to have the requirements for smart meters regarding support of islanded network operation. Particularly relevant requirements are presented in order of decreasing relevance:

- High-resolution measurement of the electricity demand.
- Possibility of connection and disconnection of the

units by electric company.
- Ability to limit consumption and feed-in power.
- Control of internal producers, consumers and storage facilities in accordance with the requirements of the distribution grid operation coordinated by the grid operator.
- Connection to Smart-Home systems and control of the internal energy management within the housing unit.
- Enabling autonomous supply of the unit and the provision of additional services for the distribution grid.

K. Feasibility study of different supply scenarios

The feasibility study of different supply scenarios included: verification of the feasibility of different scenarios of black start and islanded operation using the generic network restoration strategy; analysis of whether a defined switching state can be applied to all the loads to be supplied by the generating plants through the plants distributed to the grid areas; checking the coupling conditions to other grid areas.

L. Assessment of cost

The costs associated with the implementation of the technical concept are calculated for each supply scenario or the stage of expansion under consideration.

M. Development of profit mechanisms and revenue models

The profit mechanisms and revenue models for the operation of the estimated production plants and storage capacities are to be developed for their entire life cycle. The revenues for new regenerative generation plants considering possible subsidies (EEG), or the appropriate average conditions from competitive tender competitions should be calculated. For micro CHPP units, the revenues are to be calculated for the expected operating time, including possible subsidies, contractually agreed minimum reductions in electrical energy and heat as well as acquisition, installation and operating costs. Preliminary forecasts for fuels are also included for the entire operating period. CHPP units and cogeneration plants supplying critical infrastructures have to be evaluated including (and negotiating) municipal budgets for the provision and allocation of alternative costs for the provision and operation of conventional emergency units, for example in hospitals and nursing homes. In addition, potential subsidies, contractually agreed minimum reductions in electrical energy and heat, acquisition, installation and operating costs have to be taken into account, as well as the establishment of price forecasts for fuels. Storage capacities should be calculated on the basis of expected revenues, initially from the provision and introduction of primary and secondary control, as well as later on the marketing of interim storage of electricity from regenerative generation plants.

N. Determination of implementation order

Comparison of cost and revenue figures in the form of a business model over the planned lifetime has to be conducted. Individual investments have to be prioritized with regard to their economic advantage. Profitability of the overall project or estimation of the resulting total loss is to be considered.

VII. Conclusion

Obviously, implementing capability of self-supply, islanded operation and black start on distribution network level is a comprehensive task affecting all spheres of duty in network operation. In the study presented, it was attempted to compose all essential fields of action to facilitate a structured design planning of decentralized grid with graded capability of is- landed operation. Comprehensive planning and consistent implementation is required to utilize regenerative energy sources within the distribution network area at best and to increase the system's resistance to crises.

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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.

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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.

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.

$\mathcal{P}_i^{\text{EPS}}$ – 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

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

subject to

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

where $x_i^s = x_i^I + X_i^{II} + X_i^{III} - x_i^d$,

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

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, $k = 1, \ldots, K$, it is necessary to find:

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

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

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

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

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

$$y_i \geq 0, \; x_i \geq 0, \; z_{ij} \geq 0, \; i = 1, \ldots, n, \; j = 1, \ldots, n, \; i \neq j. \tag{12}$$

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

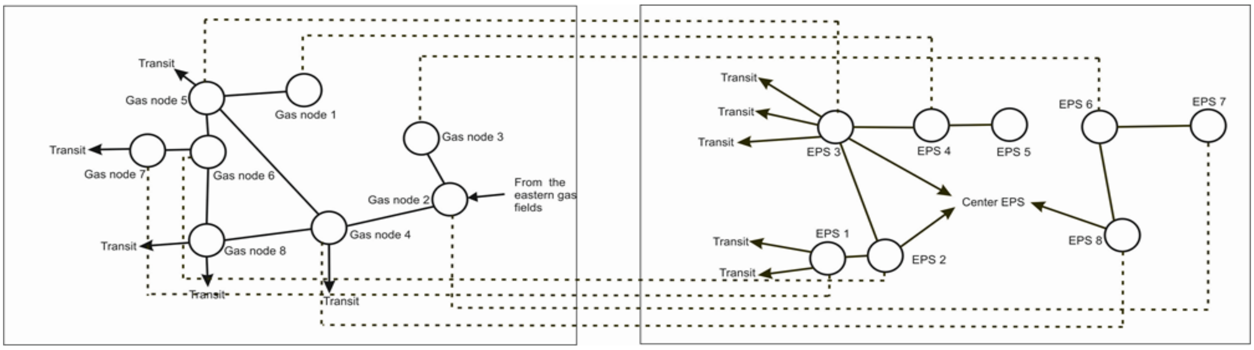

Figure 1. Calculated schemes of gas supply system (a) and electric power system (b) in RFD.

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	
	$\mathcal{P}_i^{EPS}$	E_u	$\mathcal{P}_i^{EPS}$	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

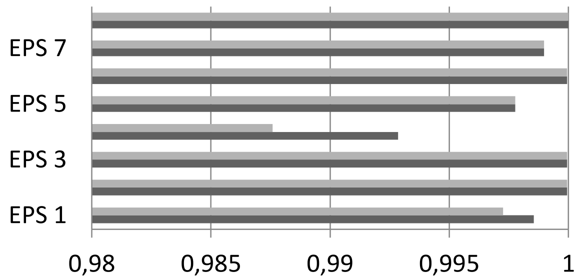

Figure 2. Probability of failure-free operation.

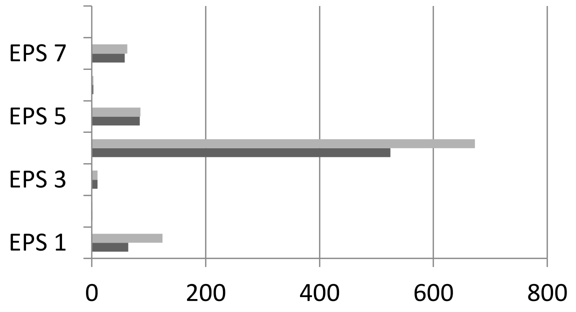

Figure 3. The mean value of electricity undersupply.

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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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.

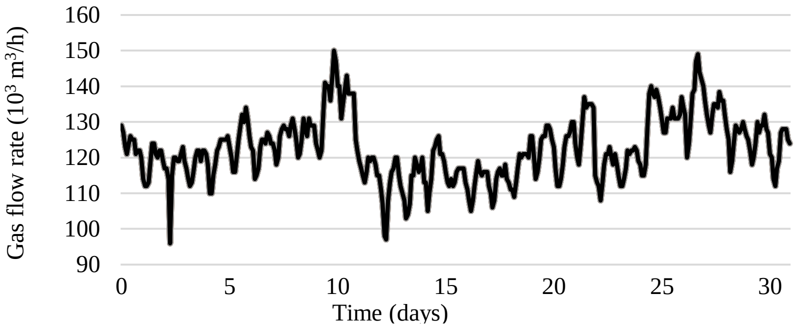

Figure 1. Gas flow rate through GDS-1 in city of Perm in December 2003.

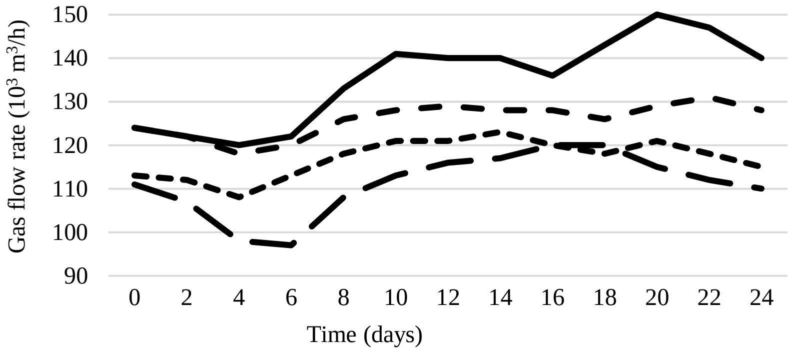

Figure 2. Daily chart of gas supply through GDS-1 in Perm for 10, 11, 23, 13 December (from top to bottom).

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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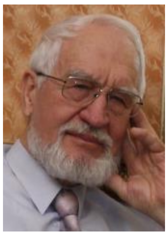

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Technology to Ensure Energy Security in Development of Russia's Energy Strategy

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***Abstract* — The paper discusses the primary challenges facing Russia's energy security in the context of energy development plans presented in the Energy Strategy of Russia until 2030. The study examines the development of a methodological framework for the identification of areas in which the suggested solutions for Russia's energy development must be adjusted to meet the energy security requirements. The paper involves research based on a multi-criterion model via combinatorial modeling. The research findings make it possible to formulate the energy development direction that best meets the requirements of energy security. An algorithm for the research and an illustrative example are presented.**

***Index Terms* — energy security, energy strategy, threats, modelling.**

I. Introduction

Energy security in terms of the economy and population of a country is understood as a condition of being protected against shortage of economically accessible energy resources of acceptable quality, and against energy supply disruption. For normal operation of the energy sector the condition of being protected implies, in a long-term context, satisfaction of the country's demand for electricity, heat, boiler and motor fuel. In extraordinary situations, for example, severe emergencies at energy facilities, the condition of being protected supposes assured minimum necessary energy supply to the country's vitally important consumers.

One of the most important goals of Russia's national policy is to ensure energy security. This goal has become considerably more urgent in the last 20 years due to internal and external factors. The transition to a market economic model is complete, and the adverse effects of the 1990s have been mainly overcome. However, signs of crisis are still observed in some sectors and regions. Studies on energy security are a significant component of the national security policy.

The energy sector is the most important component of the Russian economy, providing employment for the population, the functioning of productive forces, the consolidation of regions and a considerable part of government revenues and currency receipts. In 2017, the share of value added by energy industries of the GDP of Russia was more than 31 percent, while that of exports was 67 percent and that of tax proceeds to the Russian Federation budget system was more than 49 percent. In our estimates, Russia's fuel resources comprise approximately 6 percent of the world's oil, 18 percent of its coal and 24 percent of its natural gas reserves. Furthermore, the energy sector is the largest consumer of products made by other branches of the economy and should play a leading role in its technological development and upgrading.

For Russia, as a major exporter of energy resources (more than 10 percent of global exports), energy security also means energy sovereignty and nondiscriminatory access to external markets, which could minimize the impact of noneconomic factors on the activity of Russian companies.

II. Research Methodology

A. *Main targets of the Energy Strategy of Russia until 2030*

The concept of long-term national development underlying the Energy Strategy of Russia until 2030 (ES-2030) envisages large-scale structural transformations in the economy in terms of both GDP and the sector of industrial production. The market demand is supposed to foster the outpacing development of less-energy-intensive sectors of industrial production that specialize in high-technology and science-intensive products, while energy-intensive production will develop much more slowly, which should result in the structural transformation of Russia's economy towards less-energy-intensive sectors and industries.

According to the ES-2030, in the first stage of its implementation (2010–2015), prospecting work will be

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activated in the traditional areas of energy resource production. Moreover, all necessary conditions (normative, including legal, tax, institutional, etc.) will be created to develop a mineral resource base of the energy sector in remote and difficult-to-access areas of the country, including East Siberia and the Far East, the shelf of the northern seas and the Yamal Peninsula. A centralized vertically integrated system for the control of mineral resources will be created to allow their most efficient and comprehensive development. By the end of the first stage, the ratio of the annual additions to reserves and the volume of energy resources production will near 1.

In the second stage (2016–2022), active development of oil and natural gas will start in East Siberia; the Far East and shelf areas, including the areas in the Russian sector of Arctic; on the Yamal Peninsula; in the Gulfs of Ob and Taz; the European North; and the Caspian Region. The prospecting work will be performed by advanced technologies using 3D seismic methods. The volumes of prospecting will rise, and its efficiency will be enhanced. This will provide a steady re-production of the mineral resources of the main industries within the energy sector.

In the third stage (2023–2030), the development of the new areas will be continued based on advanced exploration methods and technologies, through public-private partnerships and the attraction of investment, including that from foreign investors. Maintenance of the production volumes of energy resources will call for considerable capital investment in advanced technologies for their exploration and production. Energy resources in the main areas of their production will decrease.

It must be noted that Russia has long faced serious problems hindering the accomplishment of the plans formulated in ES-2030. These are strategic threats to energy security.

B. Strategic threats to Russia's energy security

Despite the stabilization of the gross energy indicators and their subsequent increase, there are some negative trends in Russia's national and regional energy development:

- the quality of hydrocarbon resources involved in the economic turnover steadily decreases, the efficiency of exploration is insufficient, and the share of difficult-to-extract reserves rises;
- the wear of fixed production assets in the energy sector is impermissibly high, while the rates of their renewal and creation of construction reserves are low, the service life of most of the facilities has expired, and there is an obvious lag between the domestic energy sector and the world scientific and technological standards;
- emergency situations affecting the fuel and energy supply systems of the country and its regions arise;
- no progress has been made in energy conservation;
- investment shortage in the gas and electric power industries (no more than 70 percent of the funds envisaged in ES-2030 are invested in their development);
- the diversification of the energy balance structure remains insufficient (the natural gas share in the primary energy balance exceeds 50 percent, and that in the fuel balance amounts to approximately 70 percent). The energy sector of European Russia is characterized by uneven availability of natural energy resources;
- the price and tax policies remain inflexible, which leads to a considerable rise in energy carriers' prices for final consumers. The high prices of energy resources and low efficiency of their use decrease the competitiveness of products made by Russian enterprises and bear heavily on the budgets of all levels.

The key strategic threats to the energy security of Russia were discussed in [1-4 and others]. These threats are wasteful energy consumption, slow elimination of gas and coal price distortions, a lag between additions to the explored reserves of hydrocarbons and their production volumes, a reduction in gas production due to the economic risk of the developing gas resources of the Yamal Peninsula and shelf of the northern seas, an extremely high share of natural gas in the energy balance of Russia's European regions, an insufficient level of investment in the energy industries, severely worn equipment and low equipment upgrading rates in the energy sector.

C. Possibilities of satisfying the domestic demand for fuel and energy in Russia

The negative consequences of the considered strategic threats are applicable to the entire country and all entities of the Russian Federation. Realization of the threats in the considered time horizon can considerably change the estimates of the level of development required for various industries within the energy sector presented in the documents that underlie the Energy Strategy of Russia until 2030. The studies carried out in [2] show that the potential realization of strategic threats to energy security may be assessed through the indicators of primary energy production in Russia.

The comparison of the targets set in the Energy Strategy of Russia until 2030 and the prospective production volumes of primary energy resources in Russia in the event that the strategic threats to energy security materialize shows that the realization of strategic threats to energy security may cause serious problems with the achievement of the targets for the production of primary energy resources outlined in the Energy Strategy of Russia until 2030. Thus, the attainment of an acceptable level of energy security for Russia in the medium- and long-term future requires considerable additional efforts by the State, energy companies and consumers.

The energy security of the country can be ensured and obligations to the world community fulfilled provided that the strategic decisions are made at the governmental level. To overcome the shortage of investment in the energy sector (including prospecting work) and intensify the upgrading of worn and obsolete equipment in the energy industries and the expansion of their capacities, it is crucial to create a favorable investment climate for and enhance the economic efficiency of energy enterprises. It is also necessary to restructure the energy balance of the country, by increasing the shares of coal, nuclear energy and, where possible, renewable energy sources, and reducing the predominant role of natural gas. To ensure energy security, it will also be very important to enhance the energy efficiency of the economy, which can be implemented through the upgrading of the basic production assets in the energy industries.

It is essential to consider the issues of energy security when addressing the problems of energy development management in different countries. The national energy development options to be generated for the medium- and long-term future should give comprehensive consideration to the realizability of different strategic threats to energy security and the issues of reliable fuel and energy supply to consumers, particularly in emergency situations. In this case, energy security means that the population and economy of a country are protected from the threat of shortage of economically available energy resources of acceptable quality both currently and in the long term, and in both normal and emergency situations [1-4].

The level of energy resource self-sufficiency from an energy security standpoint differs from country to country. However, the following key factors are common:

- the ability of the economy and energy sector to supply energy carriers continuously and in sufficient amounts, thus creating the energy prerequisites for the sustainable functioning and development of the economy and for the maintenance of an adequate standard of living for the population;
- the ability of consumers to consume energy efficiently and limit its demand, thus decreasing the energy imbalance;
- the balance between energy supply and demand, considering the economically sound volumes of energy export and import;
- favorable socio-political, legal, economic and international conditions for the implementation of the indicated abilities by producers and consumers of energy resources.

How can we take into account the energy security interests in a variety of probable scenarios of economic and energy development of a country?

D. Energy security monitoring and indicative analysis

It appears that one of the necessary conditions to solve this issue is to develop an energy security monitoring system with corresponding indicators characterizing the most critical aspects of energy sector operation and potential development.

The values of these indicators should adequately describe the composition and degree of energy security threats to a country to make it possible to analyze emerging or fading negative trends. Complex interrelations and interdependences in the energy sector can bring about a rather large number of such indicators. Some of them can be specific and are calculated on the basis of primary data on the state of some process, and the others can be integrated to generalize some close or interrelated processes.

Many researchers in the world have identified the most significant indicators. In Europe, this issue is covered in [5-10], among others. In [11] the authors describe possible strategies to improve the situation with energy security by reducing the use of carbon in the Irish energy system. In [12], the authors describe a new energy security indicator. The paper presents a case study involving 28 European Union countries, as well as determines the level of impact of six different indicators on energy security. In [13], the authors discuss the topic of short- and long-term energy security assessment methods and indicators. The authors of [14] report the findings on the following: energy security definitions, changes in the themes of these definitions, energy security indexes, specific focused areas and methodological issues in the construction of these indexes, and energy security in the wider context of energy policy. The authors of [15] provide an overview of methodologies used for quantitative evaluations of security of supply. The research in [16] is devoted to the influential approach – the “four As of energy security” (availability, accessibility, affordability, and acceptability). The authors of [17, 18] consider the vulnerability approach which focuses the attention of policymakers on the assessment of risks associated with natural, technical, political and economic factors.

In Russia, the issue of the formation of energy security indicators is most fully covered in [1, 4].

To effectively comprehend the large number of energy security indicators of a country, we focused on the following most significant indicators for Russia as determined by an expert:

- the average physical depreciation of fixed assets in the energy industries;
- the share of the predominant fuel type in the structure of consumed fuels (or in the energy balance);
- the relationship between the expected undersupplies

of energy resources to Russian consumers and the total demand for them;
- the relationship between the annual increase in commercially recoverable reserves of primary energy resources and their production;
- the relationship between the actual excess of production capabilities of energy industries to supply the corresponding resources and the total demand for them (including export);
- the relative decrease (increase) in the energy consumption per unit of GDP.

Unlike Russia, an energy-independent country that exports its energy resources, for many countries, it is crucial to follow not only the share of fuel dominating the energy balance but also the share of imported energy resources and especially the share of the largest energy supplier (company, region, country) in their total import.

Naturally, the values of indicators themselves without proper processing and interpretation do not indicate the critical or non-critical phenomena and processes. To estimate the values of indicators, it is necessary to substantiate certain threshold values, such as:
- a pre-critical value as a threshold between the acceptable and pre-critical states of the energy sector in terms of the aspect described by this indicator;
- a critical value as a threshold between the pre-critical and critical (unacceptable) states.

Comparison of the estimated value of indicator with its threshold value points to a qualitative state (degree of a crisis) of the considered process or phenomenon. This is how an individual indicator (an individual phenomenon) can be estimated. However, to estimate the energy security level for a state or a scenario of economic and energy development, it is necessary to develop a mechanism for the integration of the values of all of the considered indicators, that often interact with one another directly or indirectly. In other words, an integrated estimate of the energy security level is necessary. It should take into account, where possible, expected changes in most of the indicators for the studied time horizon.

E. Integrated estimate of energy security

General scheme of the study.

The aforementioned integrated estimate can be obtained by mathematical models that adequately reflect the most important points of operation and development of the energy industries and their interrelations. First of all, these are the models of the national energy sector operation and development. They consider the operation and lines of development of all energy systems as a single complex and take into account the energy needs of the economy. Specialized simulation models are applied to provide information support and make the studies on the balance models of the energy sector closer to the operation and development of real energy systems.

Studies based on such a package of models consider the inter-industry aspects of energy sector reliability and make it possible to comprehensively assess the energy sector capabilities to meet the consumer demand for final energy resources under different operating conditions and in different development scenarios. The capability to diversify the fuel and energy supply and fuel interchangeability are also taken into account.

The general scheme of these studies has two levels:
1. Comprehensive assessment of the implications of possible changes in the operation of energy systems and the entire energy sector, determination of vulnerable points in the fuel and energy supply and the generation of possible solutions for the energy security of the country.
2. Assessment of energy development options in terms of energy security requirements and identification of the areas in which these options should be adjusted to provide national energy security.

Level of the energy sector.

The studies on validation of the adjustment areas of energy development scenarios (based on the comparison of the values of the indicators corresponding to a specific scenario and threshold values) can be conducted on the economic mathematical model of the energy sector [1]. The model assesses the current state of the energy sector in normal and emergency situations and determines the areas for the adjustment of the suggested scenarios of the national energy development from an energy security standpoint.

Mathematically, the optimisation problem of energy balances for Russia's regions solved by this model is a classical linear programming problem. Conceptually (in an energy and economic sense), the problem is based on the territorial- production model of the energy sector with the modules of electric power industry, heat, gas and coal supply, and oil refining (fuel oil supply).

The optimisation calculations for the considered situations make it possible to determine

a) the level of possible shortage in individual energy resources for the considered categories of consumers in different areas and the country as a whole (as a value of the discrepancy between the specified demand for an individual energy resource and the possibility of its production taking into account its reserves, the ability to source the energy resource from other regions or countries, its substitution by another energy resource, etc.);

b) the changes in transfer capabilities of inter-area transport ties, which are determined by comparing the respective indices of the considered and initial option;

c) the rational use of the production capacities of energy facilities as well as the distribution of the main energy resources by consumer category. This is achieved by the analysis of specific interacting economic indices that characterise the costs of additional demand for each type of fuel and energy by federal district.

Level of energy systems.

The second component of the research tools is industry-related simulation models of the oil, gas and electricity supply. It is shown in [3]. Unlike the balance model of the energy sector, these models are mainly oriented toward a day-long interval and allow us to study all possible changes in the fuel and energy supply in the case of emergency situations and to identify the technological flaws that hinder normal fuel and energy supply.

Research into a certain scenario of energy development makes it possible to obtain the cost of the solution and potential physical amounts of energy undersupply if a threat to energy security materialises. An additional study provides us with the cost of measures to be taken to fully meet the demand for energy resources in this situation. This cost represents the difference in the functional values of the first and the next solutions. Undoubtedly, to obtain adequate estimates, it is necessary to pay special attention to the formation of financial and production indicators used in the calculations. The most important indicators considered here are the indicators of equipment wear, the energy resources situation and the dynamics of changes in the energy: GDP ratio as well as the potential costs of importing the deficient energy resources.

Integrated estimate.

After determining the cost of the measures to meet the demand specified in the studied scenarios of energy development, we can obtain comparative characteristics of different options. The main subject for comparison here will be the sum of the following components:

- the cost of the solution for the conditions dictated by the studied option of energy development, considering the realization of energy security threats (with a possible shortage of energy resources for consumers);
- the cost of meeting all demand for energy resources under the existing conditions.

The studies based on the economic and mathematical model of the energy sector provide an adequate description of the processes, which enables us to take into account the values of most of the indicators that describe the technological, financial and economic characteristics of the energy sector operation. As a result, we obtain an integrated estimate of the energy security level in terms of the part and the aspect described by a set of indices considered in the model.

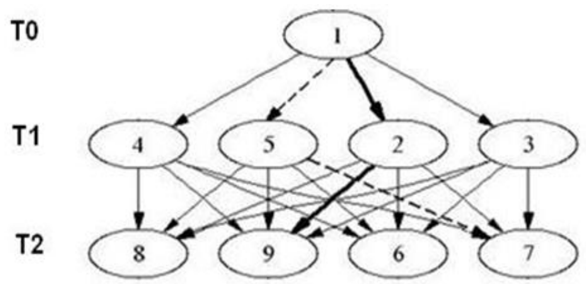

Figure 1. Graph of the energy development.

III. Formation of Specific Directions for the Energy Development Correction in Terms of Energy Security

It is extremely important to follow the values of the most important indicators and their dynamics and to use this analysis to develop ways to solve the corresponding problems to maintain an acceptable level of energy security in the country. This can be carried out only by considering all possible scenarios of energy development in terms of energy security and by choosing the solutions that meet the energy security requirements and, of course, comply with sensible investment limits. In addition, based on expert analysis of such rational, in terms of energy security, scenarios of the national energy development, we can identify specific directions for the adjustment of the national energy development scenarios in terms of energy security.

A. Formation of a complete set of all possible energy development scenarios

In principle, very little is left to do; we must only form a complete set of all logically possible future scenarios of the national energy development. This can be performed by combinatorial modeling ([9], among others), which make it possible to

- identify energy development options and estimate their admissibility in terms of resource, financial and other constraints;
- compare the variants based on different criteria to choose the most suitable;
- identify the trajectories of energy development that are rational in terms of energy security.

In the initial stage of research, the structure of the energy sector is divided into several parts, for example, in terms of territory. For each part, experts construct a graph of development by reference years. Next, by combining the states of different parts of the energy sector that belong to the same time interval, we obtain a set of energy sector states for a definite time moment. The obtained energy sector states correspond to the nodes of the energy development graph, which are then connected with one another by arcs (transitions) (Fig. 1.).

Each transition from state to state represents a trajectory of energy development with the cost of this development and its specific features of fuel and energy supply. In

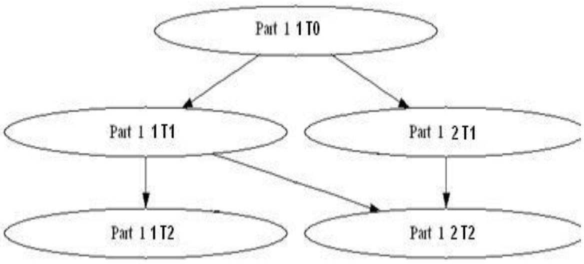

Figure 2. Potential nuclear energy development in the European part of the country.

Figure 1, the trajectory running, for example, through vertices 1, 5 and 7 (dashed line) is more preferable financially and provides the minimum shortage of energy resources for consumers compared to the other trajectories. However, states 5 and 7,
for example, may fail to meet the energy security requirements because the values of the most important energy security indices exceed the threshold values (for example, the threshold of energy import from one supplier is considerably exceeded). Therefore, a slightly more costly variant can be chosen, which consists of states 1, 2 and 9 (bold line) but meets the energy security requirements.

B. Example of the usage of the energy development correction principle in terms of energy security

Let us illustrate how this module works. We will make a simplified analysis of potential levels of development for three energy industries: nuclear energy, gas and coal. Suppose that in the time horizon until 2030, the production capabilities of these industries can develop moderately or remain at the same level (designating such a development intensity by symbol 1) and can develop intensively (designating such a development intensity by symbol 2). The main time samples are the initial state 2016, 2020, and the final time sample 2030.

The territory of Russia will be conditionally represented by three main economic areas: part 1 (European part of the country and the Urals), part 2 (Siberia) and part 3 (the Far East).

For each conventionally considered part of the country, each of the three chosen energy industries may develop with characteristic 1, i.e., moderately, or characteristic 2, i.e., intensively. There can be transitions between other states at different time points. For example, Fig. 2 depicts the possible nuclear energy development in the European part of the country. In the parameters assumed for the example, the graph of development of any energy industry in any economic zone will be identical.

For each of the considered parts of the country, we can now construct a graph of potential options for its energy development until 2030. Within the considered example, in such a graph for one zone, we can consider the transitions between eight energy sector states (three energy systems, each with two potential states) at each of the future time samples. Thus, in such a graph, it is necessary to analyze 16 prospective states of the energy sector in terms of energy security for each economic zone.

By combining different states of the energy sector of these three conventionally separated parts of the country, we can obtain a graph of development for the entire national energy sector. Even for the simplest example at one-time sample, it is necessary to calculate 512 different combinations of states of the individual energy industries. Hence, for two time samples, it is necessary to make calculations for 1024 prospective states. Because it is impossible to display the complete calculated graph, Fig. 3 presents its fragment characterizing only four potential prospective states of the national energy sector at each time sample.

C. Estimation of a rational trajectory in terms of energy security

Estimating the cost of each of the potential options of the national energy development, we can identify a trajectory that is rational in terms of cost minimization and potential shortage of energy resources for consumers from the complete graph, Fig. 4.

We can comment on the selected trajectory as follows.

In 2016, Russia generated approximately 197 bkWh of nuclear power, of which Siberia produced 0 kWh and the Far East - 0.2 bkWh. According to the selected trajectory, by 2020 the total generation of nuclear power could make up nearly 210 bkWh, including 208 bkWh in European part, 1 bkWh in Siberia and 1 bkWh in the Far East. As the trajectory suggests, by 2030 the total production of nuclear power could amount to 250 bkWh including 247 bkWh in European part, 1 bkWh in Siberia and 2 bkWh in the Far East.

The trajectory of moderate development of nuclear power in Russia's European part is less favorable from the production of nuclear energy in the European part could amount to 200 bkWh by 2020 and no more than 210 bkWh by 2030. This situation does not allow us to approach the better structure of the incoming part of the national energy balance.

In 2016, Russia produced approximately 641 bcm of gas, including 589 bcm in European part and in the Urals (including the Tyumen region), 19 bcm in Siberia and 33 bcm in the Far East. According to the chosen trajectory, by 2020 the total production of natural gas and associated petroleum gas could be around 660 bcm, including 590 bcm in European Russia and in the Urals, 30 bcm in Siberia and 40 bcm in the Far East. By the year 2030, the total production of gas could approximately make up 700 bcm, including 600 bcm in European part and in the Urals, 50 bcm in Siberia and 50 bcm in the Far East.

Intensive development of natural gas production in Russia's European part would be too expensive. Given the reduction in natural gas production at the currently operating fields, it is practically impossible to intensively increase gas production. The trajectories of moderate development of natural gas production in Siberia and the Far East are less favorable from the standpoint of energy security. With other (in comparison with the chosen) development trajectories, the production of natural gas in Siberia could be 20 bcm by 2020 and no more than 30 bcm by 2030. In the Far East, these values could be 35 bcm and 40 bcm, respectively. Such a situation does not allow us to achieve a better structure of the incoming part of the energy balance in these regions of Russia.

In 2016, Russia produced 386 mln t of coal, of which 330 mln t was produced in Siberia and 40 mln t - in the Far East. According to the chosen trajectory, by 2020 the total coal production could make up 400 mln t, including 20 mln t in European part, 330 mln t in Siberia and 50 mln t in the Far East. By 2030, as the trajectory suggests, the total coal production could be about 450 mln t, including 40 mln t in European part, 340 mln t in Siberia and 70 mln t in the Far East.

The chosen trajectory indicates the need for an intensive increase in the production of steam coals in Russia's European part and the Far East. This should lead to a better structure of the incoming part of the energy balance of the regions and the strengthening of their energy security. With moderate development, the production of steam coal in the European part of the country by 2020 could be 18 mln t, and by 2030 - no more than 30 mln t. In the Far East, these values could be 45 mln t and 50 mln t, respectively. These values are not enough to achieve these goals. Given the limitations on the railways capacity, intensive development of coal production in Siberia is inappropriate.

IV. Conclusion

It is not necessarily the case that the obtained trajectory (for example, the one presented in Fig. 4), which is "rational" from the viewpoint of energy security, will be rational for the national energy development. The characteristics of the trajectory only demonstrate that, for all of the considered conditions, the other lines of development will be either more expensive or worse in

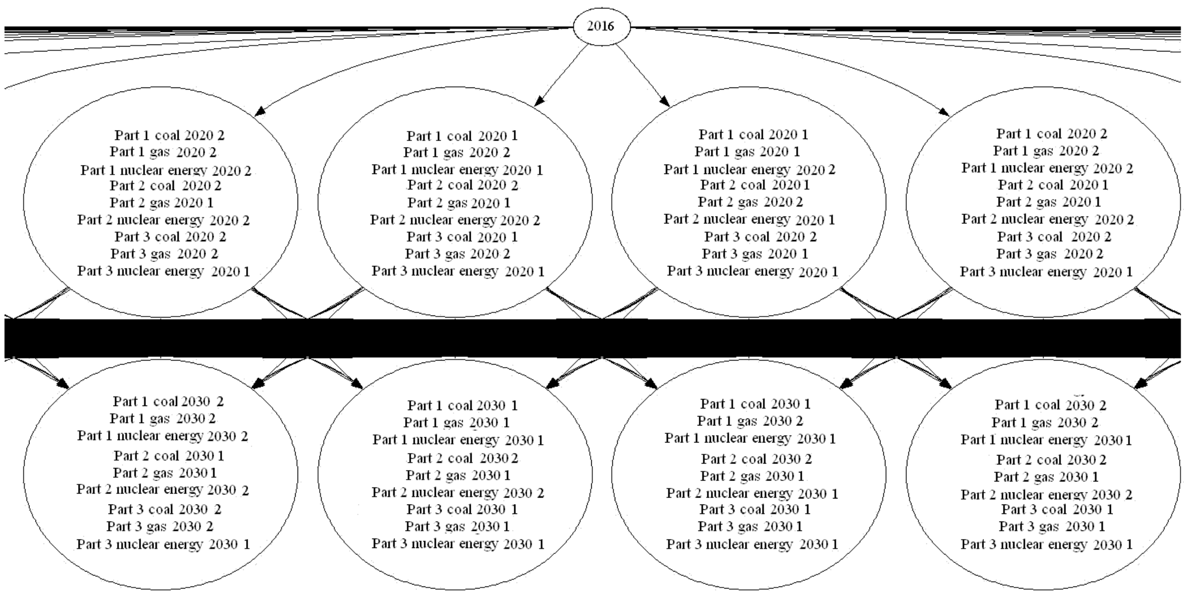

Figure 3. Fragment of a graph of possible energy development in the country.

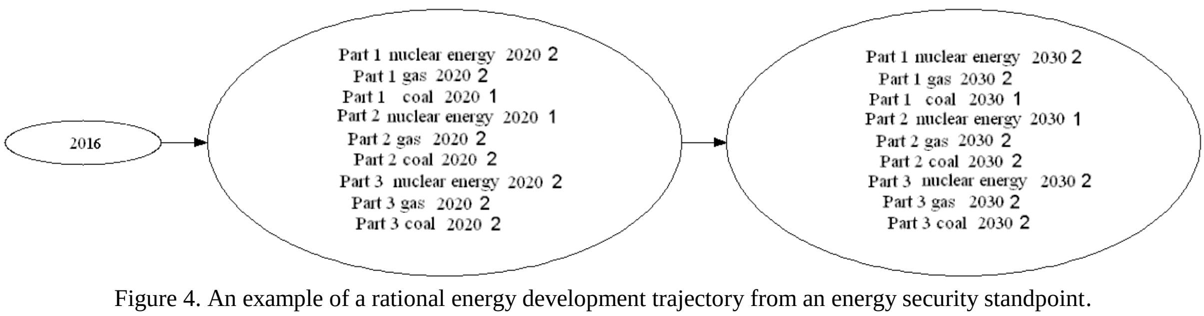

Figure 4. An example of a rational energy development trajectory from an energy security standpoint.

terms of energy security in certain aspects. Experts may consider the lines of development close to the "rational" trajectory to be even more interesting in terms of the country and its future economy. However, this is the goal (and the final stage of the algorithm suggested above) - to develop as many trajectories of energy development, which are rational in terms of energy security, as possible, and determine the general lines for the adjustment of the suggested solutions (prepared by the corresponding governmental institutions) for the national energy development, which would take into account the energy security requirements.

In the given example oriented towards Russia, the determining elements for the construction of possible trajectories of energy development were represented by certain regions and their energy strategies. The approaches suggested above can also be applied to other countries, where other elements can serve as determinants. For instance, in countries importing fuel and energy resources, where energy security issues are especially urgent, these determinants can be represented by the types and amounts of the used fuel and energy resources, places and amounts of their purchase at different time points, and necessary levels of diversification of fuel and energy supplies.

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Impacts of Risk Perceptions on Foreign Direct Investment in Energy Generation and Transmission Projects in Russia

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***Abstract* — This paper deals with an issue relevant for Russia's energy policy, namely, the need to attract private investment, including foreign direct investment, in renovation and upgrading of energy infrastructure. Based on the survey that involved private investors from several countries, the paper addresses the question of how investors perceive private investment risks existing in Russia. Further, the conclusions are made about how these perceptions might affect private investment in energy systems projects in Russia. The results demonstrate that improvements in policy and institutional frameworks are needed in order to attract private investment, especially, in such projects with medium and long-term planning horizon and return of investment as deployment and upgrading of energy generation and transmission infrastructure in Russia.**

***Index Terms* — energy policy, foreign direct investment, Russia, risk perceptions, energy generation and transmission projects**

I. Introduction

Energy is vital to cover mostly all kinds of basic needs, including food, water, communications, transportation and safety. Investment in energy generation and transmission projects is also a driver for well-being and the quality of life, and a source of employment opportunities as well as for multiplier effects on socio-economic development. Energy is a critical infrastructure, which is essential for functioning of all energy dependent infrastructures and is vital for functioning of a modern society. Energy is also one of the most important economic sectors in Russia, which contributes a significant share of the country's domestic product, being an engine of economic growth and energy trade revenues holding a major part in the country's balance of trade.

The development of the energy sector in Russia nowadays is also affected by a number of problems. One of the problems is the aging of energy infrastructure and the need of new investment in its renovation, replacement and diversification. Considering high volumes of necessary investment, involvement of private capital seems to be essential. However, current level of private investment in renewable of energy infrastructure is not sufficient, which can be explained, among other factors, by how private investors perceive risks existing in the sector and profitability of investment.

For instance, during the last five years the volumes of investment in energy sector renovation and diversification were only around 60 percent of the necessary volumes identified by the Energy Strategy of the Russian Federation [1]. The Energy Strategy places an emphasis on the need to increase volumes of private investment in energy infrastructure renovation and the need to improve economic and regulatory environment for investment to secure reliable energy supply.

The volumes of foreign direct investment (FDI) in Russia, as a kind of private investment, were volatile during the last decade. In the year 2015 Russia experienced the low inflows in comparison to the year 2014 due to different reasons such as dynamics in the oil prices, devaluation of national currency, financial sanctions or single large-scale deals, which were concluded in the year 2014. In the year 2016 inflows surpassed the outflows but mainly due to a major single investment, when some shares of Rosneft were sold to a Singapore joint venture. The drop of FDI in the last decade might be also due to the perceived high political and policy risks. We are testing this assumption in our research.

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Another assumption is connected with the regional integration processes, namely, the formation of the Eurasian Economic Union (EAEU) and how this regional integration affects perceptions of political risks. EAEU was created on January 1, 2015 on the basis of the Customs Union (2010) and the Common Economic Space (2012). On February 2, 2012, the Eurasian Economic Commission (EEC) started its work. The member states of the Eurasian Economic Union are: Russia, Belarus, Kazakhstan, Armenia and Kyrgyzstan. The EAEU population is 182.7 million people. In 2016 the total volume of foreign trade in goods of the EAEU member states with third countries amounted to USD 509.7 bln, including exports –USD 308.4 bln, imports – USD 201.3 bln. Volume of mutual trade in goods of the EAEU member states amounted to USD 42.5 bln.

Since 2011 several common markets of the EAEU have been launched. Among them are: the common market for goods of the Customs Union (2011); the single services market of the EAEU and the common labor market of the EAEU (2015); the common medicines market of the EAEU and the common market for medical products (2017). In next few years the following common markets of the EAEU will be created: the common electricity market of the EAEU (2019); the common market of excisable goods (2020); the common oil and oil products market of the EAEU; the common gas market of the EAEU, as well as the common financial market of the EAEU and the common market of transport services of the EAEU (2025) [20].

This paper contributes to the discussion about energy policy measures to stimulate FDI in Russia. The results on subjective risks perceptions are relevant for FDI in projects with the medium and long-term planning horizon, such as energy generation and transmission projects. We contribute to the discussion about barriers to FDI in Russia by providing an insight into subjective risk perceptions and factors, which are perceived as a largest barrier to FDI in Russia, as well as into the impact of regional integration processes on risks perceptions.

II. Background

A. Impacts of risks perceptions on foreign direct investment

The perception of risk is one of the most important factors, which influence the decision-making process of an investor. Risk is perceived as a consequence of an event and as a likelihood of this event to happen. When an investor perceives an investment to be too risky, he or she would require a higher risk premium, a government or a bank guarantee to compensate for the risk. In the event that neither of these three risk mitigation instruments are available, an investor will decline such investment. In science, such a behavior is known as risk aversion [2]. Risk aversion is closely connected with "risk perception" which is a subjective evaluation of risk and can vary, depending on experience, world views and visions [3].

The majority of the existing studies on private investment suggest that the decision to take an investment or not depends on economic factors and favorable institutional environment [4]. However, most of these studies dealt with quantifiable impacts of these factors by using statistical methods of analysis. The works on qualitative factors, such as how existing cultural, institutional, political or economic factors influence risk perceptions of private investors, were minor [5].

Several scientific studies show that risk aversion is an essential part of the decision-making process and that several qualitative factors influence risk perceptions. For example, the authors of [6] identified several factors that influence risk aversion. Among them are quality and standards of bureaucracy, regulations and complexity of contracts. The scientific evidence [7] finds that quality and complexity of bureaucracy affect risk aversion as it is connected with uncertainty for investment. Another study [8] adds to this the generic host bureaucracy quality as well as tax complexity [9]. Cultural factors, such as perceptions of impacts of religion [10] or cultural differences in traditions [5] have also an impact on risk aversion.

By looking at the risk aversion and risk perceptions connected with investment in the Central European transition economies, we identified three types of risks. They were mostly connected with the governance issues and included instability of national regulations, absence of guarantees from national government on invested capital and revenues as well as political instability and the lack of support from local government [11].

There were a number of global studies on the impact of uncertainties connected with regulatory and political risks in Russia [12] [13] [14]. The majority of existing scientific studies on risks and impact on investment deal with different regions. However, only a minor share of these studies deals with the former Soviet Union countries. The majority of existing studies on transition economies focus on the investment risk in the Central and Eastern European countries, which recently joined the European Union [15].

The Ease of Doing Business developed by the World Bank is probably the most known evaluation of the factors of risk aversion in relation to private investors. The Ease of Doing Business includes time and costs which investors need to deal with logistics of trade. According to this index Russia is at the lower half of the ranking even despite a number of reforms, which have been conducted since the year 2012 to simplify documentation needed for transactions, to reduce the associated costs and implement electronic documentation system. The costs of border regulations remain the most problematic factor. In the other areas, such as starting business or dealing with insolvency, Russia ranks above the average for transition economies. The same concerns the enforcement of contracts or registration of property.

This evaluation, in turn, has an impact on risks perceptions. For example, the Doing Business rank of a country influences perceptions of regulatory environment and influences investment decision [16].

The authors of [17] identified four factors, which influence risk perceptions of FDI in the projects in Russia. These factors include political, revenue, operational and regulatory risks. Interviews with investors, conducted by researchers, show that political risks are perceived as most serious and likely risks for foreign direct investment.

However, there were no studies on perceptions of probability and likelihood of risks. Moreover, the identified risk perceptions, which are relevant for private investors, were not discussed in regards to the private investment needed for renovation and replacement of energy infrastructure.

B. Energy policy in Russia

Fossil fuels play an essential role in the energy policy of Russia, given the abundant gas, coal and oil resources available in the country. Currently Russia holds 32 percent of global natural gas reserves as well as 10 percent of explored coal reserves and 12 percent of oil reserves [18]. Russia also has large oil shale reserves, and is a large nuclear energy producer generating over 5 percent of the global nuclear energy. Renewable energy sources are represented in Russia mainly by hydropower energy, which contributes to 21 percent of electricity generation, with the largest hydropower potentials in Siberia and the Far East. Despite available potentials for other kinds of renewable energy, currently renewable energy sources contribute a minor share in energy generation and these are mainly small-scale projects.

Today Russia is one of the largest energy exporters in the world. Energy trade also plays an important role for the Russian economy, by contributing to around 60 percent of the Russian export and providing around 30 percent of the Russian Gross Domestic Product. The European Union countries, such as Germany, Italy, France and Hungary, are the major trade partners of Russia supplying 25 percent of the EU gas consumption. Russia also exports electricity to Latvia, Lithuania, Poland and Finland. Plans also exist to increase energy exports to the Eastern energy markets, including China, Japan, Korea and other countries of the Asia-Pacific region.

The energy market of Russia is dominated by a number of large-scale, mainly state corporations. For instance, the natural gas market is divided among four companies (Novatek, Itera, Northgas and Rospan), the oil market is divided among seven companies (Rosneft, Lukoil, TNK-BP, Surgutneftegaz, Gasprom and Tatneft), the nuclear market is dominated by Atomenergoprom, which is a holding of a couple of companies, and the electricity market is dominated by InterRAO and Gazprom Energoholding. If there is a minor tendency to liberalization on energy generation market, energy and electricity transmission and distribution markets are dominated by monopolies with the state control.

The energy policy and energy investments in Russia are regulated by the Energy Strategy, which was adopted in the year 2000 for the period up to 2020. The additional commitments from the year 2006 for the period up to 2030 indicate the need for new guidelines for development of energy sector in light of the increased role of innovation in the Russian economy as well as the special attention to energy development in the regions of East Siberia, the Far East, North-West, Yamal Peninsula, and the continental shelf of Russia. The current Energy Strategy of the Russian Federation up to 2030 was adopted on the 13th of November 2009.

Despite important role of energy in the economy of Russia and positive balance of trade, private investment, especially FDI in gas and electricity sector remains small. In the year 2016 Russia attracted EUR 439 billion of total FDI, from which EUR 9.7 billion went to electricity and gas sectors. The share of FDI which went to mining and quarrying was ten times higher, namely, EUR 98 billion [18].

One of the aims of the Russian energy strategy is to improve regulations for stimulating private investment in energy sector. The strategy also includes mechanisms to achieve this aim, namely, tariffs, taxes, customs, antimonopoly regulations and institutional reforms. The strategy also identifies strategic directions for development of the energy sector in Russia, including 1) transition to innovative and energy efficient development, 2) changes in structure and scale of energy production, 3) development of competitive market environment and integration into world energy system [1].

III. Methodology

The methodology of this research is based on qualitative data collected in frames of a dialogue between stakeholders and foreign investors from several European countries, including Austria, Germany, Lithuania, France and others. The data were mainly collected through questionnaire, which recommended itself as a method free from interviewer bias [19].

The stakeholders dialogue included a questionnaire with structured and semi-structured questions. The structured questions included the multiple choice options where respondents could provide their evaluations of a given factor on the scale from "very bad" to "very good" or on the scale from "not significant" to "significant". The risks were evaluated according to the seriousness of concern about them and perceptions about their likelihood.

The questionnaire was developed based on a review of existing literature on FDI risks and factors that influence the investors' decision. These included institutional, economic, political and cultural factors. Russia was among five countries evaluated in this research. Other countries were Azerbaijan, Kazakhstan, Kyrgyzstan and Ukraine. The questions were developed according to the methodology of social research, namely, proceeded in logical sequence moving from easy ones to more difficult ones. All technical expressions were explained and demographic personal questions were placed at the end of the questionnaire [20].

The data collection was performed in the period from August to November 2017, and involved questionnaires and stakeholders dialogue. The respondents were from different economic sectors such as financial services (23 percent), production of consumer goods (17 percent), energy production and distribution (15 percent), agriculture (12 percent), automotive sector (10 percent), industrial equipment and machinery (8 percent), construction and real estate (7 percent), telecommunication (5 percent) and transport (3 percent). The questionnaire was distributed through online survey tool as well as in a printed version during the workshop with representatives of the Schneider group, which is a part of the Lisbon to Vladivostok group (L2V) and is an association of companies working in the European and EAEU regions. The stakeholders dialogue also took place during the workshop. The workshop was conducted at IIASA in October 2017. The printed version was also sent to stakeholders by mail. Altogether we distributed 207 questionnaires through online survey. This number also includes participants in the workshop. We received 26 completed questionnaires, from which 2 were disqualified due to missing answers to some questions. Thus, the response rate is 10 percent, which is typical of online surveys. Indeed, the number of questionnaires would be sufficient for an in-depth qualitative study, however, we argue that here the number is also sufficient for the goals of our research as we addressed a very targeted group of stakeholders. As evidenced by scientific research, the results could be considered to be robust from a smaller sampling when this sampling is well selected.

The questions were scored on the 0-5 point Likert scale (never, very low, low, moderate, high, very high) to avoid risky skewness [21]. The results were analyzed with the help of the statistic programs such as SPSS. The Cronbach's alpha coefficient was applied to investigate the questionnaire reliability.

IV. Results

While speaking about economic and institutional factors as a framework for private investment in Russia the majority of respondents think that business environment in Russia for private investment is very good. Most of them perceive the economic factors to be also good. At the same time, a significant share of respondents evaluates institutional factors as poor (Figure 1).

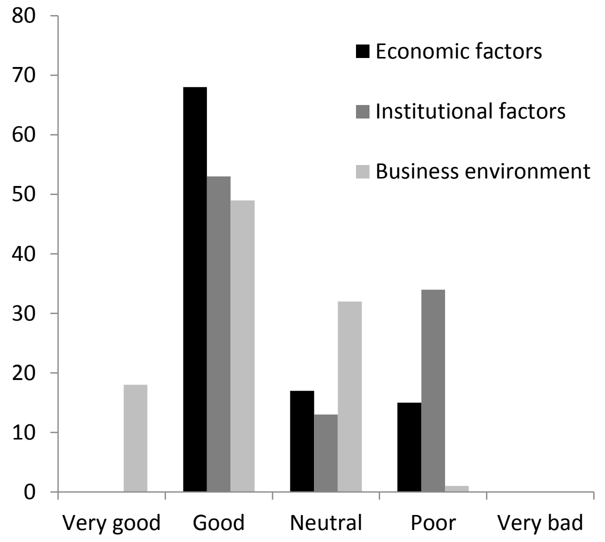

Figure 1. Economic, social and business environment factors.

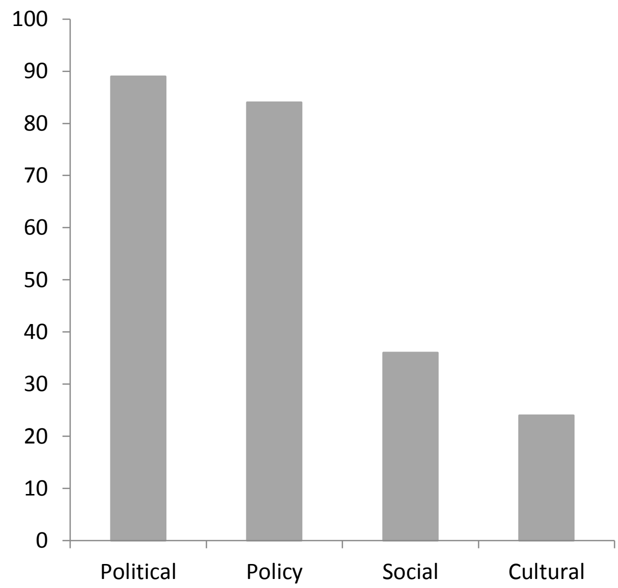

Figure 2. The perceived difference between political, policy, social and cultural factors in Europe and in Russia.

Further, respondents were asked to evaluate political, policy, social and cultural factors in Russia and compare them with these factors in the countries of the European Union. The aim was to understand how large is the perceived difference between these factors in Russia and in Europe and if respondents perceive this difference as a barrier to private investment in Russia. The results indicate that respondents think that political factors and policy have the major difference to the European countries. At the same time cultural and social factors were perceived to be more similar (Figure 2).

Our results demonstrate that private investors perceive financial and governance risks to be the most significant risks (Figure 3).

The financial risks included the competitive pricing, the time and cost of bidding, bank and financial services as well as the level of equity, external indebtedness, achieving financial closing, joint control with the banks, cost overruns, generation of cash flows and securing operational cash flow. From them the risk to generate not sufficiently attractive rate of return as well as the risk to keep the joint control with the banks over assets were perceived as the most serious in terms of their impact on FDI.

The likelihood of political risks was perceived to be very high in Russia. Namely, over 90 percent of all participating respondents think that the political risk in Russia is likely. The high likelihood of regulatory risks is perceived by the lower number of respondents (85 percent), followed by the revenue risks (75 percent) and the operational risks (60 percent).

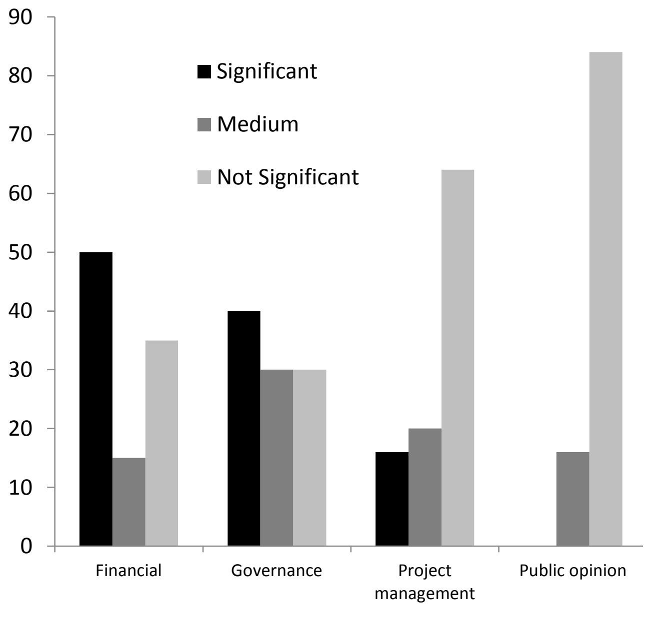

Figure 3. Seriousness of concern about the financial, governance, project and public opposition risks.

Therefore, the governance risks, including the political risks, were perceived as the most likely risks in Russia. However, the financial risks, including the generation of attractive rate of return, were perceived as the most significant.

V. Discussion

Scientific literature shows that the willingness of foreign investors to participate in medium and long-term planning horizon projects in Russia, such as energy generation and transmission projects, depends on perceptions of risks for this investment. In the event that risks are perceived as serious or likely, investors expect higher risk premiums to compensate for the risk or refrain from the investment. Therefore, the investment decision depends on combination of two elements such as the occurrence of a negative event and the level of financial impact [22].

Our results demonstrate that the financial risk is the most significant in terms of impact on investment. At the same time the political risk is the most likely risk in Russia. The risk of public opinion, under which we mean possible public opposition due to concerns about the need for projects or their location, as well as concerns about distribution of risks, benefits, costs and the engagement possibilities, was not perceived to be significant. In this research, we have not identified why this is the case, due to the lack of concerns or due to available participation options and the loss of hope to be heard and to have an opportunity to contribute to the decision-making process.

The respondents perceive the difference between Russia’s political framework and policies and those in the European Union as one of the major obstacles to FDI. This also correlates with estimations of the institutional frameworks provided by our survey when the development and state of institutional framework was perceived as the most problematic area among three evaluated areas such as economic factors, institutional factors and business environment. The dominant role of state-owned, often monopoly companies is one of the reasons behind the large role given to political and policy risks.

Our results allow evaluating perceptions of European companies which deal with private investment in Russia. They indicate the areas where efforts are necessary to increase attractiveness of private investment in medium and long-term horizon planning projects such as energy generation and transmission. The efforts are mainly necessary to improve the institutional frameworks and to balance the difference in political and policy environment of Russia and the EU [23].

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The Effect of Length of Forecast Horizon on Rational Aggregation in Long-Term Forecasting of Energy Systems Development

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***Abstract* — The paper examines the rational aggregation of models that are employed to address energy sector forecasting challenges specific to various forecasting time frames. Possible approaches are proposed. The paper concludes with estimates of the potential impact of the magnitude and nature of input data uncertainty on forecast and aggregation errors.**

***Index Terms* — aggregation, energy sector, forecast error, forecasting time frame, Monte Carlo simulation, uncertainty.**

I. Introduction

The ongoing shift to the new social and technological order, the accelerating rate of scientific and technological advance, drastic changes that are expected to take place within the structure of energy production and consumption, changing requirements to environmental and energy security all contribute to the growth of uncertainty with regard to future conditions of the energy sector development. Obviously, the longer the forecasting time frame, the more uncertain are future conditions and the less reliable are forecasts.

Published forecasts of energy sector development in the USA and Europe that are made for 15 - 20 years ahead prove the non-linear nature of the escalation of the uncertainty range as the forecasting time frame extends (see Fig. 1). The minimum to maximum range of values of primary energy consumption volume in the USA for all cases and scenarios covered by the forecasts grows from the low 5-10% for the 5-year time frame to the high 13-23% and 22-38% for the forecasts made for 15 and 25 years ahead, respectively. The "Energy Strategy of Russia to 2030" (approved in 2009) claims that the difference between total energy consumption volumes under the worst and the best case scenarios amounts to 7% for the first 5 years and subsequently grows to 22% and 31% for the forecasts made for 15 and 20 years ahead, respectively. One of the lines of research undergoing active development and aiming at making long-term forecasts more evidence-based is the growing sophistication of research tools.

The state of the art of computer and information technologies makes it possible to build arbitrarily complex systems of models. However, under enormous and ever growing uncertainty of input data the following considerations are likely to challenge the practicality of making research tools ever more complex: 1) more granular treatment of data, increase in the number of entities subject to forecasting, and disaggregation of employed models all require additional information inputs,

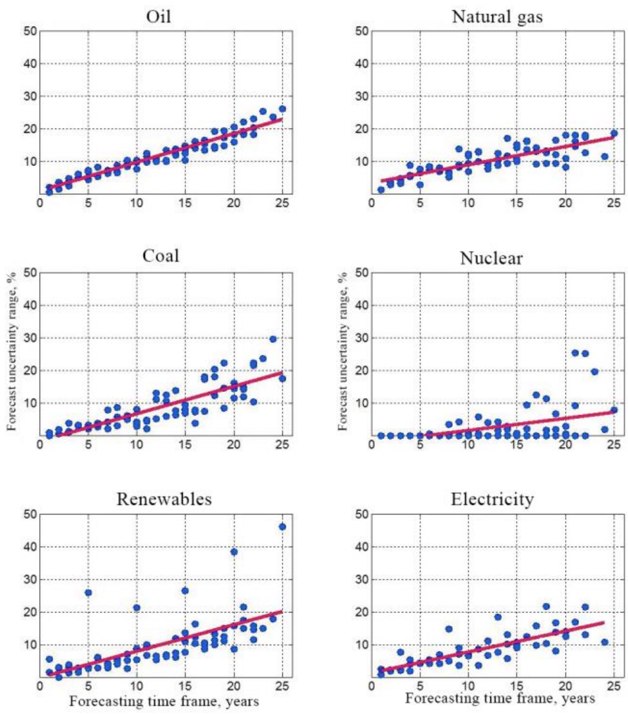

Figure 1. The uncertainty ranges of forecasts of the US energy consumption volumes as a function of forecasting time frames.

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which increases the likelihood of a higher forecast error; 2) merging industry-level and regional systems and models within a unified system of models with fully automated calculations entails the problem of the optimality criterion that these models are to share; 3) the more complex such systems of models grow the more difficult it is to track and interpret unforeseen results; and, finally, 4) a high opinion of the complexity of the tools oftentimes results in excessive and unjustified confidence in long-term forecasts.

The above and other deficiencies are all the more poignantly manifest themselves when the very same models that share the identical level of aggregation are applied to forecasting of the energy sector development for both medium-term (up to 10-15 years) and long-term forecasts.

A key principle that guides systems studies and the process of improvement of research tools is the trade-off between the required precision of calculation results and the precision of the information used to generate them [2]. The principle is analogous to the well-known Occam's razor principle and assumes building models that are as simple as possible yet capable of accounting for defining properties of the studied system that are required to appropriately tackle the task under given conditions. This echoes the following quote attributed to Albert Einstein as well: "Everything should be made as simple as possible, but not simpler" [3].

Striving for utterly comprehensive while mathematically tractable treatment of development dynamics and non-linear relationships within the studied system as well as the detailed representation of its structure can go against the grain of the inherent uncertainty of input economic data and the mutable nature of properties of complex systems that are being modeled, which can even entail negative outcomes.

The principle of correspondence between research tools and actual uncertainty of the input data fed into them as well as the required degree of forecast accuracy has so far been implemented based on intuitions held by model developers and model users and remains more of an art than a science. A more evidence-based approach to the implementation of the principle can be developed by means of the quantitative analysis and juxtaposition of the actual uncertainty of input data and the import of calculation results obtained thereby in order to identify possible issues and make decisions more substantiated. It is obvious that the value of forecasts and requirements for their validity depend on the forecasting time frame and the actual problem being solved.

The time-honored tradition is to treat the aggregation problem as a problem of reducing the dimensionality of a model so that the losses of information generated by the model are kept to a bare minimum. It appears that given large uncertainty of input data and large dimensions and complexity of forecasting models it is reasonable to raise the problem of the rational aggregation of such models. To this end, it is necessary to account not only for the magnitude and nature of the input data uncertainty, but also for the possible and maximum acceptable error of key variables to be forecast. There are no such versatile methods that can be applied to solving the problem for an arbitrary system and an arbitrary time frame.

This paper covers possible approaches to rational aggregation of optimization models employed for long-term forecasting of the national energy sector development and regional energy supply systems. These approaches include the following: an evaluation of the input data accuracy (its uncertainty range), a study of the effect that various aggregation levels of these data and models have on the results generated by multi-variant calculations, an identification of an acceptable accuracy level for the variables to be forecast.

II. Aggregation In Long-Term Forecasts Of The National Energy Sector Development

To illustrate the above, it will suffice to refer to the beginning of the widespread use of optimization models back in the middle of the 20th century with the emergence of more elaborate computerized systems of models built on top of them in the decades that followed (see e.g. [3,4]). In a number of cases, their composition and the level of aggregation remain independent of the length of the forecast horizon.

The principle of correspondence between research tools employed and the uncertainty of input data is fulfilled by a multi-stage approach to narrowing down the uncertainty range of conditions and results of forecasting studies [5,6]. The approach implies the multi-stage narrowing down of the length of the forecast horizon, iterative calculations generated by models of various hierarchical levels used to handle specific forecasting time frames, and the reconciliation of totals in time. In doing so, the initial stage covers the time range of over 15-20 years and the minimum number of levels and models (see Fig. 2). It is worth noting that most of the models of energy-related industries development and those of regional energy supply systems are optimization models.

Iterative calculations (carried out in top-down and bottom-up fashions) make it possible to account for features specific to the development of systems of various hierarchical levels that make up the integral national energy system. Within each of the time frames, it is the problems that are deemed most significant that are to be solved. To this end, there are various possible aggregation levels for the energy facilities, energy links, and geographical areas that are subject to being modeled.

When using multi-level systems of models, one can employ well-known methods of iterative aggregation [7,8,9].

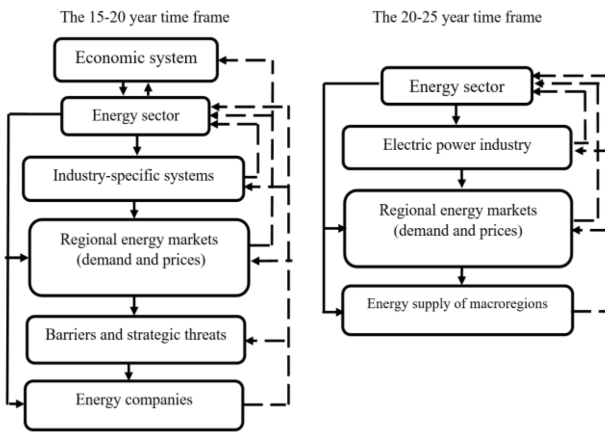

Figure 2. Interactions between hierarchical levels, problems, and models specific to various time frames of long-term energy sector forecasting studies.

In Russia, methods of iterative information aggregation in hierarchically built systems of models underwent active development in the 1970s and 1980s. Back then they were applied to the coordination of decisions generated by industry-level and regional model hierarchies of energy systems that account for both producer and consumer behavior patterns [12,13]. Such methods assume aggregation and disaggregation of all interrelated models at each iteration step. In so doing, the end of calculations is marked by achieving an acceptable level of aggregation. The latter is defined as the optimality criterion for the upper level model taking the same value for two successive iterations.

The limitation inherent in such an approach is that multi-level model systems that are designed to forecast the national energy sector development, have different top-level models for medium- and long-term forecasts (see Fig. 2) with each of the hierarchical levels applying their own optimization criteria. Furthermore, under major uncertainty, there is no need to strive for the perfect match of results of iterative calculations.

It may be feasible to favor separate aggregation of models for each hierarchical level over their combined aggregation. To this end, it is possible to implement the following calculation steps:

1. Building a basic (reference) model that is as comprehensive as possible in its most detailed consideration of energy system facilities, energy links, and system properties.
2. Using multi-variant calculations to identify the input data that have the most decisive impact on key variables to be forecast.
3. Estimating the input data uncertainty range. The estimates are possible to attain if assisted by an analysis of available forecasts of their assumed behavior. Such analysis when backed by expert judgment can also provide insights into the nature of the data uncertainty (a probability distribution of values of a given variable within a certain uncertainty range).
4. Finding an approximate value of the minimum possible calculation error for the reference model calculations under given uncertainty of input data. This value can serve as a reference point for the minimum forecast error, which is always larger than zero.
5. Benchmarking calculation results under a varying level of model aggregation against reference model calculation results, and identifying corresponding aggregation errors.
6. Based on the results of a comparative analysis of such errors against the allowed (acceptable) error one arrives at a rational level of model aggregation.

III. Aggregation Of Geographical Areas In Long-Term Forecasts Of The Electric Power Industry Development

Models and methods used to substantiate development strategies of the Russian electric power industry are covered in sufficient detail in [14]. When optimizing the power generation mix 10 to 15 years in advance, one accounts for power plant operating conditions and cross-system flows of generation capacity and power. This calls for highly detailed optimization models. A case in point is the well-known SOYUZ model [15] that treats the national territory of Russia as divided into regional energy systems. A system of models used for long-term forecasting of the national energy sector, the rational electric power industry development can be represented in a less aggregated way.

This class of models includes MISS, a stochastic statistics-based simulation model and its software implementation [16]. The model is developed to tentatively assess the competitiveness of available types of power plants and options to fulfill the energy demand of macroregions under ambiguous information on expected conditions.

The optimality criterion used in this model is the minimum cost of power generation (production) in a given region under the following constraints: the demand for electric power in a given area, its export or import potential, the capacity of already operating plants and the potential for generation capacity additions for various types of power plants, and constraints on gas production and supply in the area. All of the above constraints are specified as ranges of possible values. The upper and lower boundaries of possible values are also provided for fuel prices, capital intensity, and technical and economic indicators that influence the cost of electricity.

Variables of interest of the model are as follows: the capacity of new power plants, the amount of electricity they generate, consumption volumes for various types of fuels, producer prices at each of the plants as well as the weighted average and marginal electricity generation price in a given region.

To account for information uncertainty, one has to generate and study multiple optimal solutions (hundreds thereof) under various combinations of input data. This implies the use of well-established repeated random sampling Monte Carlo methods (experiments) by the MISS model.

When possible combinations of input data values (all treated as interval estimates) are generated, the numeric parameters that define the type of probability distribution of values within the ranges are varied. This allows generating random variables of the most diverse types of probability distributions ranging from uniform to normal, to lognormal, to exponential, etc.

The MISS model was used to estimate the effect of aggregation on the mix of generation capacity additions and the generation cost in European Russia and Siberia [17].

For basic models, each macroregion was made up of six regional energy systems so as to account for energy and fuel supply conditions and cross-system energy links specific to them. During the aggregation process, the six regions were consolidated into a single macroregion. In doing so, instead of specific uncertain ranges of fuel prices we used generalized ones as well as overall constraints on the maximum possible additions of gas-fired, coal-fired, nuclear power, and hydroelectric plants.

It follows from the calculations (see Table 1) that model aggregation leads to the increase in the error of the electricity cost calculations by a mere 1-2%, while the uncertainty of the electricity cost forecast itself is approximately twice as low as the fuel cost forecast error for balancing power plants in a given region. The effect of aggregation on the mix of electricity generation capacity additions is much more pronounced. The corresponding share of combined cycle gas turbine (CCGT) plants grows by 1.2-1.5 times.

The aggregation error increases when a fixed range of probable values is fed into the MISS model which are assumed to be best modeled not as a normal distribution but as interval (uniform) uncertainty. The error also increases as the input data uncertainty range extends, which is inevitable when the forecasting time frame grows larger (see Table 2).

In the long run, it is power plants of emerging types that will play an increasingly important role. That is why as the forecasting time frame increases, the impact of model aggregation on the mix of electric power generation sources will remain more significant than that on the projections of electricity prices.

The calculations carried out using the MISS model demonstrate that under assumed conditions the level of investment risk associated with options of electric power supply in Siberia is higher than that in European Russia. The risk level of investing in a given plant was defined as an inverse value of the frequency (probability) of its inclusion in optimal solutions generated by multi-variant calculations.

Table 1. Deviation of aggregated model calculation results relative to reference values.

Input data specification	Electricity price		Share of CCGT plants	
	European Russia	Siberia	European Russia	Siberia
Average values	1	0.5	6	9
Normal distribution	2.1	0.1	12	10
Interval uncertainty	2.4	0.2	18	12

Note: Calculation results are for the assumed 2020-2025 conditions. The deviation is presented as percentage, while structural changes (the share of CCGT plants in the total added generation capacity of power plants) are in percentage points (pp).

It is reasonable then to assume that energy supply forecasting studies for the regions of higher investment risks should be carried out with reliance on more granulated (less aggregated) models.

IV. Approaches To Judging Acceptable Accuracy Of Forecasts

Multi-variant calculations by way of optimization and stochastic models enable plotting the curve of changes in the model's objective function values and key variables to be forecast as a function of the aggregation level. It is more challenging to identify an acceptable level of the forecast error. As of now, there are no versatile methods that would provide such an assessment. Therefore, in practice one has to trust one's intuition backed up by the knowledge of task-specific factors and one's accumulated experience.

One of the major objectives of long-term forecasts of

Table 2. The effect of the increase in the uncertainty range and the average gas price on calculation results generated by reference and disaggregated models.

	Units	Gas price increase, %		
		5	10	25
Average electricity price				
before aggregation	%	2	4	12
after aggregation	%	3	5.5	14
Decrease in the CCGT plants share				
before aggregation	pp	14	24	28
after aggregation	pp	13	15	17

Note: Calculated for European Russia.

energy systems development is to provide government agencies on a par with companies with takeaways to be used for making timely investment decisions. To this end, it is crucial to estimate risk and returns of large-scale projects of electricity generation capacity additions. Such estimates have to be based on forecasts of plausible energy price and demand behavior.

The investor values more remote rewards less than more immediate ones. By varying the values of key input data variables for any of the time periods and by estimating the effect of such variations on the project value, it is possible to arrive at conclusions bearing on the acceptable decrease in the forecast precision for more remote time periods within the forecasting time frame.

Such an approach was applied, in particular, to assess the sensitivity of investment projects returns calculated as the Net Present Value (NPV) a) for investment projects of nuclear power plants construction to the changes in demand (production) volume that occur over time and b) for projects of Combined Cycle Gas Turbines (CCGT) construction to the changes in gas prices.

The calculation results (see Fig. 2) show a notable non-linear decrease in sensitivity of the project value to changes in gas prices in more remote time periods. Under assumed input data the surge in demand for electricity by as high as 20% exerts significant effect on the NPV only within the time frame limited by the first 15 years. Accordingly, forecast performance requirements can safely be relaxed for electricity demand forecasts at the end of the nuclear power plant life cycle.

As the length of the forecast horizon extends, requirements for fuel price forecast performance notably relax as well in the case of the CCGT construction project valuation. Even under the scenario of a 1.5-2-time increase in the gas price at the end of the forecasting time frame, the decrease in the project's net present value does not exceed 2-3% (see Fig. 3).

In the case that the results of forecasting studies are used to inform investment decision making, the risk value

Table 3. Correspondence between the uncertainty of input data and forecast performance

Variable	Units	Generation cost		
		CCGT plants	System's average	Marginal
Uncertainty range	cents per kilowatt hour	6.7-7.4	7.0-7.6	7.8-8.1
	%	10.4	8.6	3.8
Correspondence between inaccuracy of data for electricity and gas prices	% / %	0.32	0.26	0.12

Note. Calculations for the energy systems of Siberia with gas prices assumed to fall within the \$100-\$133 / sm^3 range.

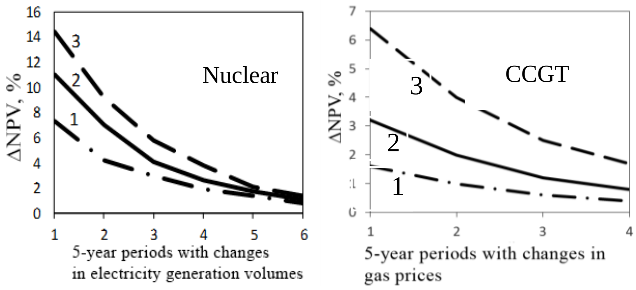

Figure 3 Changes in the project's NPV as a function of changes in the electricity generation volume (an NPP construction project) or gas prices (a CCGT plant construction project) in one of the five-year periods within the forecasting time frame. Increase by 25% - Curve 1, increase by 50% - Curve 2, increase by 100% - Curve 3.

assumed for the project valuation can serve as a plausible reference value, alongside the error inherent in projections of the key variable (for example, electricity prices).

The error for a given time frame can be identified by a sensitivity analysis of forecast variables as they respond to changes in input data within a predefined range of their possible values.

To illustrate this point, Table 3 lists the results of the analysis of the effect that the gas price has on the power plant electricity generation cost. Calculations were carried out using the MISS model as applied to one of the scenarios of Siberian electric power industry development within the 2020 to 2025 time period.

The calculations indicate that under assumed conditions each 1% decrease in the accuracy of a gas price forecast leads to an increase by approximately 0.26% in the minimum forecast error with respect to the average electricity cost.

V. Conclusion

Rational aggregation of models employed in practical forecasting work entails assessing and accounting for the effect of uncertainty of the input data on the probable error in key variables to be forecast. It is also essential to understand what magnitude of the forecast error can be safely deemed acceptable when making timely decisions (be they investment, managerial, or strategic ones).

Obviously, the priority and complexity of efforts to accommodate these factors are determined by the forecasting time frame and the particulars of the problem. The wider the range of the input data uncertainty (that is known to grow with longer time frames), the greater the unavoidable forecast error, which hence makes the use of more aggregated models all the more justified.

The approaches proposed herein to identify rational aggregation of energy facilities and geographical areas in various stages of forecasting studies include: an evaluation of input data accuracy (its uncertainty range) as changing over time, a study of the effect that various aggregation levels of these data and models have on the results yielded by multi-variant calculations, an identification of acceptable accuracy of the variables to be forecast.

As of now, there are no universally applicable methods that would facilitate such an assessment. In the case that the results of forecasting studies are used to inform investment decision making, the risk value assumed for large-scale project valuations can serve as a plausible reference value, alongside the error inherent in projections of key variables. The latter is dependent on the input data uncertainty range and increases as the length of the forecast horizon extends into the future.

Acknowledgement

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A Model for Control of Steady State of Intelligent Integrated Energy System

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***Abstract* — Modern cities and industrial centers boast a developed energy infrastructure, including fuel, electric, heating, and cooling systems. The integration of many separate systems into a single technological entity can provide new functional capabilities, the application of more advanced technologies for operation, and the establishment of intelligent integrated energy systems (IIES). Such systems have a multidimensional structure of functional features and properties of development. They combine a large number of components; intelligence; efficiency; reliability; controllability; flexible use of energy conversion, transportation, and storage technologies; and active demand. The IIES control represents an urgent and a rather challenging task. The paper is concerned with a model for control of a steady state of an intelligent integrated energy system. An algorithm intended for the calculation of joint operating conditions of electric and heating systems when integrated is presented. The results of the research into the joint operation of electric and heating systems are demonstrated on the example of a typical urban area with residential housing that has district electric and heating systems. The obtained results highlight the problems related to separate consideration of expansion and operation of the energy systems, as well as equipment wear and the need to improve the technological and technical level of these systems and use them as a basis for an intelligent integrated energy system.**

***Index Terms* — Intelligent integrated energy system, elements of concept, intelligent integrated energy system control, mathematical modelling.**

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I. INTRODUCTION

Modern energy sector represents a complex infrastructural system, including fuel, electric, heating and cooling systems. Despite various types of services, they render, their common goal it to create comfortable working and living conditions for the population, and to effectively facilitate the development of the national economy. To perform their functions, each of them has their production, transportation and distribution structure connecting them with consumers. They often overlap and compete in the market for energy services. This, in particular, refers to the electric, heating, gas and other systems. Being functionally independent, these systems can interact with one another under normal and emergency conditions, through the interchange of primary energy and use of energy carriers. All this is indicative of their natural integration which grows increasingly stronger with the establishment and expansion of intelligent information and communications systems. Jointly, they represent a new structure, i.e. the intelligent integrated energy system [1, 2]. This structure combines certain independence of the systems involved with their coordinated participation in the accomplishment of the main goal of providing social and economic activities. The information system represents an infrastructural framework for the intelligent integrated energy system.

The intelligent integrated energy systems have a multidimensional structure of functional features and properties of development. They combine a great number of components; intelligence; efficiency; reliability; controllability; flexible use of energy conversion, transportation, and storage technologies, and active demand.

Technological structure of the intelligent integrated energy system should provide:

— Effective integration of renewable energy into the energy system;

— Use of alternative energy sources, the sources operating on hydrocarbon fuels and easily transportable fuels;

— Maneuverability of the system;

— Support of an effective integration of energy and fuel infrastructures.

Conceptually, the integration is performed in three

aspects, in terms of [2, 3]:
— System, representing the integration of systems by type, including electric, heating, cooling and gas systems; in each specific case, either all or some of them can be integrated;
— Space, reflecting the extent of the systems with differentiation into super-, mini- and microsystems;
— Functions, determining the system activity (its purpose). These include energy (technological), communications and control, and decision making functions.

Within the spatial (scale) structures, we consider the following interrelated systems [2, 3]:
— Super-systems, i.e. traditional centralized energy supply systems, including large-scale electricity and heat sources, gas fields, underground gas storage facilities, as well as electric, gas and heat networks;
— Mini-systems, i.e. decentralized (distributed) systems, including mini electricity and heat sources (including those unconventional and renewable) that are connected to the distribution electric, heat and gas networks, and these networks themselves;
— Micro-systems, i.e. individual systems with unconventional and renewable electricity and heat sources, as well as house electric, heat and gas networks.

The functions of the intelligent integrated energy system include:
— Energy functions representing, production, transport, distribution and consumption of electricity, heat/cooling and gas at all levels and scales;
— Communications and control functions representing measurement, processing, transmission, exchange and representation of data, control of operation and expansion of the metasystem;
— Decision making functions, i.e. intelligence of the metasystem, including models and methods for decision making on expansion of the integrated energy systems and adjustment of systems for their control.

All functional properties of the intelligent integrated energy system are strongly interconnected with one another in terms of input and output parameters of states, structure of forecasts, both at the level of operation and at the level of expansion. They form a totally new technological architecture that describes the organization of the metasystem, including the design solutions of its components, their interrelations with one another and external environment, as well as the principles of evolutionary development of such a multi-link structure.

The properties expected to be acquired by the intelligent integrated energy system are:
— Flexibility, i.e. the capability of a system to adapt to a current level of energy consumption, variation in the ambient temperature, considering general changes in the urban infrastructure system, and adequately respond to internal and external impacts;
— Intelligence, i.e. the capability of the system to respond to the consumer needs (reduce or increase energy generation).
— Integration, i.e. the system is integrated into an urban environment, both in terms of the city planning and allocation of energy facilities and in terms of interaction among all systems of life support services of a city (electricity, heat water, fuel systems; sewerage, etc.).
— Centricity, i.e. control based on a distributed communications network where each component of the system can interact with any other component. Telecommunications network underlies the control.
— Efficiency, i.e. the equipment used meets all the modern requirements of energy efficiency. The maximum efficiency of the system is ensured by an optimal combination of technologies, including the maximum involvement of local energy resources.
— Competitiveness, i.e. the technologies are cost effective and energy resources are available to the population. Consumers can manage their energy consumption to reduce payment for it.
— Reliability, i.e. the system meets a growing demand for energy, in particular, by using renewable resources and local fuels.

II. Literature Review

Various energy supply systems, such as electric, gas, heating and other systems were normally designed and operated independently of one another. The advances in technologies and equipment, the emergence of new conditions and opportunities, however, make the interaction between different types of energy systems much stronger, which leads to a considerably increasing interest in the research on joint operation of these systems. A widely applied approach to study the integrated systems is based on consideration of such systems in the form of an energy hub. For example, in [4] the authors suggest a method for optimal energy generation and conversion in an integrated energy system with different energy carriers, which involves the energy hub conception. This method is widely applied in the studies related to optimal operation and design of integrated energy systems [5, 6].

The determination of an optimal load of generating equipment implies obtaining an optimal schedule of generating equipment startup and shutdown to meet the expected demand, given costs and constraints of a system. In the context of the integrated energy systems, this refers to the optimal startup and shutdown of each generating unit to meet the demand for several types of energy. The authors of [7] propose a solution to the problem of optimal loading of generating equipment based on the energy hub conception. For solving this problem, it is very important to consider the energy storage possibility. The authors of

[8] consider planning of electricity and heat storage as part of the problem of optimal loading of generating equipment. The authors of [9] compare energy and exergy approaches to solve the problem of optimal use of generating equipment.

The problem of the integrated energy system control can also be solved by determining optimal power flow. The determination of optimal power flow is reduced to the load distribution among energy sources, which meets the constraints of the energy transmission system in terms of cost minimization. Solving the problem of optimal power flow in the integrated energy system requires the consideration of the need for several energy types, which is met by using several energy sources and devices for energy conversion, and satisfaction of the transportation system constraints for each energy carrier. The optimal power flow in an integrated electric and gas system was investigated in [10]. For solving this problem, the authors developed a mathematical model in which the objective function is determined by a set of points for various components that are characterized by the minimum operation cost of the electric and gas systems and do not violate the constraints of the electric and gas transportation system. A method for calculation of optimal power flow for the integrated electricity, gas and heating system is presented in [11]. The method is focused on the power flow and optimality condition of Kuhn-Tucker for the case with several energy resources.

The calculation of the optimal power flow for several periods of time is related to the planning of the energy system operation for a set time horizon. In [12], the study is focused on modeling of an optimal power flow coordinated in time for electric and gas system for the case of distributed energy resources. Due to relatively slow flow speeds and specific features of storage in the gas and heating systems, it is important to take into account the dynamic behavior of these energy systems during several periods of time to solve the problems of control and scheduling of the systems. The authors of [13] study a method for calculation of optimal power flow and scheduling for integrated electric and gas systems with a transient model for the natural gas flow. The calculations were performed to compare the solutions obtained with steady state and transient models of natural gas transmission systems. A model of optimal power flow for several time periods was developed to study combined electricity and gas networks in Great Britain [14, 15].

Some studies are focused on centralized and decentralized control of integrated systems. In [16], the authors present the findings of the research into the centralized control, which involves an approach to the control with projection models for integrated energy systems. The central controller determines the actions for each energy hub to ensure better efficiency in terms of stability of transportation system, use of storage devices and forecasts of loads and prices. In [17], the authors propose a hierarchical centralized control of an integrated microgrid. The controller receives the data on transient characteristics of the natural gas flow and operation of energy converters. To take into account the dynamic characteristics of different systems, the controller was divided into three layers: slow, medium-speed and fast. The study is focused on the control of executive mechanisms when the renewable generation fluctuates, start of a conditioner, start of a microturbine, demand response and charge of energy storage. Further, the results of this research were extended to the control of an integrated energy system [18]. A strategy of real-time control of the integrated electric and heating system was proposed in [19]. The strategy of control has a hierarchical centralized architecture and is designed to maintain frequency of power supply system at a level of 50 Hz and a temperature of district heating water equal to 100^0C. An approach to solving the scheduling problem is presented in [20], where optimization is performed for a time period of 24 hours, and a strategy of real-time control compensates for a gap between a scheduled load and a real load by control actions.

Although, the centralized architecture of control can provide the best total energy system performance, its complexity limits its wide practical application. The distributed control architecture divides the common optimization and control problem into subproblems that are solved with individual models. The local control action to be performed, however, depends on the actions of neighboring controllers and should be coordinated. In [21], the authors propose a distributed control system for combined electricity and natural gas systems. The system consisting of several interrelated energy hubs was controlled by corresponding control agents. In [22], these results were extended to the studies of distributed control based on projection models and the use of storage devices in gas systems.

The integration of electric and heating systems is most pronounced in cities and populated areas, and manifests itself in: the combined electricity and heat generation; the use of energy storage systems to ensure flexibility of cogeneration operation; and the use of electric equipment for heat production, transport and distribution. The joint operation and scheduling of electric and heating systems based on cogeneration are discussed in [23]. The interaction between electric and heating systems in the view of the need to ensure the required demand response is considered in [24]. Various electricity and heat supply options were compared when solving the problems of operation and scheduling in terms of techno-economic and environmental indices in [25, 26]. In [27], the authors consider trigeneration systems (combined production of electricity, heat and cooling power).

The sources of combined electricity and heat generation interconnect electric, heating and gas systems. In [28], the authors applied Sankey diagrams to illustrate energy flows through the electricity-heat-gas networks when considering several scenarios for the involvement of cogeneration power plant and heat pumps. The research was also focused on the impact of different technologies on operation of each network. The implications of switching from hydrocarbon fuel to renewables in the electric system for the district heating systems and gas network were studied in [29, 30].

III. Specific Features Of Intelligent Integrated Energy System Control

Control of an intelligent integrated energy system, including electric, heat and gas systems represents a challenging task. The urban infrastructure of centralized energy supply has interacting dispatching services ensuring on-line control of electric and heating systems. The centralized energy supply can be backed up by autonomous energy plants for short-term use in emergencies that can lead to interruptions in the energy supply to consumers.

Operating conditions of heating systems are static and determined by variable heat consumption characterized by inertia. This is a precondition for the consideration and scheduling of heating system operating conditions during some time period (for example, 24 hours long). Unlike heating systems, electric power systems are characterized by dynamics and simultaneity of electricity production and consumption processes. Their operating conditions should be scheduled in real time.

It is convenient to divide electricity consumption into direct and indirect in the case of joint operation of heating and electric systems. The direct electricity consumption is determined by the load of power and control equipment of heating system (pumping stations and electric boiler plants) under normal operating conditions. The indirect electricity consumption is determined by variation in the load of consumers in electric system in case of changes in the operating conditions of heating system. For example, forced disconnection of a heat source or unexpected cold spell can lead to an increase in electricity consumption to compensate for heat shortage. Normally, the increase in electricity consumption occurs due to interruption in the heat supply to consumers. Thus, the electricity consumption level is connected with the level of heat production.

In order to describe electricity consumption we should identify the nodes with direct electricity consumption and the nodes with indirect electricity consumption in the heating system. Since the operating conditions of consumers determine the operating conditions of both electric power system and heating system, it is assumed that the level of consumption with the accuracy to a single consumer is known (based on projection, normative framework, direct measurements and processing of measurements). Under the known consumption, the state variables are calculated with standard software intended for the calculation of load flow and flow distribution in respective networks.

The basic elements for the interface (interaction) between electric and heating systems within the intelligent integrated energy system are heat and electricity consumers as well as power and control equipment of electric and heat networks. A list of attributes of the heat and electricity consumer is presented in Table 1.

A list of attributes of power and control equipment (electric boiler plants, pumping stations, etc.) is presented in Table 2.

An algorithm for the combined calculation of electric

Table 1. Attributes of a Heat and Electricity Consumer

No.	Attributes of Consumer as a Component of Electric System	Attributes of Consumer as a Component of Heating System
1.	City address	City address
2.	Code of node number (number of a contract)	Code of consumer (number of a contract)
3.	Feeder code	Feed pipe code
4.	Supply transformer substation code	Pumping station code
5.	P_{max}, MW(contracted power of consumption)	Heat consumption curve (MW)
6.	P_{comp}, MW (power compensating for heat shortage)	Heat undersupply volume (MW)

Table 2. Attributes of a Power and Control Equipment

No.	Electric System Component Feeding Heating System Power Equipment	Heating System Equipment Component
1.	Equipment code	Equipment code
2.	Code of supply feeder	Code of supply line or transformer substation of electric system
3.	Code of supply transformer substation	Codes of adjacent pipes
4.	City address	City address
5.	P_{max}, MW(contracted power of consumption)	Electricity consumption curve (MW)
6.	P_{comp}, MW (power consumption under change in operating conditions of power equipment in heat network)	Change in the electricity consumption under change in operating conditions (MW)

power and heating systems for some time instant, for which the electric loads of heating system equipment are known, is reduced to the determination of values of state variables (nodal capacities and voltage, transformer ratios, and their functions) based on the calculation of feasible load flow in electric power system, given the loads of the other electric system consumers. For formalization, it is convenient to introduce individual nodes, where the load of heating system equipment is connected.

The calculated scheme of electric power system in terms of heating system operation is demonstrated in Fig.1. Under normal operating conditions, the amounts of electricity consumed by heating system are determined and they are assigned to the electric system nodes, according to the city addresses. To this end, the above tables associating the heat consumption nodes with the electricity consumption nodes are used.

Change in the heating system condition is analyzed, and the volume of required additional electricity, if necessary, and its distribution among nodes of the calculated electric system scheme are determined. If the problem is solved for the time interval, whose duration is taken equal to an hour, an increase in electricity consumption is numerically equal to load. Change in loads of the electric boiler plants and pumping stations also influences electric system operation, because they are electricity consumers. The feasible condition of the electric system is determined for the specified loads of heating system equipment and the loads of remaining electric system consumers. Calculation of power flow in terms of the corrected loads makes it possible to determine the degree of loading of transmission lines and transformers. The regulatory documents indicate that in the short run the overloading of transformers should not exceed 40% of the rated transformer capacity and that of cable lines should not exceed 25% of their rated transfer capability [31]. If the feasible solution does not exist, organizational and technical measures should be developed to eliminate causes of such a situation. Otherwise, the values of current state variables are used or corrected.

IV. Model Of Intelligent Integrated Energy System Control

The considered model of the steady state control of the intelligent integrated energy system can be applied to any time period divided into t intervals.

The suggested approach to steady state control of IIES is to ensure that this system operates with the minimum costs at the considered time interval. Therefore, the costs of energy system operation and maintenance should be minimized. The objective function has the form:

$$\min F_{obj2} = C_f + C_{dep} + C_m + C_{net}, \tag{1}$$

where

$$C_f = \sum_{i=1}^{N}\sum_{t=1}^{T} c_f^i (F_w^{it} + F_q^{it}), \tag{2}$$

$$C_{dep} = \sum_{i=1}^{N}\left(f_{dep}^i K_i \sum_{t=1}^{T}(P_i^t / P_{i\max})\right), \tag{3}$$

$$C_m = \sum_{i=1}^{N}\sum_{t=1}^{T} f_m^i (W_i^t + Q_i^t), \tag{4}$$

$$C_{net} = \sum_{t=1}^{T}(f_{net}^e W^t + f_{net}^h Q^t), \tag{5}$$

subject to:

$$E_{k\min} \le E_k^t \le E_{k\max}, \quad k \in N_{par}^e, \quad t = 1,...,T, \tag{6}$$

$$H_{k\min} \le H_k^t \le H_{k\max}, \quad k \in N_{par}^h, \quad t = 1,...,T, \tag{7}$$

$$0 \le P_i^t \le P_{i\max}, \quad i = 1,..., N, \quad t = 1,...,T, \tag{8}$$

$$F_{w\max}^{it} \ge F_w^{it}, \tag{9}$$

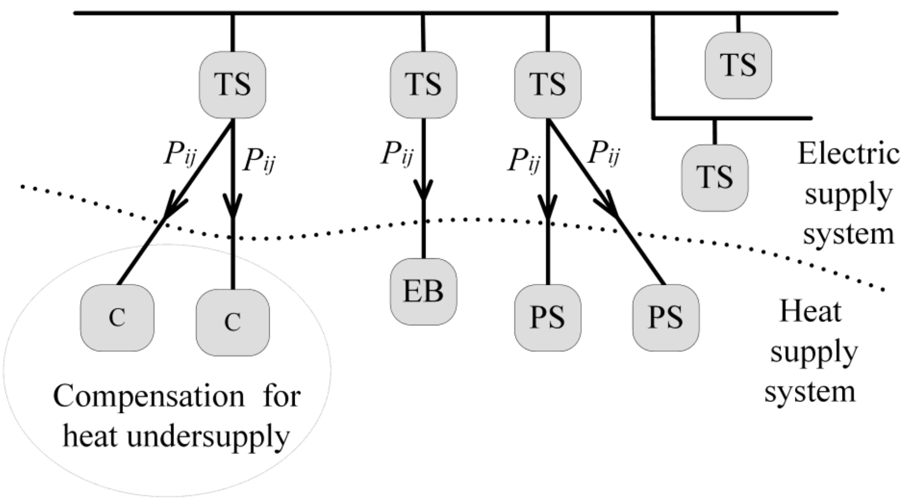

Figure 1. The calculated scheme of electric power system in terms of heating system operation.

$$F_{q\max}^{it} \geq F_q^{it}, \qquad (10)$$

and balance between electricity and heat production is:

$$\sum_{t=1}^{T}(W^t + Q^t) = \sum_{i=1}^{N}\sum_{t=1}^{T}(W_i^t + Q_i^t) = \sum_{t=1}^{T} P_i^t \Delta t, \qquad (11)$$

where C_f – fuel costs; C_{dep} – depreciation costs of energy sources; C_m and C_{net} – operating costs of energy sources and networks, respectively; c_f^i – cost of the fuel used at each source *i* out of the total number *N*; F_q^i – volumes of fuel used at source *i* for heat production; F_w^i – volumes of fuel used at source *i* for electricity production; f_{dep}^i – capital recovery factor; K_i – capital investment in source *i*; P_i – used (installed) capacity of source *i*; $P_{i\max}$ – maximum (installed) capacity of source *i*; f_m^i – specific values of operating costs of source *i* (maintenance, semi-fixed costs, consumption of other primary energy resources except for fuel, etc.); W_i – supply of electricity from source *i*; Q_i – supply of heat from source *i*; f_{net}^e – specific values of operating costs for electric networks; f_{net}^h – specific values of operating costs for heat networks; W – total values of electricity outputs in the system; Q – total values of heat outputs in the system; E_k – parameters of the current state of electric network; $E_{k\min}$ and $E_{k\max}$ – technically admissible limits of operating parameters of the electric network; H_k – parameters of the current state of heat network; $H_{k\min}$ and $H_{k\max}$ – technically admissible limits of operating parameters of the heat network; P_i – used (installed) capacity of source *i*; $P_{i\max}$ – maximum (installed) capacity of source *i*.

The operating parameters (6) and (7) are determined from the calculation of operating conditions of electric and heat networks by using special mathematical models of load flow which are based on the known network laws of Kirchhoff.

Electricity consumption in the system W_{cons} is related to its supply as follows:

$$W_{cons} = W(1 - l_w), \qquad (12)$$

where l_w – a share of power losses in the system.

The amount of electricity consumed in the system can be divided into three parts:

$$W_{cons} = W_{cons(e)} + W_{cons(h)} + W_{pump}, \qquad (13)$$

where $W_{cons(e)}$ – electricity used to cover electric loads of consumers; $W_{cons(h)}$ – electricity consumed by electric heaters to cover part of heat (heating) load; W_{pump} – electricity used in the motor drive of pumping stations in the heat network.

Based on (12) the heat consumption in the system Q_{cons} is related to its supply as follows (we make an assumption that the electric energy consumed by electric heater is completely transformed into thermal one):

$$Q_{cons} = Q(1 - l_q) + W_{cons(h)}, \qquad (14)$$

where l_q – a share of heat losses in the system.

The amount of fuel consumed at source *i* for electricity or/and heat production, respectively, can be determined as follows:

$$F_w^i = W_i / \eta_e^i, \quad i = 1,...,N, \qquad (15)$$

$$F_q^i = Q_i / \eta_h^i, \quad i = 1,...,N, \qquad (16)$$

where F_w^i – volumes of fuel used at source *i* for production of electricity; F_q^i – volumes of fuel used at source *i* for production of heat; η_e^i = factors of fuel efficiency at source *i* for electricity production; η_h^i = factors of fuel efficiency at source *i* for heat production.

The coefficient f_{dep}^i is determined by the following equation:

$$f_{dep}^i = [r(1+r)^{n_i}] / [(1+r)^{n_i} - 1], \qquad (17)$$

where *r* – a discount rate which can be represented by the cost of funds; n_i – depreciation rate of equipment at source *i* as a result of its wear due to operation.

The indices f_{dep}^i, r and n_i are normally assumed annualized.

Model (1) – (11) makes it possible to control the operating conditions of the integrated intelligent energy system during any period of time, considering changes in the electric and heat loads during this period. The efficiency of energy production at the sources also changes, hence for each source *i* there is an efficiency characteristic according to which the coefficients η_e^i and η_h^i take certain values depending on the time interval *t*. Thus, the fuel consumption at sources in equation (2) is determined considering the time-variable efficiency:

$$F_w^{it} = W_i^t / \eta_e^{it}, \quad i = 1,...,N, \quad t = 1,...,T, \qquad (18)$$

$$F_q^{it} = Q_i^t / \eta_h^{it}, \quad i = 1,...,N, \quad t = 1,...,T . \qquad (19)$$

Requirements for reliability of the integrated intelligent energy supply system operation can be specified by the following conditions which should supplement equations (6) – (11):

$$R_j^e \geq R_{0j}^e, \quad j \in J , \qquad (20)$$

$$R_j^h \geq R_{0j}^h, \quad j \in J . \qquad (21)$$

Reliability is normally assessed by several indices that characterize its different properties. Here for each index we should set condition (20) or (21) depending on the type of supply (electricity or heat). The assessment of the reliability involves two main nodal reliability indices – availability factor and probability of failure-free operation.

V. Study Of Intelligent Integrated Energy System Operating Conditions

The algorithm of calculating conditions of joint operation of electric and heating systems subject to their integration comprises the following stages [32]:

1. Physical layout of sources on the terrain plan and assignment of their parameters.
2. Generation of schemes of heat and electric networks.
3. Determination of time period and step.
4. Calculation of flow distribution in the heating system for the determined time step.
5. Estimation of condition feasibility of the heating system.
6. Assessment of reliability indices of the heating system.
7. Determination of consumers of power and control facilities of the heat network, whose power demand changed.
8. Determination of consumers with unserved heat load, and the volume of undersupplied heat.
9. Determination of transformer substations supplying electricity to power and control facilities of the heat network, whose power demand changed.
10. Determination of transformer substations supplying electricity to the consumers with undersupplied heat.
11. Change in capacity of the transformers determined in steps (9) and (10).
12. Calculation of conditions of the electric system.
13. Estimation of condition feasibility of the electric system.
14. Assessment of reliability indices of the electric system.
15. If the feasible solution exists, then calculation of costs on energy system operation and transition to step 3), otherwise, development of organizational and technical measures to eliminate causes of the formed situation.

Consider some results of the studies on joint operation of the electric and heating systems by the example of one of the districts of Irkutsk city with centralized electricity and heat supply.

A graphical model of the integrated energy system is presented in Fig. 2. It contains an electric system (blue lines in Fig. 2) and a heating system (red lines in Fig. 2).

The studies were performed on the basis of multivariate

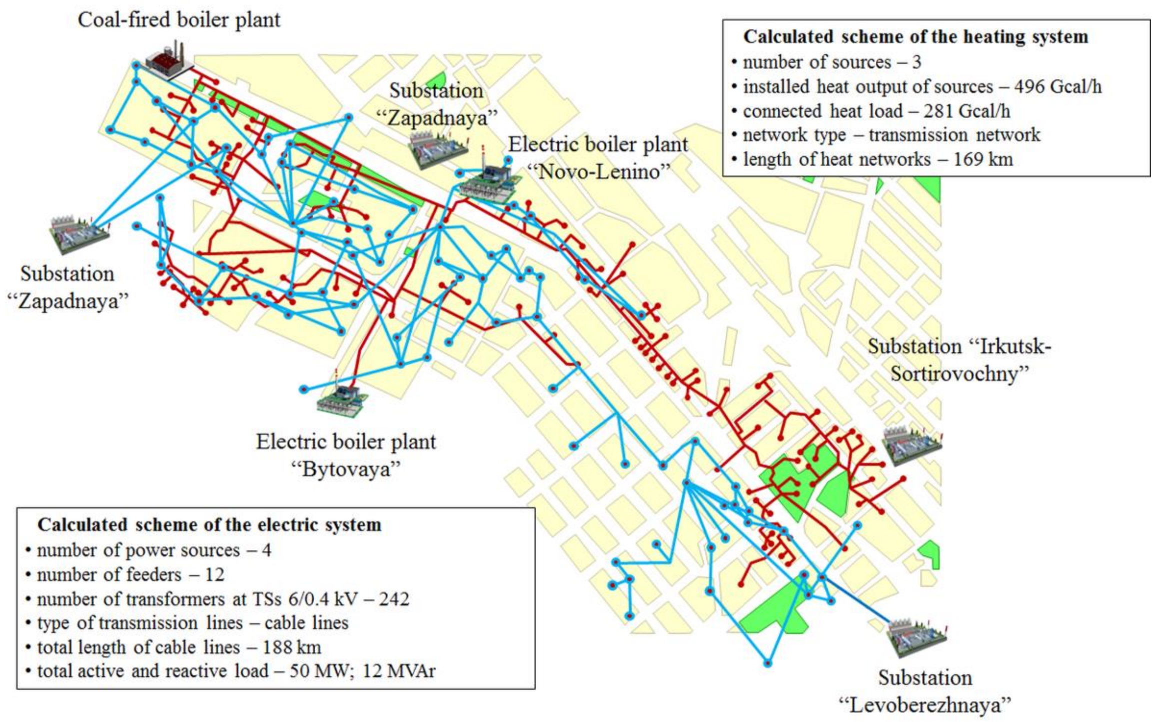

Figure 2. A scheme of the integrated energy system.

calculations of operating conditions of the electric and heating systems and generalization of their results using the corresponding software designed at ESI SB RAS. The calculated loads of the energy system of the district corresponded to winter loads. A day with a step equal to one hour was taken as a time period.

When the electric and heating systems operated independently, the costs of energy supply amounted to 359,122 RUR/day. In accordance with the above model of IIES control, joint operation of the electric and heating systems allows their energy flows to be distributed so that the operation and maintenance costs are minimized integrally for both systems. The energy supply costs in this case decreased and made up 298,071 RUR/day. Operation of the systems as a single integrated entity considerably decreased the costs, improved the technological potential of mutual redundancy and fuel diversification, enhanced the comfort level, etc. At the same time, the studies also revealed shortcomings caused by the need of separate development planning of the electric and heating systems. This fact was confirmed by calculations of conditions with increased consumer demands due to abnormal fall of ambient air temperature, in emergency situations, unforeseen repairs and so on.

An increase in electric load because of abnormal cold snap, for example, by about 30 MW, which seems quite real, made it impossible to supply 14 MW of electricity to consumers even with the available capacity reserve and led to overloading of transformers at 18 transformer substations. Load decrease in the heating system could improve the situation and reduce load of the electric system to 4 MW. However, this measure was not implemented because of the absence of automatic and intelligent control of conditions of the electric and heating systems. All of these things show that transition to operation of electric and heating systems as an integrated entity leads to essential saving of costs and a set of technological effects and at the same time requires certain engineering modifications of the systems, their substantiation and implementation.

VI. CONCLUSION

Intelligent integrated energy systems have versatile functions and a developed technological structure which includes a heterogeneous configuration of basic components: production systems, systems for transportation of energy carriers, systems of load-controlled consumer, systems of energy storage, integration tools, information-communication platform, metering and measuring systems and also intelligent control systems. These facts essentially complicate coordination and control of conditions of such a metasystem. The suggested model and algorithm of calculating the conditions make it possible to perform studies, plan operating conditions of IIES and generate recommendations on their implementation. At the same time, the conducted studies reveal unavailability of the existing energy systems to joint operation. Hence, they should be transformed to create a proper structure and provide with required parameters.

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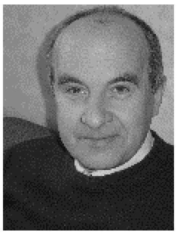

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The Combinatorial Modelling of Vietnam Energy Development

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***Abstract* — The paper describes a combinatorial modelling approach to the research of energy sector development. The idea of the approach is to model a system development in the form of a directed graph with its nodes corresponding to possible states of a system at certain moments of time and arcs characterizing the possibility of transitions from one state to another. The combinatorial modelling is a visual representation of dynamic discrete alternatives. It allows simulating a long-term process of system development under various possible external and internal conditions, and determining an optimal development strategy of the system under study. The formation and analysis procedures of energy development options are implemented in the software package "Corrective". The distributed computing environment is needed to compute an energy sector development graph. In 2015, the Institute of Energy Science of Vietnamese Academy of Science and Technology performed a study on Vietnam sustainable energy development from 2015 to 2030. Based on the data from this study the combinatorial modelling methods are applied to the formation and analysis of Vietnam energy development options taking into account energy security requirements. The constructed Vietnam energy sector development graph consists of 531442 nodes. It is computed on the cluster located at the Institute for System Dynamics and Control Theory of Siberian Branch of the Russian Academy of Science (Irkutsk). The obtained optimal path of Vietnam sustainable energy development provides the minimum costs of energy sector development and operation under deterministic conditions.**

***Index Terms*—combinatorial modelling, energy sector, decision support, distributed computing environment.**

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I. Introduction

The study of long-term energy development with regard to uncertainty (ambiguity) of the initial information and development conditions should be conducted on the basis of general energy research approaches that employ special methods, models, databases and software. The models should consider a rather long time period (30-40 years) and distinguish several stages in the development and operation of energy systems. The models should also explicitly consider discreteness of the energy facility development options. Tools to generate and analyse energy development options must be well-founded and flexible. They should be based on some general organizing research, algorithms to develop and choose energy development options.

There are two approaches to energy models used to project the future energy demand and supply of a country or a region: top-down and bottom-up.

Top-down energy models try to describe the economy as a whole on a national or regional level and to assess the aggregated effects of energy and/or climate change policies in monetary units. These models simulate economic development, related energy demand and energy supply, and employment taking an aggregated view of the energy sector and the economy [1].

A bottom-up energy model has a relatively high degree of technological detail (compared to top-down energy models) used to assess future energy demand and supply. As regards the mathematical form, the bottom-up energy models have been developed in the form of simulation or optimization models, and more recently of multi-agent models [1].

One of the drawbacks of the conventional bottom-up energy model like MARKAL [2], EFOM [3], TIMES [4], MESSAGE [5] opposite to the integrated model of the USA national energy and transportation systems [6] is a complicated way of interregional transport facilities representation at a detailed level.

There are some investigations on the Vietnamese energy sector in literature. The author of [7] employs optimization methods and empirical studies to examine sustainable long-term development in the Vietnamese power sector and determines the ways to implement sustainable energy options for the power sector in practice. In [8] the authors summarize the results of the national Master Plan for developing the electricity supply sector to meet increasing electricity demand. They also describe the evolution and current status of Viet Nam's energy policies, including those related to energy security, energy efficiency and conservation, the environment, and development of renewable energy sources, as well as strategies for power sector development and restructuring of the energy sector toward greater use of competitive energy markets. In [9] the research is focused on the development and implementation of various Energy Efficiency and Conservation policies and programs in Vietnam. The authors of [10] provide an overview of the current energy policies with a view to identify the areas where further policy effort is needed in order to facilitate a sustainable development of the Vietnamese energy sector.

It is impossible to describe and test all distinctive combinations of external conditions and energy development options within the frames of an energy sector model, taking into account uncertainty, energy security threats and other factors. This leads to a huge number of possible energy sector states and takes a lot of time to generate and analyse using usual methods of research. To deal with this issue the combinatorial modelling approach is used. The combinatorial modelling is a visual representation of dynamic discrete alternatives and permits to simulate the long-term process of system development under various possible external and internal conditions, and to determine an optimal development strategy of the system under study.

This paper describes the software that implements some combinatorial modelling approach procedures and considers their application to study some aspects of sustainable energy development of Vietnam under deterministic conditions.

II. Energy Sector Model

The balance mathematical model [11] evaluates the energy sector state at a certain time period with regard to energy security (ES) requirements [12]. The model allows:

- Considering the entire energy sector from production of energy resources to final consumption in various economic sectors including all stages of energy conversion;
- Investigating energy technological and territorial structure development.

The objective function of the energy sector model is

$$(C,X)+\sum(r^t,g^t)\rightarrow min \quad (1)$$

The first component of the objective function reflects the operation costs of the energy sector. The vector C contains specific operating costs for the existing, reconstructed, upgraded and newly built production, transformation and transmission facilities.

The second component represents the losses due to the energy resource shortage for different consumer categories. The energy resource shortage g^t of category t is equal to the difference between R^t and Y^t. Vector r^t consists of the components called "specific losses" for consumer category t.

The objective function of the energy sector model is reduced to the equations:

$$AX - \sum Y^t=0 \quad (2)$$

$$0\leq X\leq D \quad (3)$$

$$0\leq Y^t\leq R^t \quad (4)$$

where $t=1,.., T$ is a category of consumers;

T – the number of consumer categories;

X – the decision vector whose components represent the intensity of energy facilities usage (storage, production, conversion and transmission of energy resources);

Y^t – the decision vector whose components characterize the energy resource consumption for different categories t;

A (the matrix of facility technology factors (production, transformation) and transmission of energy resources;

D – the vector that determines technically possible capacities of production, conversion and transmission facilities;

R^t – the vector that defines energy resources demands of the category t.

III. Combinatorial Modelling Approach

The procedures of the formation and analysis of energy development options are based on the representation of components belonging to an investigated system in the form of a directed graph. The graph nodes correspond to the possible states of the components at certain moments. The graph arcs define the admissibility of transitions between states. The research on the development of the entire system is performed by analysing various combinations of states and transitions of particular components. This approach is known as combinatorial modelling [13].

A component is a structural unit of the system under research. It may be a factory, a power plant, a set of similar energy sources or a consumer category. The degree of aggregation of the energy production or consumption facilities depends mostly on the goals of the study and database capabilities.

The first step of the combinatorial modelling approach is to describe the basic scenario of energy development to investigate as a graph with one node for each time moment

(Fig. 1). These nodes contain essential information to create new possible states of the energy sector.

In the second step, the infrastructure of the energy sector is divided into several components by territorial or industrial criteria. For each component, a development graph is built. It contains changes in the energy facility parameters at the time period considered. The development graphs of two energy facilities are shown in Fig. 2. The source nodes corresponding to moment 0 do not have numbers because they will not participate in the next construction of the energy sector graph.

The third step is combining data of the reference graph with information on different components of graphs belonging to the same moment in time. This results in the set of possible states of the energy sector for each moment in time. The states (nodes) of the modelled system are linked by transitions (arcs) to form an energy sector development graph.

The energy sector development graph shown in Fig. 3 is constructed by means of combination of nodes and arcs of the graphs in Figures 1 and 2. The number of generated possible energy sector state is shown inside the circle in Figure 3. The numbers above the circle are combinations of the graph nodes in Figures 1 and 2. The beginning of all paths in the generated energy sector development graph is a common initial node at moment 0.

The fourth step is to check the validity of nodes and arcs of the energy sector development graph, since not all possible energy sector states and transitions can be valid. For this purpose, there are system-wide constraints in the combinatorial modelling. Two types of them can be distinguished:

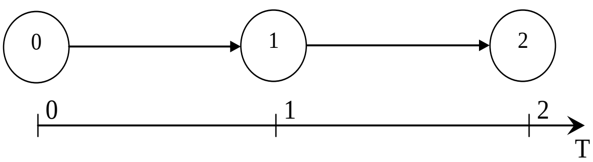

Figure 1. Basic scenario of energy sector development.

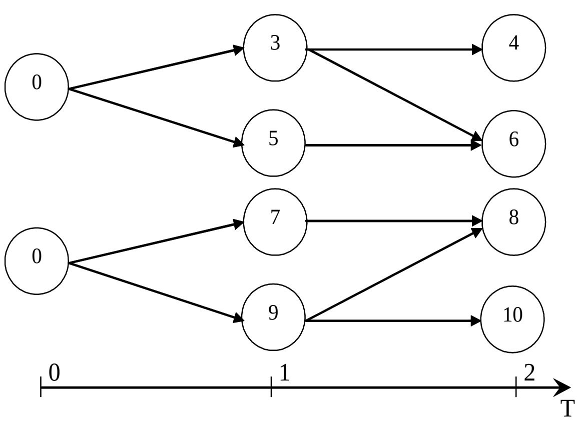

Figure 2. Development graph of two energy facilities.

- Logical conditions. Some development alternatives of a component can depend on the implementation of certain development variants of other components.
- Balance and other design constraints. These are constraints on the available raw resources and products at every time moment and transition. They can be defined by balance equations or inequalities.

Lists of pairs of incompatible nodes are used to implement logical conditions. A couple of incompatible nodes are a pair of nodes of graphs of different components, and their combination with a possible system state is not possible or does not make sense for some reasons.

The model of the energy sector (1) - (4) is of the second type of system-wide constraints. The admissibility of an energy sector state depends on the correctness of the decision results.

If ES requirements exist, then ES status of a possible energy sector state is estimated by means of ES indicators. The ES indicator value is calculated based on the computation results of economic-mathematical model. The ES status is determined by comparing ES indicator values and thresholds.

The energy sector development graph shown in Fig. 3 has four nodes that did not pass the validity check (Fig. 4).

The fifth stage is to build a graph containing valid states and transitions. States and transitions that are unreachable from the initial state are determined during the passage from the initial node to the end nodes. Then, the blind states and transitions are determined during the reverse passage. It is impossible to build a path from the initial node to the nodes with blind states and transitions at the last time moment. The invalid, unreachable and blind states and transitions are removed from the graph which contains possible energy sector states and transitions.

In the last stage, a set of system states to form optimal and suboptimal paths can be determined with the algorithm based on the concept of dynamic programming [14].

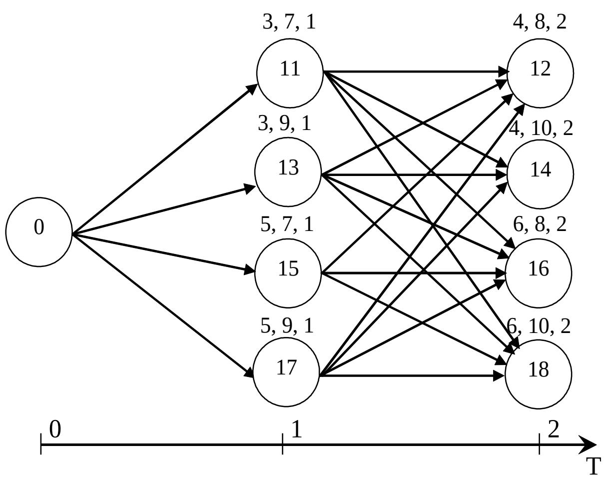

Figure 3. Energy sector development graph.

The graph consisting of valid energy sector states and transitions is shown in Fig. 5. It was made from the graph shown in Fig. 4 where an optimal way to ensure minimization of costs of energy sector development and operation is presented by the bold lines.

The main problem facing the combinatorial modelling methods implementation is a large number of system states and transitions to be simulated. It grows exponentially with the increasing number of system components and their states. That is why the combinatorial modelling approach is usually used with distributed computation technologies [15].

IV. Software Package "Corrective"

The above procedure of the construction and analysis of energy sector development graph is implemented in the software package Corrective [4]. It consists of the following modules:

1. Module m_1 designs a basic scenario of the considered energy sector development,
2. Module m_2 constructs an energy sector development graph,
3. Module m_3 checks the validity of a possible energy sector state (node of development graph),
4. Module m_4 supports expert analysis of energy sector development paths.

Figure 6 depicts a scheme of information and logical links between modules of the Corrective software in the form of a bipartite directed graph where modules m_1, m_2, m_3, m_4 are black ovals.

The main aim of module m_1 is to read information from a database (DB) *A* and to transform it into the basic scenario of energy sector development *B*. DB operates under control of the database management system Firebird.

Module m_2 implements the methods of combinatorial modelling. After constructing the graph, each node is completely independent of others regarding calculations. Total computation time can be significantly reduced with the help of distributed computing technology. This is achieved by dividing the set of *N* nodes into groups of smaller size and processing them simultaneously in a distributed computing environment (DCE). List of input parameters *C* includes specified energy development strategies and can involve ES indicators and disturbances that may occur during the time period considered.

The kernel of module m_2 consists of several tens of scripts written in Lua programming language. The key part of m_2 is the model generator, which generates a new possible state of the energy sector. The generator is controlled by a set of rules that transform raw data *B* and *C* into the components of the energy sector model. Researcher can change these rules.

Module m_3 is used to check the validity of each possible state of the energy sector of set *D* with the multistage constraint system. In the first stage, the energy sector model (1)-(4) is solved as a linear programming problem. If its solution exists, then m_3 can validate ES status by indicative analysis. Finally, the state is added to the set *E*.

Module m_4 enables researchers to identify the optimal energy sector development paths based on set *E*, and to compare the found optimal path with others.

V. Modelling Of Sustainable Development Of Vietnam Energy Sector

The Vietnam energy sector model was developed from 2011 to 2015 on the basis of the energy sector model presented above during the joint research conducted by the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Science (ESI SB RAS) and the Institute of Energy Science of Vietnamese Academy of Science and Technology (IES VAST).

In order to analyse the characteristics of the key socioeconomic regions, the Vietnam energy sector structure and some other related issues, the supply and demand balance is calculated for eight regions: Red River Delta, Northeast, Northwest, North Central, South Central

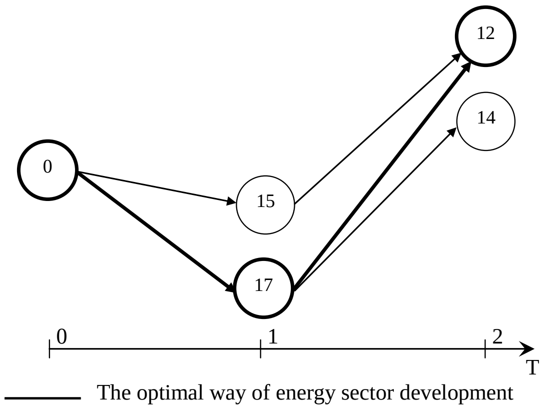

Figure 4. Optimal way on energy sector development graph.

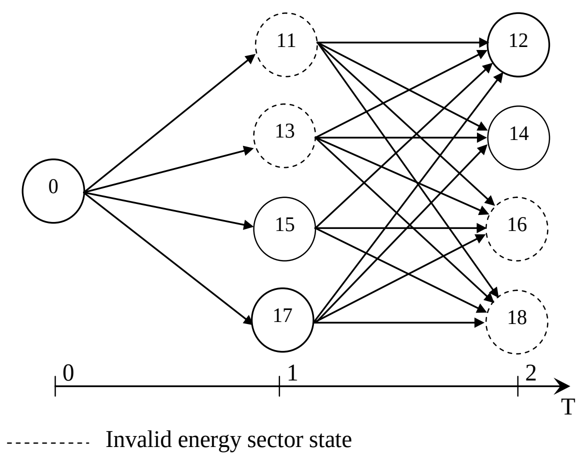

Figure 5. Valid and invalid energy sector states and transitions on energy sector development graph.

Coast, Highlands, Southeast and Mekong Delta. Input data include energy supply (costs and value of production, import and export), conversion and transportation of energy, energy consumption. Specifically, the regional parameters of production capacity, costs of production, transport capacity, transport costs are based on the data from the individual production and transportation facilities. The data on regional energy consumption are obtained and calculated based on energy consumption data for five key economic sectors: industry, agriculture, transportation, commerce- service and residential.

In 2015, IES VAST employed module m_1 to investigate the sustainable energy development of Vietnam from 2015 to 2030, with regard to the energy security requirements. The energy development scenarios are assessed according to energy security and sustainable development criteria. These scenarios should meet the national energy demand for the socioeconomic development; apply the suitable and efficient energy technology, minimize the environmental impacts from the energy system, and achieve the cost-effective energy system development.

Different energy development scenarios for the period of 2020-2030 were built considering capacity variations for the following energy facilities: domestic coal production capacity (baseline, increase by 10 % and decrease by 10 %), domestic natural gas production capacity (baseline, increase by 10 % and decrease by 10 %) and domestic hydropower generation capacity (baseline, increase by 10 % and decrease by 10 %).

Optimally, natural gas capacity should be increased by 2020 to meet the national energy demand, then it should follow the base scenario by 2025 and 2030. Hydropower capacity remains stable for the whole period of 2020-2030, while the coal capacity reduces by 10% by 2020.

Below the algorithms for combinatorial modelling were applied using the same assumptions and data for the formation and analysis of Vietnam energy development.

In the first stage, the basic energy sector development graph was constructed. In the second stage, the component development graphs were built for the pairs of industries and regions of Vietnam (marked with "+" in Table 1). A typical component development graph is shown in Fig. 7, where the component capacity fluctuation is shown in circles.

In the third stage, an energy sector development graph that consists of 531442 nodes is constructed. Each of possible Vietnam's energy sector states is described by the model (1) - (4) that consists of several thousands of variables and hundreds of equations. In the next stage, the computational experiment on the new energy development graph is performed with DCE, which includes the high-performance cluster Academician V.M. Matrosov [16]. The cluster is located at the Institute for System Dynamics and Control Theory of Siberian Branch of the Russian Academy of Science (Irkutsk).

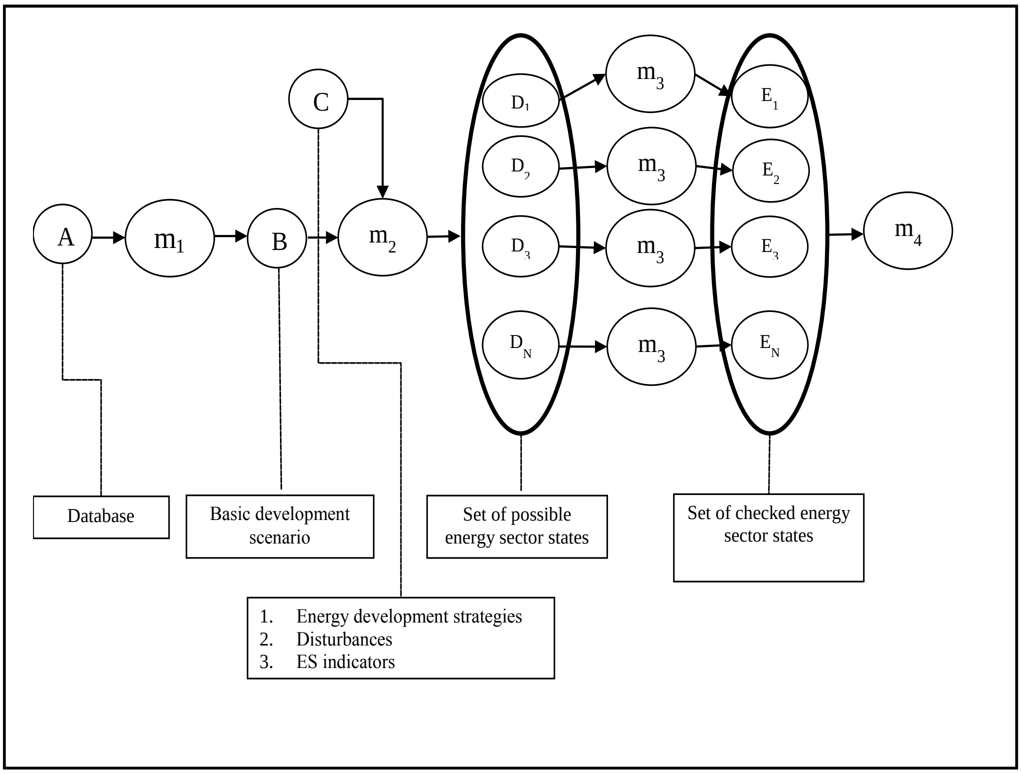

Fig. 6. The logical scheme of software package Corrective.

Table 1. Energy industries and regions of Vietnam.

Region	Domestic coal production	Domestic natural gas production	Domestic hydropower generation
Red River Delta	+		
North East	+		+
North West			+
North Central Coast		+	+
South Central Coast			+
Central Highland			+
South East		+	+
Mekong River Delta		+	

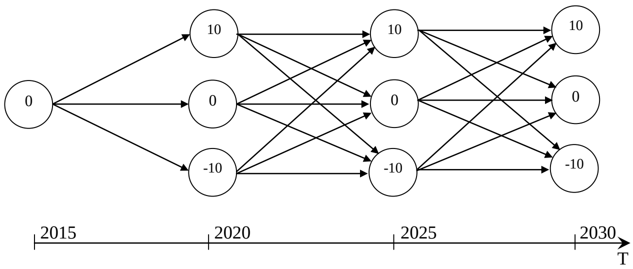

Figure 7. A typical development graph of Vietnam energy industry.

In the fifth stage, we obtain the optimal path with minimum development and operation costs as a criterion, where the natural gas production increases and the coal production reduces for all time moments.

VI. Conclusions

The advantages of the combinatorial modelling are the clarity and compactness of representation of modelled system development options in the form of a directed graph. The graph clearly illustrates both differences of various system development paths and their common states and transitions.

The advantage of this approach is a complete description of the object development options. The traditional approaches to compare the development options based on the multi-criteria methods usually enable researcher to make just a few options. The choice depends on the researcher's intuition and experience. Such selection, even if it is right, always reflects certain subjectivity and thus depreciates the level of result proof.

The resulting set of the admissible system development paths can be applied in many forecasting tasks where, for example, the uncertainty should be taken into account. Among the admissible system paths, one can choose not merely the best way but also the paths close to it according to research criteria.

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Daily Reconfiguration of Distribution Network with Renewable Generation

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Abstract **– The paper is concerned with the approaches to reducing losses in primary distribution network, considering reliability of power supply to consumers. The distribution network reconfiguration is the main procedure for the minimization of losses. A proposed reconfiguration algorithm is based on the graph theory methods and implemented in a high-performance program for load flow calculation. An algorithm is devised to optimize daily load curve of load-controlled consumers, considering daily electricity price charts, constraints on state variables and invariable daily electricity consumption. The research is focused on individual and joint impact of reconfiguration, renewable generation, and optimization of load curves of load-controlled consumers on reduction in daily power and voltage losses. Consideration is also given to the influence of renewable generation on the number of switchings at reconfiguration, and the possibility of choosing some constant reconfiguration under which daily power losses could be compared with the losses obtained for hourly reconfiguration. The research into how the uncertainty of the day-ahead forecast data on load and generation affects the value of power losses in distribution network is conducted. The results of the research demonstrate that the information uncertainty does not affect much the loss reduction at reconfiguration.**

Index Terms – load-controlled consumer, graph theory, distribution network, loss reduction, reconfiguration, renewable power generation.

I. Introduction

Most of the energy losses in the electric power systems are known to occur in distribution networks. These losses make up 10-13 % of all the generated electric energy. The problem of energy loss reduction in the distribution network that consists of a medium voltage distribution network (primary) and low voltage distribution network (secondary) remains important for engineers and researchers. This paper is concerned with an issue of reducing energy losses in the primary distribution network which feeds secondary distribution network transmitting energy to end consumers.

The primary distribution networks are weakly closed, however owing to normally open tie switches between feeders, they operate as open. Apart from the normally open tie switches, there are normally closed sectionalizing switches that can disconnect one of the feeder sections. Closing of a tie switch and opening of a respective closed switch allow us to obtain a new radial configuration of the distribution network. Such a procedure called reconfiguration algorithm enables us not only to enhance power supply reliability but also to reduce energy losses, and hence energy consumed from supply network, currents in tie lines, voltage losses in distribution network, and, moreover, more fully involve renewable generation in the case it is used in the network.

In a traditional passive distribution network, power flows go from primary distribution substation being the only supply source along the branches of a tree scheme to a leaf node. Voltage deviations increase as the distance between source and the dangling node rises. Thus, voltage behaviour in the traditional distribution network is predictable and its monitoring is unnecessary.

Transition to active distribution network is related to the use of distributed generation, energy storage systems, and active demand. Directions of flows in the branches of the active distribution network vary during a day. The load nodes can become generator nodes and voltage deviations can exceed admissible values. Therefore, such networks must be monitored.

In passive distribution network the flows and voltage are measured only at the primary distribution substation. The conditions of the secondary distribution substation are normally unknown [1]. In the future intelligent distribution networks active distribution networks will be part of advance metering infrastructure [2] and operator of distribution network will receive data on loads and generation in real time. In this paper, however, we assume that the distribution network operator has a short-term forecast of active and reactive loads and active power generation of renewable

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energy sources represented by wind turbines and photovoltaics. Daily load curves and generation schedules of renewable energy sources are taken from the research [3] which is also devoted to the problem of energy loss reduction under hourly reconfiguration of distribution network. Energy losses per hour are numerically equal to average power losses during an hour. Therefore, in an analysis of losses for a concrete hour we will consider power or energy losses.

Since the forecasts of loads and generations contain errors, the most pressing problems are the assessment of an impact of forecast errors on the errors in energy losses in the distribution network under its daily reconfiguration, and the assessment of reconfiguration justifiability under uncertain initial information.

In our research reconfiguration is considered as the main tool of reducing power losses in the distribution network. A great many algorithms for solving this problem are presented in publications. According to [4], they include the algorithms of mixed integer and nonlinear programming, and heuristic methods such as Genetic Algorithms, Artificial Neural Networks, Ant Colony, Harmony Search, and Tabu Search. The other algorithms involve linear load flow to calculate losses at network reconfiguration, because nonlinear load flow is considered to be time-consuming. In [4], the authors solve the problem of distribution network reconfiguration by applying both the algorithms for the construction of a maximum spanning tree and the simplified approaches to specification of currents and power losses. It is probably this simplification that did not allow the researchers to find better solutions, which were obtained with the help of other algorithms, for example, in [5].

The proposed reconfiguration algorithm is based on the methods known in the theory of graphs and intended for the construction of a maximum spanning tree [6] and determination of branches of independent loops by their chords [7]. These methods are included in the high-speed program of steady state calculation, which is the main advantage of the proposed algorithm compared to the reconfiguration algorithm in [4]. The main stages of the algorithm that does not take into consideration the presence of several generation sources in the distribution network are presented in Section 2 of this paper.

Section 3 is focused on the study of the impact of renewable generation and/or reconfiguration on losses. The impact of renewable generation on the number of switchings at reconfiguration is studied, and the possibility of determining a scheme of switchings providing the minimum daily losses within the entire range of variations in nodal power is demonstrated. The assessment of losses was illustrated along with the expected characteristic of voltage, whose deviations decline with reduction in losses. Moreover, the impact of renewable generation and reconfiguration on the currents in distribution network is analysed.

Section 4 is concerned with another possibility of reducing losses of energy and currents in tie lines. This is regulation of hourly energy consumption by load-controlled consumers, which leads to a change in the daily load curve. An overview of the methods for active demand control is presented in [8]. The authors of [8] solve this problem by the linear programming method.

In Section 5, the linear analytical method of probabilistic load flow is applied to assess the impact of uncertainty of the day-ahead forecast of loads and generation on energy losses caused by the distribution network reconfiguration. In [9], the authors study the impact of uncertainty of the initial information on reconfiguration losses by using the probabilistic load flow based on the point method.

II. Reconfiguration Algorithm

Power losses in a closed network are normally lower than in an open network [10]. This condition is not met in the event of circulating and interchange currents in the loop. The circulating currents are caused by phase-shifting devices in the loop, and the interchange currents are caused by several supply sources. Nevertheless, in the case of reconfiguration, it is necessary, where possible, to make power losses in the open network close to the losses in the closed network.

This condition can be met by the construction of a spanning tree with the minimum sum of power losses in its chords in the closed network. Such a criterion however may prove unacceptable, if resistance in the branch with high current virtually equals zero. Therefore, the criterion of the minimum sum of absolute values of currents in chords is more reliable. The maximum spanning tree with the minimum currents in chords can be constructed by the known method of the theory of graphs [6]. In this method, the network graph branches are arranged in a descending (variant I) or ascending (variant II) order of absolute values of currents in them [11]. In a cycle, depending on the number of branches, the branches, in which either one or both nodes are not yet included in the tree, are successively connected to the spanning tree. In the event that both nodes of the branch enter the tree, such a branch is called a chord. The algorithm divides all the branches of the network graph into the branches of the spanning tree and the chords.

To determine branches of each independent loop by its chords, we construct a submatrix of a block of trees of the second incidence matrix [7]

$$N_t = M_{ch}^T \left(M_t^T\right)^{-1}. \quad (1)$$

This matrix contains the number of rows equal to the number of chords and the number of columns equal to the number of tree branches, where M_t and M_{ch} are submatrices of the first incidence matrix, that correspond to the branches of the tree and chords. Expression (1) serves as a basis for the topological algorithms used to construct the first incidence matrix $\left(M_t^T\right)^{-1}$ inverse to the block of trees and the second incidence matrix N_t.

The algorithm consists of two steps. In the first step, we determine the composition of disconnected chords. In the beginning, all the switches are closed. Then, the load flow is calculated in the number of iterations equal to the number of independent loops in the graph of the distribution network, and a chord with the minimum current to be open is determined.

In the second step, we check the possibility of reducing power losses by replacing the chords opened in the first step by the branches of the spanning tree in a loop connected to the chord. For each of the chords considered in the first step we do the following: close the next chord; identify the branches of the loop connected to it; calculate the load flow; mark the nodes to the left and to the right of the chord nodes that have the degree above two; simulate a successive disconnection of branches situated between such nodes, with calculation of load flow and determination of total losses; open the previous or new chord that corresponds to the minimum total losses. If the loop does not have nodes with the degree above 2, then the disconnection of all branches of the loop is simulated. It is recommended to repeat the second step of the algorithm once again.

Efficiency of the proposed algorithm for distribution network reconfiguration is confirmed by the example of the test 119-node distribution network, Fig. 1 [5]. The test scheme includes 15 tie switches. With the closed tie switches in the test scheme the power losses in it amount to 819.67 kW, at the open tie switches they increase to 1298.5 kW.

Figure 2 presents the curves that illustrate changing power losses in the test network. Comparison of the results reveals that the composition of chords coincides with the composition in [2], allowing the maximum reduction of network losses from 1298.5 kW at the open tie switches to 870.12 kW. The algorithm is shown to be successfully applied to reduce power losses at each hour of the daily load curve.

III. Hourly Reconfiguration Of Distribution Network

Power losses under optimal configuration, which were taken for some conditions, will not be optimal in the entire range of variation in the nodal powers. This means that reconfiguration should follow changes in loads and generation. We will illustrate the efficiency of applying the proposed algorithm of distribution network reconfiguration to reduce losses at each hour of a daily load curve and generation.

The algorithm performance and subsequent analysis of factors that have an effect on the losses are illustrated by a 33-node scheme [12] (Fig. 3), including 37 sectionalizing switches and 5 tie switches. Daily curve of an hourly variation in active, Fig. 4a, and reactive power loads at nodes 1-33 and variations in active power generated by renewable energy sources at nodes 6,9,13, 32, Fig. 4b, are taken from [3].

Figures 5 a, b demonstrate the performance of the

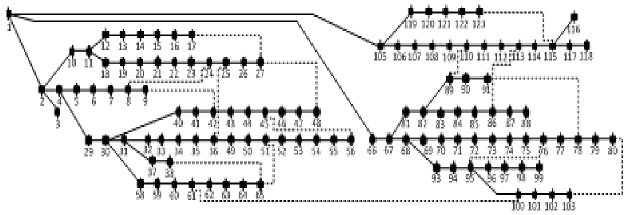

Figure 1. Initial spanning tree of a 119-node distribution network. The lines with the tie switches are shown by dotted lines.

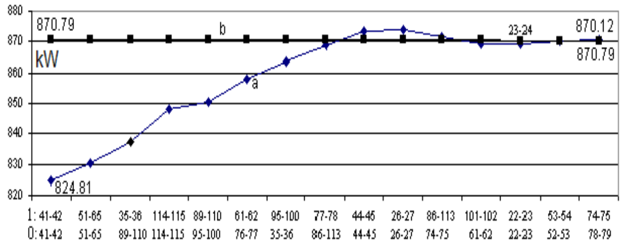

Figure 2. Change in the power losses in the test network scheme on Fig.1, for (I variant) of the RC algorithm in: a- first, b- second stages (0-initial composition of chords, 1- chords obtained after the first stage; replacement of chords in the second stage is shown above the curves b).

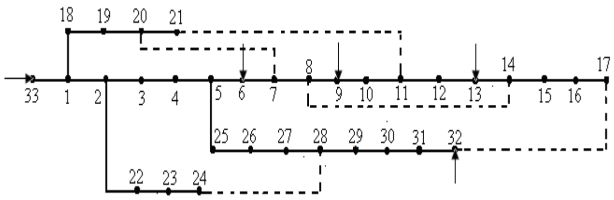

Figure 3. Scheme of a 33-node distribution network. The lines with the tie switches are shown by dotted lines.

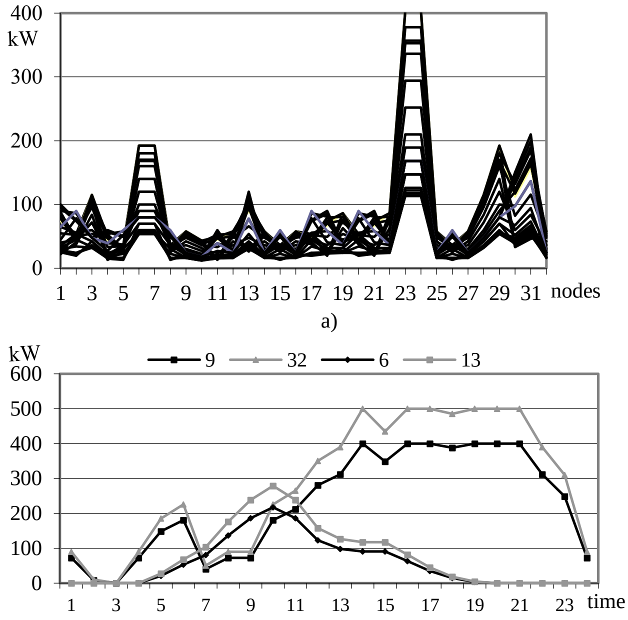

Figure 4. Variation in active power of loads at the nodes of distribution network, Fig.1 (a) and active power of renewable energy sources (b) during a day.

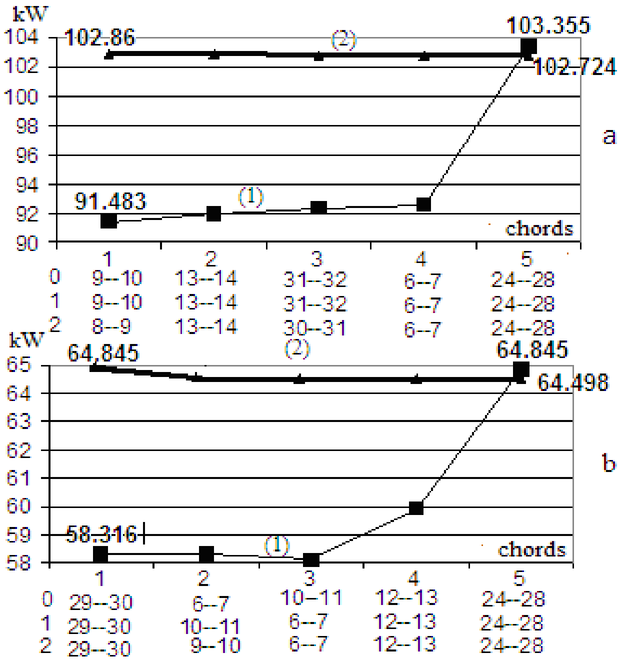

Figure 5. Change in power losses at reconfiguration of a test network (Fig.3), without (a) and with (b) renewable generation, 0 – an initial composition of chords, arranged in a descending order of currents in them; 1 – chords obtained after the first step (1); 2 – chords obtained after the second step (2).

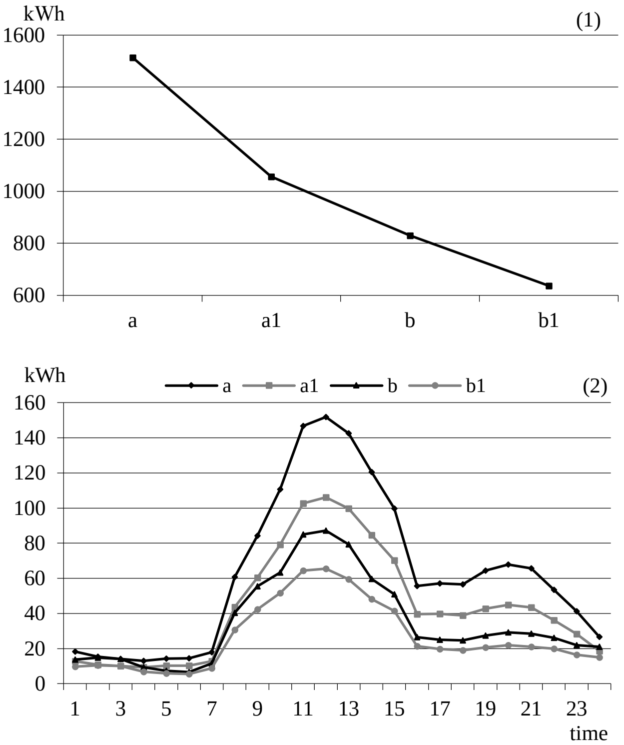

Figure 6. A change in the daily (1) and hourly (2) power losses in distribution network with and without reconfiguration and presence of renewable energy sources, a – without renewable generation and without reconfiguration, a1 – without renewable generation and with reconfiguration, b –with renewable generation and without reconfiguration, b1 – with renewable generation and with reconfiguration.

reconfiguration algorithm for a test network for loads and generation at hour 11. A reduction in the losses for the option with renewable generation after opening three tie lines in the first step is caused by the interchange currents.

Figure 6 presents the values of daily energy losses and curves of variation in hourly energy losses in a distribution network with and without reconfiguration and renewable energy sources.

Comparison of the losses made it possible to draw the following conclusions:

- Renewable generation has a greater effect on losses than network reconfiguration. The daily power losses make up 829.37 kWh and 1055.95 kWh, respectively;
- Simultaneous use of renewable generation and reconfiguration provides more than a two-fold reduction in losses equal to 636.98 kWh compared to the losses in the distribution network without renewable generation and reconfiguration, 1513.97 kWh;
- The involvement of renewable energy generation leads not only to a change in power flows in lines, but also to a change in their directions, and as a result, to an increase in the total number of switchings at daily reconfiguration. Their number without renewable energy sources is 16 and with renewable energy sources – 76.

A great number of switchings can lead to a switching cost commensurate with or exceeding the cost of reducing energy losses at reconfiguration. Figure 7 illustrates the possibility of selecting a constant distribution network configuration ensuring the minimum daily energy losses.

Figure 7 shows the values of daily losses under constant distribution network configuration coinciding with each of the hourly configurations obtained for it with and without renewable energy generation in the network. In the former case, such losses are compared with daily energy losses in the network without renewable generation but with reconfiguration, that are equal to 1055.95 kWh, and in the latter case, they are compared with the losses in the network

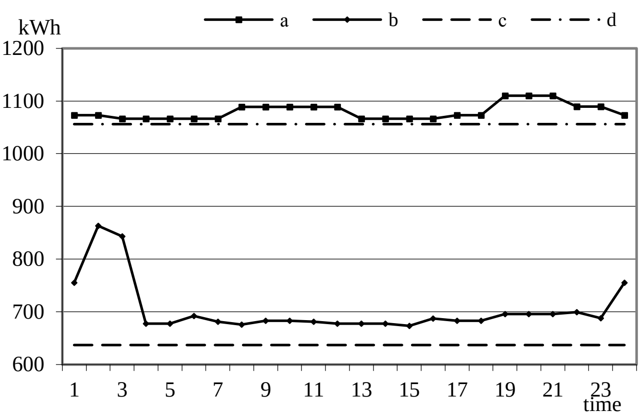

Figure 7. Comparison of daily power losses at constant configuration of distribution network without renewable generation – a, and with renewable generation – b, with daily losses obtained for optimal reconfiguration without renewable generation – c and with renewable generation – d.

with renewable generation and with reconfiguration, that are equal to 636.9 kWh.

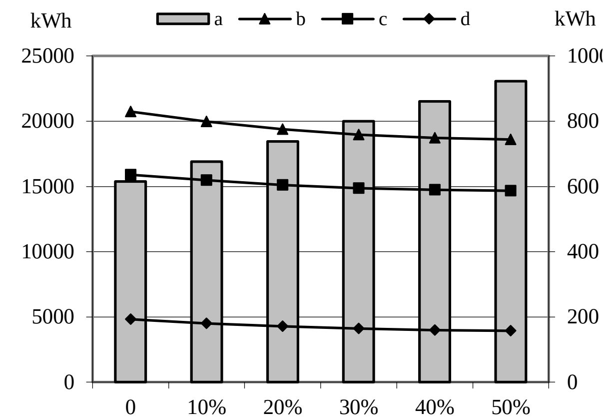

Figure 8. An increase in energy of renewable generation sources by 10%−50% − a, energy losses in distribution network without – b and with reconfiguration − c, a decrease in energy supplied to the distribution network

Comparison of daily losses shows that under constant configuration of distribution network with renewable generation that corresponds to hour 15, losses (673.6 kWh) will be higher than the optimal losses (636.9 kWh) by 36.7 kWh. Thus, a loss reduction by 36.7 kWh required 76 switchings. In the case study without renewable generation, the minimum losses under constant daily configuration coinciding for hours 3-7 and 13-16 differ from the losses under optimal configuration only by 10.5 kWh and require 16 switchings. The examples are indicative of the need to assess the cost-effectiveness of reconfiguration, which can be obtained by comparing the costs of switching and reduction in power purchase costs at loss reduction.

Figure 8 shows that with an increase in the energy received by distribution network from renewable generation sources by 10-50% in comparison with the initial values, the difference between losses in distribution network with and

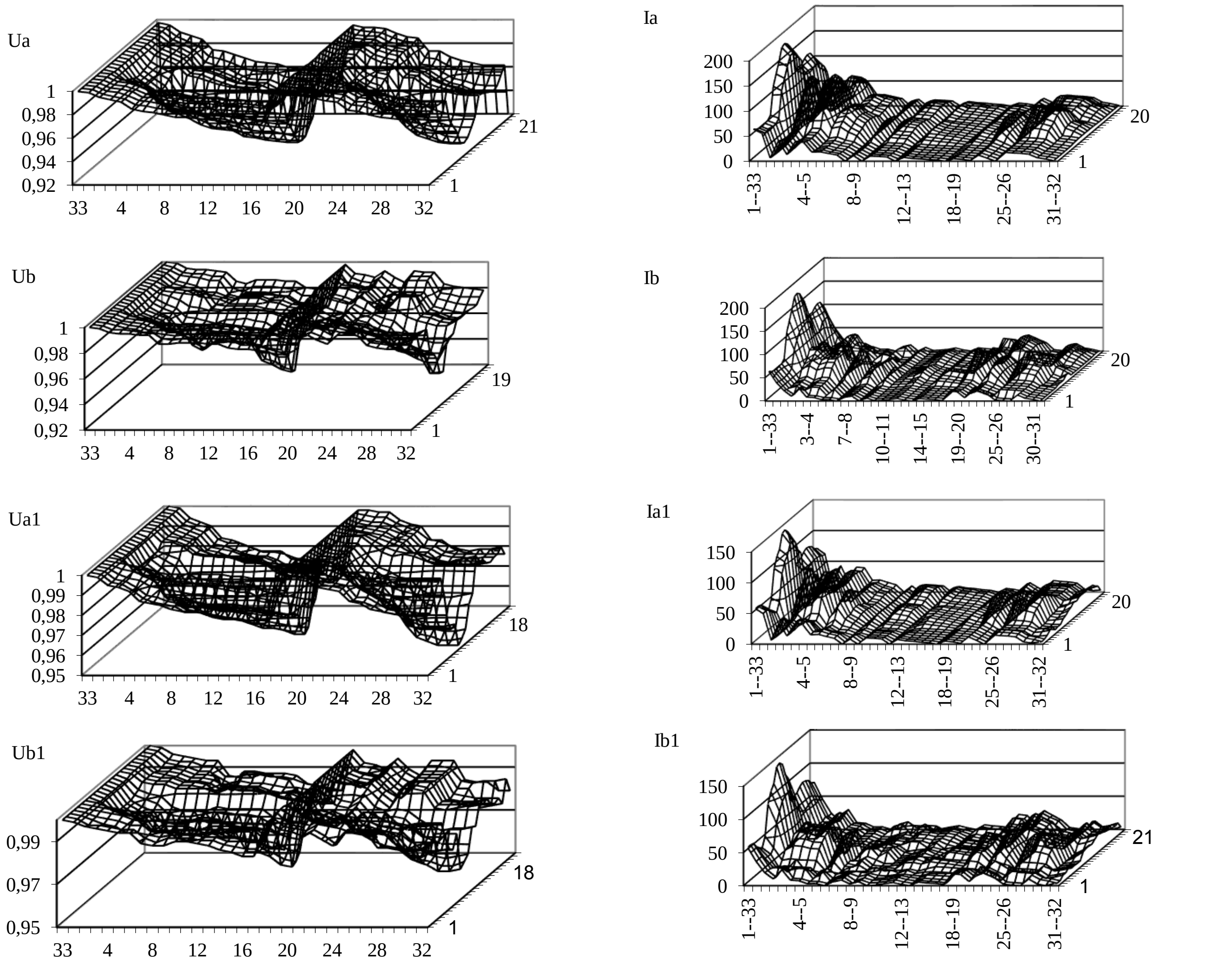

Figure 9. Hourly variations in voltage at nodes and current in branches of the test network with and without reconfiguration and renewable generation, Ua, Ia − (voltage and current) without renewable generation and reconfiguration, Ub, Ib – without renewable generation and with reconfiguration, Ua1, Ia1 – with renewable generation and without reconfiguration, Ub1, Ib1− with renewable generation and with reconfiguration.

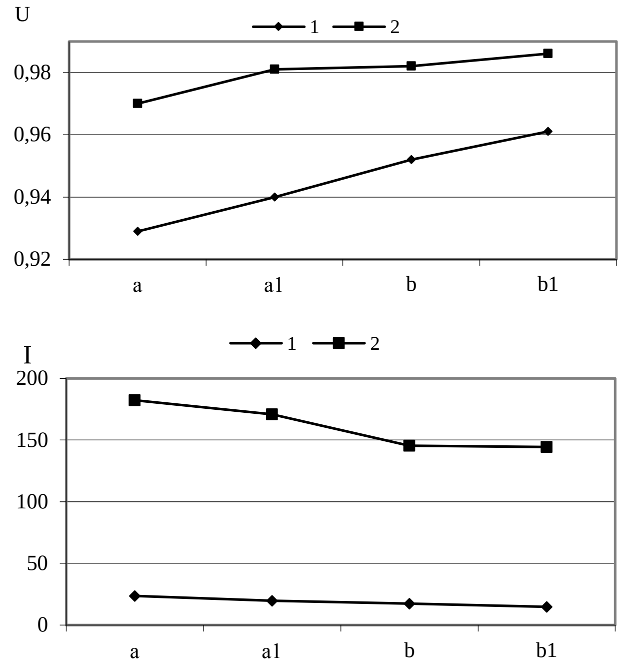

Figure 10. Minimum 1 and average 2 voltage (U), average 1 and maximum 2 currents (I) in tie lines, a – without renewable generation and without reconfiguration, b - without renewable generation and with reconfiguration, a1– with renewable generation and without reconfiguration, b1- with renewable generation and with reconfiguration.

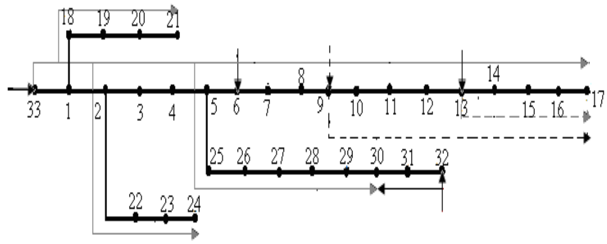

Figure 11. Active power flows from network and renewable generation sources to the load nodes

without reconfiguration is equal to the reduction in the energy coming to distribution network from the high-voltage network.

The savings in the purchase of additional energy can be used to offset the switching cost.

Hourly reconfiguration and involvement of renewable generation in the distribution network have a positive effect on both the reduction in losses and the decrease in the deviations in voltage and currents in the distribution network branches.

Figure 9 demonstrates the plots characterizing hourly variations in voltage at nodes and currents in branches of the test network with and without reconfiguration and renewable generation.

Their analysis made it possible to make the following conclusions, with their numerical confirmation demonstrated in Fig.10:

- Reconfiguration leads to a reduction in medium and maximum currents of feeders and fosters an increase in the number of nodes with high voltage.
- Renewable generation has a stronger effect on the reduction in average current and increase in voltage than reconfiguration. This is caused first of all by the fact that the distance of power transmission from source to load is educed. Figure 11 shows a scheme with disconnected tie switches with power flows going from the network and renewable generation sources.

The maximum reduction in current and increase in the minimum voltage are achieved when both renewable generation and changes in the distribution network topology by reconfiguration together affect the operation.

IV. Algorithm For Optimization Of Daily Load Curves

Optimization of daily load curves of load-controlled consumers is an additional effective way to minimize losses and reduce currents in distribution network. The problem of linear programming with constraints is applied to minimize the cost of electricity purchased at prices varying during the day

$$min\sum_{t=1}^{n_t}\sum_{i=1}^{n_p} c_t P_i^t \qquad (2)$$

where n_t – the number of hourly intervals during the day; n_P – number of load-controlled consumers; c_t –- power price at hour *t*; P_i^t – load of the i-th load-controlled consumer at hour *t*.

The constraints for each time interval include: equations of total balances of active and reactive power under constant power factor; equations of invariability of daily power consumption by each load-controlled consumer; and inequalities, determining feasible ranges of variation in power of load-controlled consumers and a slack node.

All the necessary information for solving problem (2) that lies in the determination of optimal hourly values of powers P_{i*}^t of the load-controlled consumer, is determined by calculating feasible load flow [13].

The repeated calculation of a feasible load flow is also made after solving problem (2). This is necessary for both the assessment of feasibility of all variables obtained after optimization of load curves and the assessment of an impact the optimization has on the reduction in daily energy losses. In the event that the constraints on the state variables in interval t_k are not met the upper $\overline{P_i^{t_k}}$ or lower $\underline{P_i^{t_k}}$ constraints on load $P_i^{t_k}$ are corrected:

$$\overline{P_i^{t_k}} = P_i^{t_k} + s_d^{t_k}\left(P_{i*}^{t_k} - P_i^{t_k}\right),\ if\ P_{i*}^{t_k} > P_i^{t_k};$$

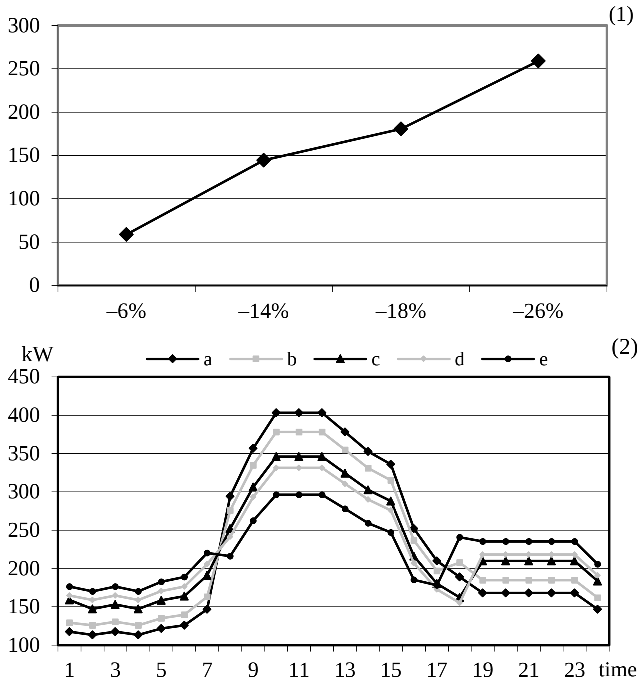

Figure 12. A cost saving on energy (1) in p.u. and change in the daily load curves of load-controlled consumers (2) at nodes 23, 24 under a feasible reduction in the maximum load at hours 8 - 17 of the day by 6% - b, 14% - c), 18% - d) and 26% - e) compared to the initial load curve a).

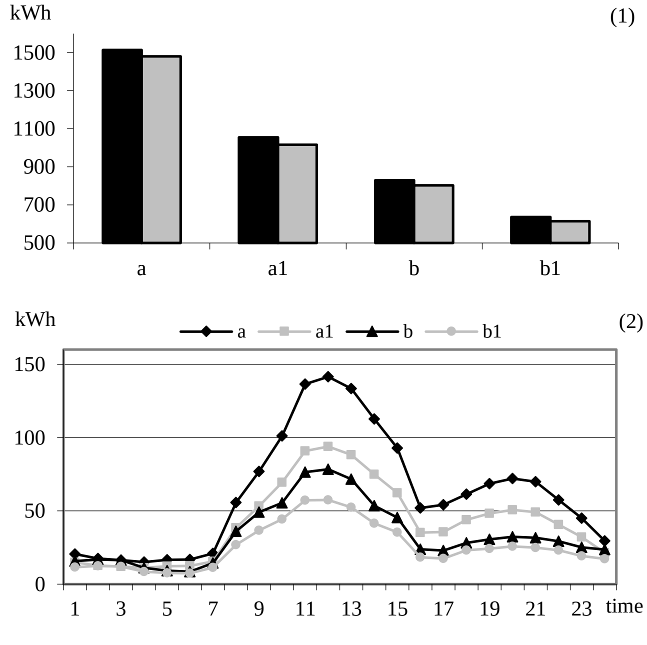

Figure 13. Values of daily energy losses without load-controlled consumers (black) and with load-controlled consumer (grey) with a feasible reduction in their maximum power by 26% (1) and values in hourly energy losses in the distribution network with load-controlled consumer (2) a – without renewable generation and without reconfiguration, a1 – without renewable generation and with reconfiguration, b – with renewable generation and without reconfiguration, b1 – with renewable generation and with reconfiguration.

$$\underline{P}_i^{t_k} = P_i^{t_k} + s_d^{t_k}\left(P_{i*}^{t_k} - P_i^{t_k}\right),\ if\ P_{i*}^{t_k} < P_i^{t_k},$$

where $s_d^{t_k} > 0$ – maximum feasible step of a variation in loads of load-controlled consumer in the direction of vector whose *i*–th component equals $\left(P_{i*}^{t_k} - P_i^{t_k}\right)$. After the limiting values in the intervals with unmet constraints are adjusted, problem (2) is solved again.

Figure 12 shows the saving costs of energy purchase at the prices varying during the day and variations in the daily load curves of load-controlled consumers at nodes 23 and 24 of a test network with the maximum total daily energy consumption equal to 10844.4 kWh.

The range of a feasible reduction in power of a load-controlled consumer from hour 8 to hour 17 is set equal to from 6 % to 26 %.

Figure 13 presents daily and hourly energy losses that make it possible to assess the contribution of the 26% reduction in maximum loads of the load-controlled consumer to the losses: in the distribution network without renewable generation (without reconfiguration and with reconfiguration), with renewable generation (with and without reconfiguration).

Comparison of the results demonstrates that load-controlled consumers have a lesser impact on the losses than renewable generation and reconfiguration. The daily losses equal to 613.91 kWh obtained by simultaneously using reconfiguration, renewable generation and load-controlled consumers are only by 23.07 kWh lower than the losses under the joint use of renewable generation and reconfiguration. The influence of load-controlled consumers on voltage losses in distribution network was also little. The introduction of load-controlled consumers in the cases with renewable generation without reconfiguration and renewable generation with reconfiguration reduced maximum currents in the distribution network from 145.34 A to 134.78 A and from 144.275 A to 133.716 A, respectively.

V. Assessment Of The Influence Of The Uncertainty If Load and Generation Data

The mathematical mean of power losses is known to increase with a rise in the uncertainty of nodal power data [13]. The question arises if the errors of determining hourly energy losses caused by the errors in the load and generation forecasts are commensurate with the payoff from the expected decline in losses under reconfiguration of the distribution network.

To answer this question we first determined optimal switchings and hourly and daily energy losses corresponding to them for the forecast values of nodal powers for each hour of a daily load curve and renewable generation. Then, the data on hourly loads, generation and hourly configuration of the distribution network were used to calculate the probabilistic load flow, which involved the determination of the standard

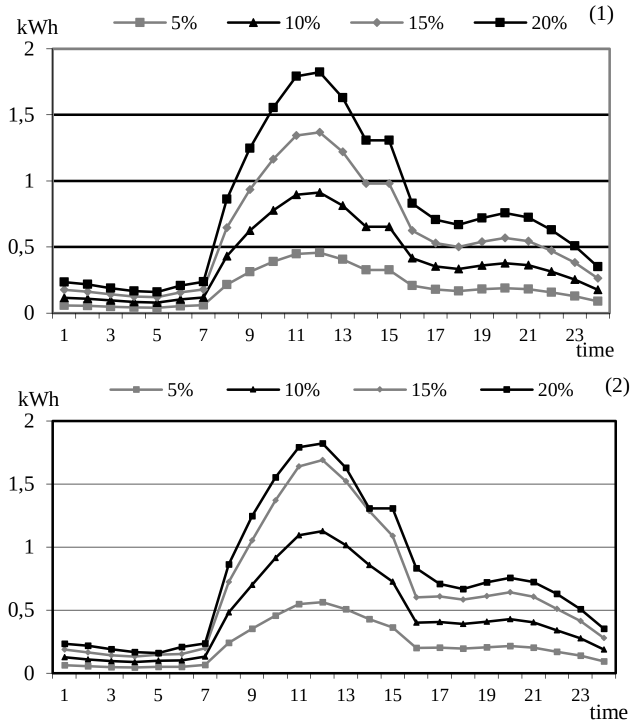

Figure 14. Standard deviation of hourly energy losses for the scheme with renewable generation and with reconfiguration (1), and without renewable generation and with reconfiguration (2).

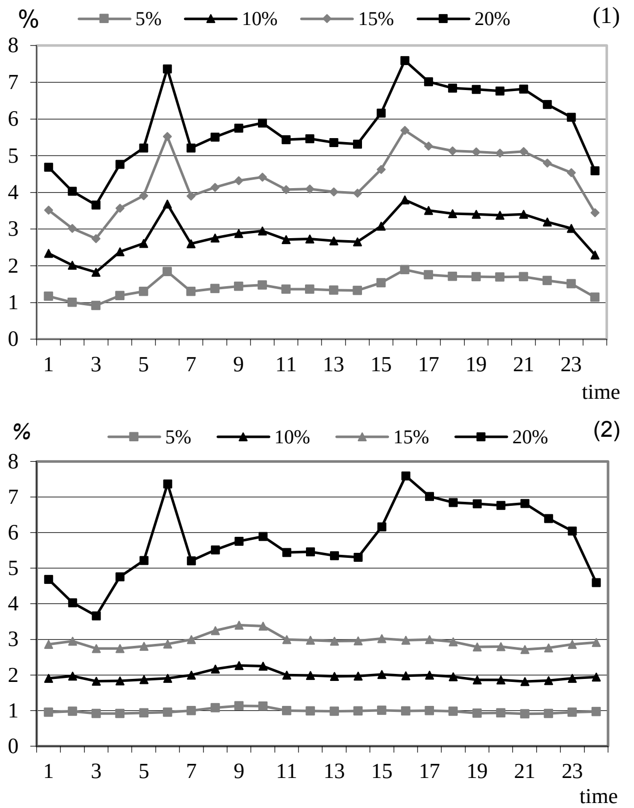

Figure 15. Errors in the determination of hourly energy losses for the scheme with renewable generation and with reconfiguration (1), and without renewable generation and with reconfiguration (2).

deviations of hourly energy losses.

The standard deviations of loads and generation of renewable generation necessary for probabilistic load flow were determined by using an inverse function of errors for a specified error of load and generation data, equal to 5%, 10%, 15%, 20% of their forecast values representing mathematical means.

The inverse function of errors enables the determination of standard deviations σ_x of normally distributed random variable x, by a specified value of interval $\Delta\varepsilon_x$, in which this variable will be with a set probability p, which in our case is equal to 0.95,

$$\sigma_{x_{p=0.95}} = \Delta\varepsilon_x / \left(\sqrt{2} erfinv(p)\right) = \Delta\varepsilon_x / 1.96 .$$

The probabilistic load flow was calculated by linear analytical method of moments. According to this method the mathematical means and covariances of nodal power at the point of solution to the nonlinear systems of steady state equations are used to calculate mathematical means and covariances of absolute values and phases of voltage, power flows and losses [14].

Interval $\Delta\varepsilon_x$ of a potential change in any of the indicated variables x, including that of energy losses, was determined by their standard deviations $\Delta\varepsilon_x = \sqrt{2} erfinv(p)\sigma_x$. An interval of a potential variation in the random value as a percentage of mathematical mean μ_x was determined as $\Delta\varepsilon_x\% = \sqrt{2} erfinv(p)\sigma_x \cdot 100\% / \mu_x$.

Figure 14 demonstrates standard deviations of hourly energy losses for distribution network with reconfiguration (with and without renewable generation). The deviations show that the hourly deviations of energy losses in both cases do not exceed 2 kWh. At the same time the hourly errors of determining energy losses, i.e. intervals of deviation of hourly

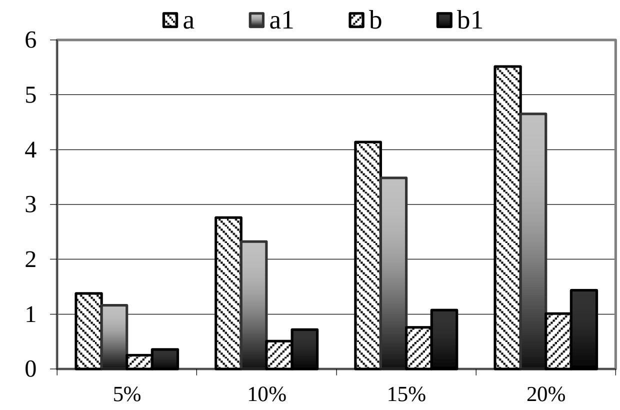

Figure 16. Standard deviations (a, a1) (kWh) and errors (b, b1) (%) of daily energy losses for the network with renewable generation and with reconfiguration (a, b), without renewable generation and with reconfiguration (a1, b1).

energy losses from their mathematical means (Fig.15), for a 20% error of the nodal power forecast do not exceed 8%.

Figure 16 demonstrates that with the maximum forecast error, the standard deviations and errors of daily energy losses do not exceed 6 kWh and 1.5% of the mathematical mean of losses.

The presented results confirm that with an increase in uncertainty of data on nodal power, hourly and daily energy losses rise, which cannot serve as grounds for the rejection of the reconfiguration aimed at reducing losses in the network.

VI. Conclusions

1. A topological algorithm for distribution network reconfiguration is generated to reduce power losses, and its possible application to the hourly network reconfiguration is demonstrated for the case of available renewable energy sources in the distribution network.

2. An algorithm is suggested to optimize daily load curve of a load-controlled consumer by the criterion of minimization of energy purchase costs, which also makes it possible to reduce the losses in distribution network.

3. The paper is focused on the study of the influence of renewable energy sources, hourly reconfiguration, optimization of load curve of load-controlled consumers, and their joint use on the daily energy losses.

4. The possibility of choosing an invariable distribution network configuration that provides the daily energy losses comparable with the losses determined at the hourly reconfiguration of distribution network is demonstrated.

5. The numerical results confirmed the effectiveness of the proposed algorithms.

6. The study shows that the errors in the calculation of losses rise with an increase in the errors of the nodal power forecast, but they do not have a decisive influence on the reduction in reconfiguration losses.

Acknowledgments

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Determination of Optimal Parameters of Heating Systems Based on Advanced Information Technologies

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***Abstract* — This paper presents a new method for the development of software to determine optimal parameters of heating systems. The method is based on the Model-Driven Engineering paradigm. The essence of this paradigm is that the software is generated on the basis of formal descriptions represented by models. This method makes it possible to automate the process of software development. The ontologies of heating systems, problems, and software are a means of representing the models. The paper proposes metaprogramming to make the software architecture flexibly adjustable to the problem of parameter optimization of a concrete heating system in the course of the problem-solving process. Metaprogramming technologies enable the development of software to change or create software components when solving the problem. The proposed method includes four stages: 1) development of a computer model of the heating system; 2) formalization of the applied problem; 3) automatic construction of the software model; 4) automatic development of the software on the basis of the model. This method underlies the SOSNA software intended for solving parameter optimization problems of heating systems. The software makes it possible to calculate large-scale systems with a complex structure with any set of nodes, sections, and circuits. The use of the software to control the expansion of heating systems will enhance their energy efficiency and cost-effectiveness. The software was applied to solve the optimal reconstruction problems of urban heating systems.**

***Index Terms* — Model-Driven Engineering, metaprogramming, ontology, software engineering, heating system, optimization methods, nonlinear programming.**

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I. Introduction

In the harsh Russian climate, heating systems are essential for the society and economy. Today's heating systems have turned into complex spatially distributed pipeline systems of district heating systems. Their complexity is related to their closed two-line schemes, a multi-loop structure, a great number of heat sources and control components (pumping stations, pressure and flow rate regulators, heat points). Nowadays, the requirements of efficiency, quality of heat supply to consumers and reliability of heating systems are increasing. Such requirements generate the need to develop and apply effective methods and software to design these systems.

Therefore, the determination of optimal parameters is crucial to ensure the efficient operation of heating systems. This task can be considered either individually or as a subproblem of a general process aimed at design of the heating system [1,2]. Large sizes of heating systems and computational complexity of applied models, methods and algorithms do not allow the determination of the optimal parameters of heating system without specialized software.

The paper presents the experience of applying the concept of Model-Driven Engineering (MDE) to create the next generation software to determine optimal parameters of heating system. This concept represents a set of methodological approaches to the automated construction of complex software systems based on the models developed in advance [3,4]. The MDE concept was used to implement the SOSNA (Synthesis of Optimal Systems in terms of Reliability) software. The software is intended for the determination of optimal heating system parameters. The development of the SOSNA software is automated. It is based on a virtual model of the heating system at issue, a formal description of the problem to be solved and knowledge on the subject domain, which are stored as ontologies [5,6]. The method proposed in the paper is universal and can be applied in the development of software for solving a wide range of problems related to design of heating systems and other pipeline systems.

The software is developed based on the advanced metaprogramming technologies [7]. The metaprogramming technologies make it possible to adjust the software to calculation of systems with different types of equipment (pipes made of steel and metal plastic, of various diameters, pumps, etc.) and different ways of its installation.

II. Determination Of Optimal Heating Systems Parameters And Methods To Solve This Problem

The optimization problem of heating system parameters is stated as follows. The set parameters include: 1) a heat network scheme consisting of m nodes and n branches, represented by directed graph $G_{\text{hss}} = (J, I)$, where J – a set of vertices (nodes), I – a set of edges (branches); $J = J_{\text{c}} \cup J_{\text{s}} \cup J_{\text{c}}$, where J_{c}, J_{s} and J_{c} – sets of consumers, sources and branching points in the scheme, respectively; $I = I_{\text{p}} \cup I_{\text{s}} \cup I_{\text{c}}$, where $I_{\text{p}} = I_{\text{e}} \cup I_{\text{n}}$ – a set of branches in the linear part of the network consisting of sets of existing I_{e} and new I_{n} branches; I_{c} and I_{s} – sets of consumer-branches and source-branches, respectively; $I_{\text{ps}} \subset I_{\text{s}} \cup I_{\text{p}}$ – branches on which pumping stations (PS) are either installed or allowed; 2) pipeline lengths in the network branches L_i, $i \in I_{\text{p}}$; 3) a set of standard pipeline diameters D; 4) a set of numbers of all pipeline construction (reconstruction) ways possible for the network U; 5) sets of numbers of pipeline construction (reconstruction) permissible for each branch $U_i \subset U$, $i \in I_{\text{p}}$; 6) lower ($P_j^{\min}$, $j \in J$) and upper ($P_j^{\max}$, $j \in J$) pressure constraints; 7) lower ($v_i^{\min}$, $i \in I_{\text{p}}$) and upper ($v_i^{\max}$, $i \in I_{\text{p}}$) constraints on heat carrier flow speed in branches; 8) vector of nodal heat carrier sinks and sources $\mathbf{Q} = (Q_1, \ldots, Q_m)^{\text{T}}$; 9) a set of heads at pumping station T; 10) constraints on the minimum available head at consumers' $\Delta H_i^{\min}$, $i \in I_{\text{c}}$.

By solving this problem we will determine optimal parameters of heating systems: 1) vector of pipeline diameters $\mathbf{d} = (d_1, \ldots, d_n)^{\text{T}}$; 2) vector $\mathbf{u} = (u_1, \ldots, u_n)^{\text{T}}$ with its components ($u_i \in U_i$, $i \in I_{\text{Л}}$) containing the numbers of optimal ways of pipeline construction (reconstruction); 3) vector of heads at pumping station $\mathbf{H} = (H_1, \ldots, H_n)^{\text{T}}$; 4) vector of heat carrier flow rates in branches $\mathbf{x} = (x_1, \ldots, x_n)^{\text{T}}$; 5) vector of pressures at nodes $\mathbf{P} = (P_1, \ldots, P_m)^{\text{T}}$.

It is necessary to minimize the total cost function that has the following form:

$$Z(\mathbf{d}, \mathbf{u}, \mathbf{H}, \mathbf{x}, \mathbf{P}) = \sum_{i \in I_{\text{p}}} Z_i^{\text{p}}(d_i, u_i) + \sum_{i \in I_{\text{ps}}} Z_i^{\text{ps}}(H_i, x_i) + \sum_{i \in I_{\text{p}}} Z_i^{\text{e}}(x_i, d_i) + \sum_{i \in I_{\text{p}}} Z_i^{\text{h}}(d_i) + \sum_{\substack{i \in I_{\text{c}} \\ \varphi(i) = (j,k)}} Z_i^{\text{c}}(x_i, P_j, P_k) \to \min, \quad (1)$$

where Z_i^{p} – costs of pipeline construction and operation in the network branch; Z_i^{ps} – construction and operation costs of pumping station; Z_i^{e} – cost of electricity used to pump a heat carrier; Z_i^{h} – cost of heat losses; Z_j^{c} – cost of electricity used to supply heat carrier to consumer; $\varphi(i)$ – function associating each branch $i \in I$ with a pair of incident nodes (j, k).

The model of flow distribution in heating system has the following form:

$$\mathbf{Ax} = \mathbf{Q}, \quad (2)$$

$$\mathbf{f}(\mathbf{x}, \mathbf{s}) = \mathbf{A}^{\text{T}}\mathbf{P} + \mathbf{H}, \quad (3)$$

where $\mathbf{A}$ – the node-branch incidence $m \times n$-matrix of the calculated scheme; $\mathbf{s} = (s_1, \ldots, s_n)^{\text{T}}$ – vector of hydraulic resistances of branches with components $s_i = s_i(d_i)$, $i \in I$; $\mathbf{f}(\mathbf{x}, \mathbf{s})$ – n-dimensional vector function with components $f_i(s_i, x_i) = s_i x_i |x_i|^{\beta - 1}$, $i = \overline{1, n}$, that reflect the laws of pressure drop in the network branches, β – exponent of power depending on pipeline type and heat carrier flow.

The system of conditions and constraints includes:

– a constraint on pressure at nodes

$$P_j^{\min} \le P_j \le P_j^{\max}, \ j \in J; \quad (4)$$

– a constraint on the heat carrier flow speed in the branches

$$v_i^{\min} \le v_i(x_i) \le v_i^{\max}, \ i \in I_{\text{p}}; \quad (5)$$

– a condition of discreteness of pipeline diameters

$$d_i \in D, \ i \in I_{\text{p}}; \quad (6)$$

– a condition of discreteness of pipeline reconstruction types

$$u_i \in U_i \subset U, ; \quad (7)$$

– a condition of discreteness of pumping station heads

$$H_i \in T, \ i \in I_{\text{ps}}; \quad (8)$$

– a constraint on available head at consumers

$$P_j - P_k \ge \Delta H_i^{\min}, \ \varphi(i) = (j, k), \ i \in I_{\text{c}}. \quad (9)$$

The minimization problem of function (1) subject to (2) - (9) is solved to determine the optimal parameters of the heating system.

Based on the theory of hydraulic circuits that was developed at Melentiev Energy Systems Institute SB RAS, we have devised effective methods for determining optimal parameters of heating systems. For branched networks, the method of step-by-step optimization was based on dynamic programming [1, 2]. For ring (multiloop $i \in I_p$) networks, we developed a multiloop optimization method based on the principle of successive improvement in solution [8, 1, 2]. An important characteristic of the enumerated methods is that they make it possible to flexibly adjust the computational procedure to the mathematical models of the used set of equipment.

Additive objective function (1) allows the application of dynamic programming for the determination of optimal parameters of branched heating systems: for the networks of such systems, the flow rates in branches $\mathbf{x}$ are uniquely determined by the tree-like structure and nodal flow rates $\mathbf{Q}$. The computational procedure based on dynamic programming suggests determining the parameters of network components (branches and nodes) by their successive fitting in the direction from consumers to sources [1,2].

The idea of the multiloop optimization method lies in decomposition of a complex optimization problem of ring heating system into two less complex subproblems [8,2]:

1) Determination of optimal parameters (diameters $\mathbf{d}$ and heads $\mathbf{H}$) of a network tree by dynamic programming method at fixed flow rates $\mathbf{x}$;

2) Calculation of flow distribution in a ring network (flow rates $\mathbf{x}$ and pressure $\mathbf{P}$) at fixed diameters $\mathbf{d}$ and heads $\mathbf{H}$.

The method of multiloop optimization suggests an iterative computational process aimed at successive improvement in the heating system parameters, during which the enumerated subproblems are alternately solved (Fig. 1). A stopping criterion for the computation is the termination of a decrease in the objective function or coincidence of pipeline diameters in neighboring iterations. Thus, by successively solving the subproblems at issue we will arrive at a solution that cannot be improved by the method of multiloop optimization.

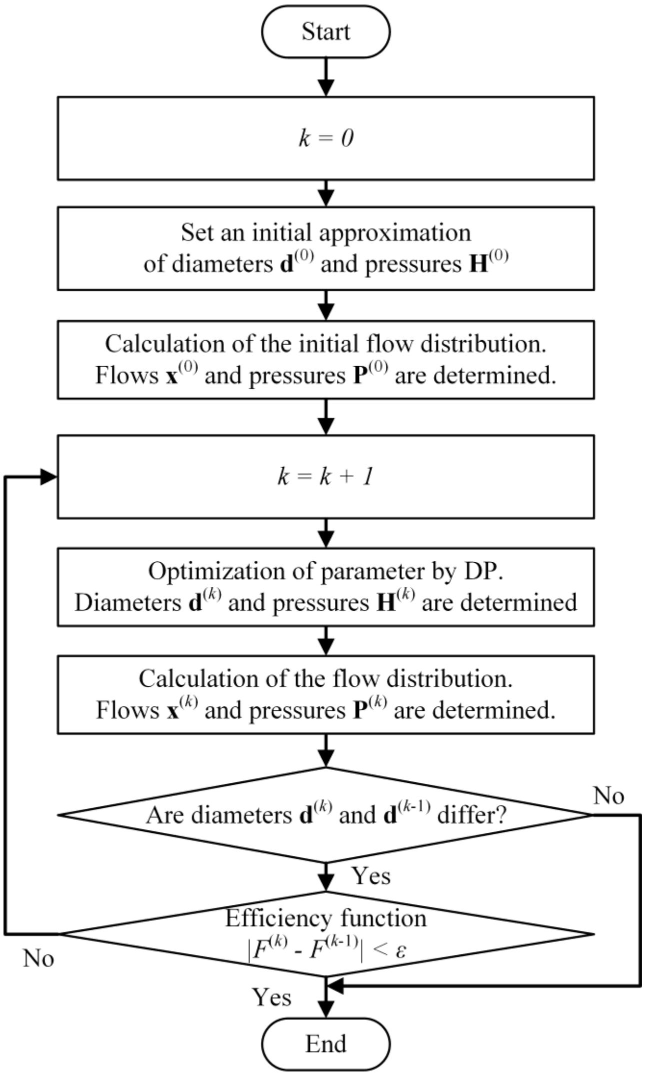

Figure1. A block-diagram of an algorithm for the determination of optimal parameters of a ring heat network by the multiloop optimization method, where N – iteration number; ε – set accuracy of the computational process

The calculation of flow distribution in the heating system is reduced to solving a system of linear and nonlinear algebraic equations. There are two main forms of such systems: with nodal flow distribution and loop flow distribution [1,2]. The problem statement in the case of nodal flow distribution implies the following. The specified parameters are: incidence matrix $\mathbf{A}$, vectors of nodal flow rates $\mathbf{Q}$ and heads $\mathbf{H}$, vector function of hydraulic characteristics $\mathbf{f}(\mathbf{x},\mathbf{s})$ and pressure P'_m at node m. It is necessary to determine the vector of flow rates in branches $\mathbf{x}$ and pressure at nodes $\mathbf{P}$, that satisfy the system of equations (2)-(3). This problem is solved by the pressure-based method [1, 2]. In the case of the loop flow distribution, the problem is solved by the method of loop flow rates [1, 2].

III. Literature Review

The development of method and software is based on the advanced metaprogramming technologies. Metaprogramming represents a programming technique capable to create programs that generate other programs when running, or programs that change themselves during execution. In Russia, the fundamental research in this area was conducted by A.P. Ershov. In 1958, he published his monograph "Programming Programme for the BESM Computer" [9]. The researchers from other countries are [7, 10, 11], to name but a few.

The automatic construction of a software system involves ontologies that make it possible to formalize the description of objects of a subject domain, their properties, and interactions among these objects. Currently, the ontologies are finding increasingly wider application in engineering [12]. Some researchers describe the experience of applying ontologies to solve power engineering problems [13, 14]. General issues related to the development and use of ontologies are discussed in [15, 16].

We have made an overview of the existing software designed to model pipeline systems and solve other energy problems. Further, a description of some software systems based on advanced information technologies is presented.

The EPANET software designed by US EPA (United States Environmental Protection Agency) offers good possibilities for modeling water pipeline systems [17]. It includes a graphical subsystem enabling work with the model of pipeline system and a set of software modules intended for solving applied engineering problems. Graphical interface is implemented in Delphi, the software modules are implemented in C++ and are connected to the main program as Dynamic Link Libraries. The software allows modeling of hydraulic conditions in the network, given all their characteristics. The program (software) includes the hydraulic analysis algorithms capable to analyze networks of any size without limitations, calculate head losses due to friction, by using the Hazen-Williams, Darcy-Weisbach and Chezy-Manning equations, and calculate head losses in branches and junctions. EPANET can also be used to simulate the application of pumps, calculate power consumption by pumps and costs, simulate different types of valves and throttles.

The Thermoflow software was designed by a group of authors headed by Maher Elmasri. The software consists of several modules that make it possible to solve a wide range of problems arising in heat power industry. The software ESteam developed by Veritech has a block structure and is capable to develop flow charts of steam turbine, gas turbine and combined cycle plants that can be used to conduct a variety of studies, introduce changes in the flow chart, represent grouped results in different ways, construct diagrams, etc. [18].

The heating systems can be designed with the software provided by different developers, for example, software from Polyterm Ltd, “Golfstream” from TIC “Sibnefteprodukt”, WADSOP, ArcView GIS, etc.

The Melentiev Energy Systems Institute SB RAS has developed original methods and software implementing these methods. This software is called a system for machine program building. This system, using the data on the flow chart components and links among them, can generate a program for calculation of a complex thermal facility [19].

The ANGARA information-computation environment developed at Energy Systems Institute SB RAS by A.V. Alexeyev, N.N. Novitsky, and V.V. Tokarev to solve the problems within the theory of hydraulic circuits involves a metadatabase for flexible access to computation modules and databases [20]. The ANGARA environment can be used to implement a technology for the end-to-end modeling of pipeline systems of different types and purposes (heat supply, water supply, etc.) with a single graphical user interface. This advanced and sought-after technology makes it possible with one software tool to obtain results relating solutions to the following tasks: 1) design; 2) calculation of states; 3) dispatching control. The process of solving the enumerated problems requires effective methods and algorithms implemented as software modules. The Angara environment ensures fast connection of the required modules, which allows flexible organization of computational processes and solving problems of any complexity.

Currently, a great number of IT specialists are investigating the methods and technologies for construction of complex software systems. These include but are not limited to: [21, 22, 23] and [9, 24].

It is also worthwhile to draw attention to the research

[25], conducted at Melentiev Energy Systems Institute. It is focused on the information technologies applied in systems studies in the field of energy and proposes an original approach to the integration of these technologies in the framework of a single software package.

The general issues of development and analysis of the algorithms are considered in the studies presented in [26-31].

Based on the literature review and an analysis of the existing software and approaches to its implementation, we can conclude that the issues addressed in the paper are of great importance.

IV. Description Of The Problem And Setting The Research Objectives

Evolution of the market for heat pipelines, equipment and technologies applied for heating system construction considerably expands the possibility for the implementation of various technical solutions. The expansion of the possibilities, in turn, requires their consideration when determining optimal parameters of heating systems, since each type of the applied equipment has its distinctive characteristics and is represented by its set of mathematical models defining its parameters and techno-economic relationships.

Concrete mathematical models for the calculation of the components of cost function (1) (Z_i^{p}, Z_i^{ps}, Z_i^{e}, Z_i^{h}, Z_i^{c}) and hydraulic characteristics of branches (s_i, $f_i(s_i, x_i)$, $v_i(x_i)$) are chosen depending on the properties of the used equipment (material, composition, way of construction, operating time, etc.).

We will bring several examples of mathematical models applied to determine optimal heating system parameters.

Function $f_i(s_i, x_i)$, showing the law of pressure drop in the network branch for a steel pipeline has the following form ($\beta = 2$):

$$f_i(s_i, x_i) = s_i x_i |x_i|.$$

Hydraulic resistance of branch s_i, where the steel pipeline is laid can be calculated by the formula

$$s_i = \lambda_i \frac{(1+\alpha_i)L_i}{d_i^{5.25}},$$

where λ_i – coefficient, depending on equivalent roughness of the branch pipeline; α_i – coefficient of local losses in the branch.

Costs of construction and operation of new pipeline Z_i^{p} are calculated by the equation

$$Z_i^{\mathrm{p}}(d_i) = (a + f_{\mathrm{p}})K(d_i)L_i,$$

where a – discounting coefficient; f_{p} – a share of depreciation charges for the pipeline; $K(d_i)$ – specific capital investment in the pipeline.

Melentiev Energy Systems Institute SB RAS has been developing software for the determination of optimal parameters of heating systems for 40 years [1,2]. The software modules of the previous generation that implement the methods and algorithms to cope with this task are intended for a certain set of equipment which considerably complicates their adjustment to the calculation of networks with some other set of equipment. Therefore, the need has arisen to develop and apply new adaptive approaches to adjust the software to modeling of real heating systems with a large set of equipment involved. The implementation of the next generation software for the determination of optimal heating system parameters calls for new methods capable to flexibly adjust software to specific features of expansion and characteristics of equipment of the studied heating system.

V. Methods For Model-Driven Engineering Of Software

Based on the conducted research, we propose a new method for model-driven software development based on the MDE conception [32]. This method allows automated software construction both to determine optimal parameters of heating systems and to cope with the other related tasks of heating system design. Let us present the main principles of this method.

1. Integration of a virtual model of a specific heating system, models of heating system components (i.e. individual subsystems) and methods (algorithms) is performed only in the context of an applied problem.
2. Software components depending on the properties of the modeled heating system (a set of models of heating system components) are developed automatically by using metaprogramming based on the virtual model of this heating system and ontologies that contain the description of equipment and applied problems to be solved.
3. The software intended for modeling a certain heating system is designed in the context of an applied problem with the help of metaprogramming, based on automatically constructed software models of heating system components, and components implementing the methods and algorithms for solving the applied problems. The process of software construction is controlled by the knowledge stored in ontologies: a heating system ontology, a problem ontology and a software ontology.

XML language [5] is used as a tool for formal representation of ontologies. This language was used to develop the domain-oriented language. MathML (Mathematical Markup Language. Site of the project: http://www.w3.org/Math/) is applied for storage of mathematical models of the heating system components.

The heating system ontology consists of: a description of a hierarchical structure of heating system; a classification of the equipment used in the heating networks and its technical characteristics; a description of heating system components and their parameters (technical characteristics, hydraulic parameters and boundary conditions); and a classification and description of the applied mathematical models (for example, equations defining the laws of head loss in the network branches, formulas for calculation of resistance, etc.). Figure 2 presents a fragment of the heating system ontology.

The problem ontology contains a description of the applied problems (for example, optimization of multiloop network parameters) and methods for solving them (for example, the multiloop optimization method), a description of algorithms, enumeration of parameters that represent initial data and parameters obtained by solving the problem.

The software ontology is intended for the storage of knowledge necessary to automate the construction and use the software. This ontology contains a description of software components, and their properties, metadata (input and output parameters, description of data formats), a description of technologies and interfaces for access to the software components.

The developed approach is intended for the use of Java [33] as the main language and programming platform.

The technique of model-driven software development includes four stages. A scheme demonstrating the interaction among the stages of this technique is presented in Fig. 3.

A. Stage 1. Construction of a virtual heating system model

In this stage, an engineer constructs a virtual hierarchical model of a specific heating system. This model represents a directed graph with its vertices corresponding to nodes (sources, consumers, connection nodes) and edges corresponding to branches (passive branches, active branches with pumping stations). For each component of the model, there is information on the installed equipment,

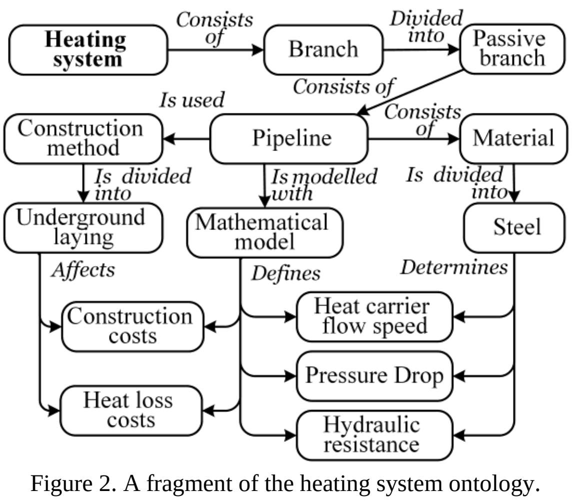

Figure 2. A fragment of the heating system ontology.

its characteristics and methods of construction. The obtained model is stored in a database for a repeated application. Figure 4 presents a model of heating system in two-line representation. It contains one heat source, transmission and distribution networks, and two heat consumers. A graphical schematic editor is used to construct the models of real heating systems consisting of thousands of components. This editor allows construction and use of calculated schemes of heating systems on a site plan.

B. Stage 2. A formal description of an applied problem

In this stage, an engineer formally describes an applied

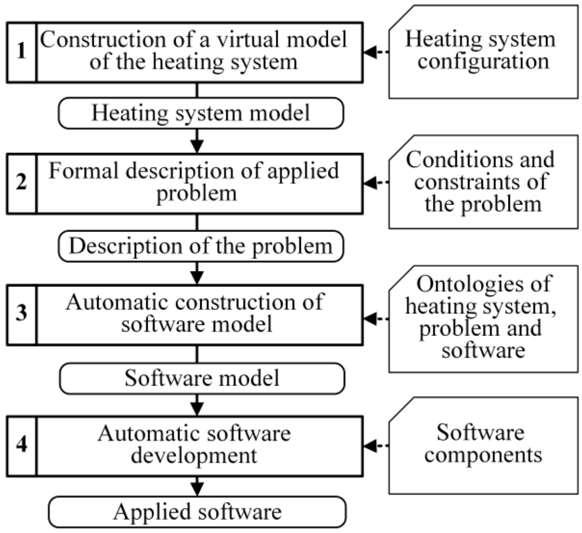

Figure 3. A technique for the model-driven software development.

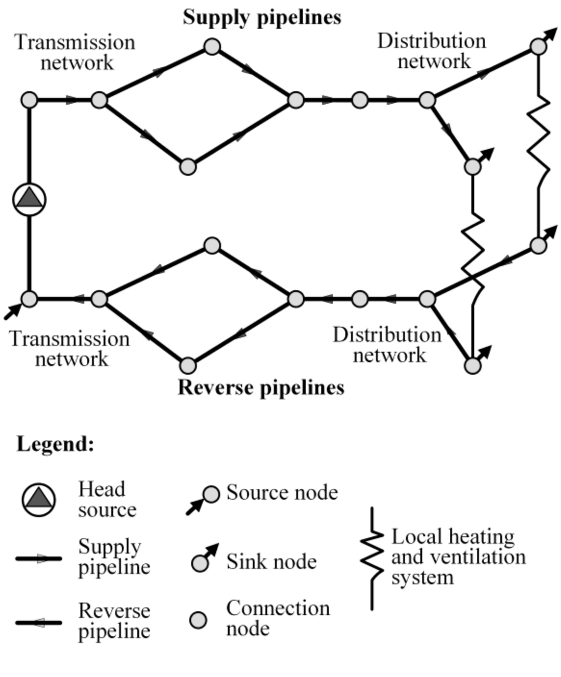

Figure 4. A model of heating system in a two-line.

problem. This implies setting conditions and constraints to determine optimal heating system parameters that include: 1) a set of standard pipelines and their characteristics; 2) constraints on pipeline construction (reconstruction) ways; 3) constraints on pressure at nodes; 4) constraints on speed of heat carrier flow; 5) design values of heat carrier sinks for consumers and heat carrier sources for sources; 6) a set of standard pumping stations and their characteristics.

C. Stage 3. Automatic construction of a software model

This stage suggests the creation of a software model intended for solving the applied problem. This model represents an aggregate of data structures that reflect the following software properties: a structure and composition of software components, description of a computational process in the form of an oriented graph, description of mathematical models of equipment, a list of applied methods and algorithms. The software model is built by an inference engine that for its operation uses a virtual model of heating system, a formal description of the problem and ontologies. The inference rules implemented in XSLT and XPath languages are applied for logical inference from the ontologies written in XML [34, 5].

An algorithm for automated construction of a software model includes the following steps.

Step 1. A list of equipment used to construct a heating system, and ways of its construction, is formed based on the virtual model of the heating system.

Step 2. A list of new equipment allowed to be installed for network reconstruction and ways of its installation is made based on formal description of the problem of determining the optimal heating system parameters.

Step 3. Based on the heating system ontology, the inference engine constructs the data structures that contain description of heating system component models necessary to solve the problem, based on the lists of equipment and ways of its installation that were formed in the previous steps.

Step 4. Based on the virtual model of the heating system, formal description of the applied problem and ontology of problems, the specific methods are chosen to solve the problems, a list of subproblems is made up, and the methods and algorithms are chosen.

Step 5. An oriented graph, defining the computational process is constructed to solve the problem of the determination of optimal heating systems parameters, based on the problem ontology. The nodes of this graph correspond to the steps of problem solving, and edges - to the links between them.

Step 6. Based on the list of methods and algorithms, the inference engine using the software ontology, makes a list of software components necessary to solve the problem of determining optimal parameters of the heating system.

Step 7. The data structures defining the relations “problem – method – component” are formed.

Step 8. Based on the description of components (implementing the methods and algorithms), and the software ontologies that were made in the previous steps, the component interfaces that implement mathematical models of heating system components are determined.

Step 9. Based on the problem ontology and software ontology, the data structures describing input and output parameters for each program component, types of data and ways of their transfer are formed.

D. Stage 4. Automatic construction of software based on its model

In this stage, the software is automatically developed based on its model, with the aid of metaprogramming techniques. The following subproblems are solved in the course of its development.

Subproblem 1. Formation of a set of software components implementing mathematical models of heating system components. Below is an algorithm of constructing a set of software models of heating system components. The algorithm consists of three steps.

Step 1. The development control component calls XSLT-processor to develop models of heating system components, necessary to solve the applied problem. XSLT processor, based on a list of equipment from the software model, mathematical models in MathML format and transformation rules in XSLT format, creates a set of data structures that contain a description of models of heating system components.

Step 2. The development control component calls code builder that, based on the data structures defining the models of heating system components, and the description of interfaces of software components from the software model, builds a software code in the Java language.

Step 3. The development control component calls the Java compiler that compiles a software code built in the previous stage to make a set of necessary models.

Subproblem 2. Loading of software components, that implement the methods and mathematical models, into the memory by the tools of reflective programming which is one of the metaprogamming types [35]. Integration of these components into a single software package is performed through standardized interfaces ensured by design patterns [21].

The system loader that implements the Factory design pattern does the following: 1) it receives a description of software components from the software model; 2) finds the components that correspond to the problem to be solved; 3) prepares data structures necessary for their fetching; 4) loads the components into the memory by using the reflective tools of the Java language; 5) transfers references to the components to the software integration environment.

Subproblem 3. Filling of the hash tables with pairs “number – reference”. These hash tables are used by software components represented by methods that receive references to the relevant software components represented by models, according to the numbers of mathematical models of components included in the heating system model.

VI. Results

The software obtained as a result of automated development according to the proposed methods consists of three architectural layers (Fig. 5): 1) a subsystem of computation control (supervisor) that contains the components controlling the computational process; 2) a computing subsystem that solves an applied problem by using the software components that implement methods, algorithms and models; 3) a subsystem of data storage that provides data exchange between database and local memory.

The developed SOSNA software has been successfully applied in Melentiev Energy Systems Institute to determine optimal parameters of heating systems when solving the problems of heating system design, expansion and reconstruction. The proposed methods of model-driven software development enable its flexible application in modeling of the heating systems with a large set of equipment.

The SOSNA software was used to perform multivariate calculations that made it possible to determine the optimal parameters and make recommendations on rational

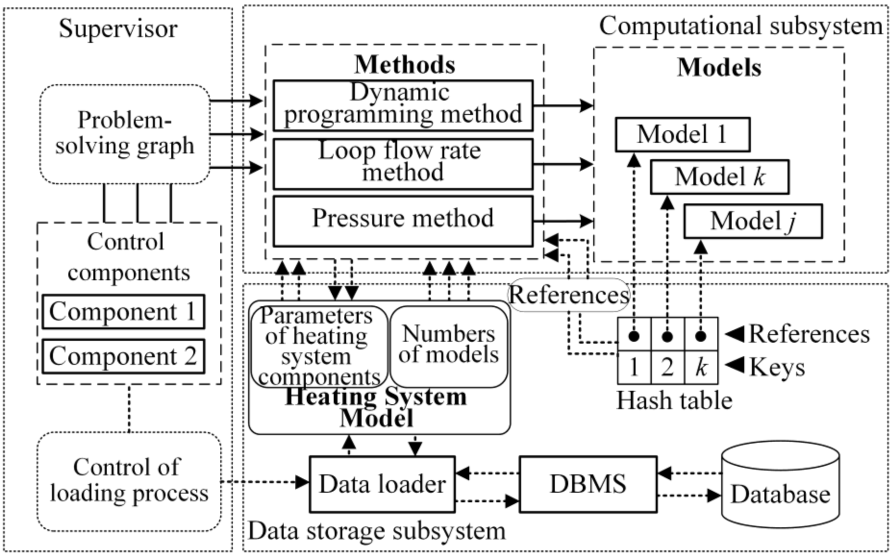

Figure 5. Architecture of software for optimization of heating system parameters.

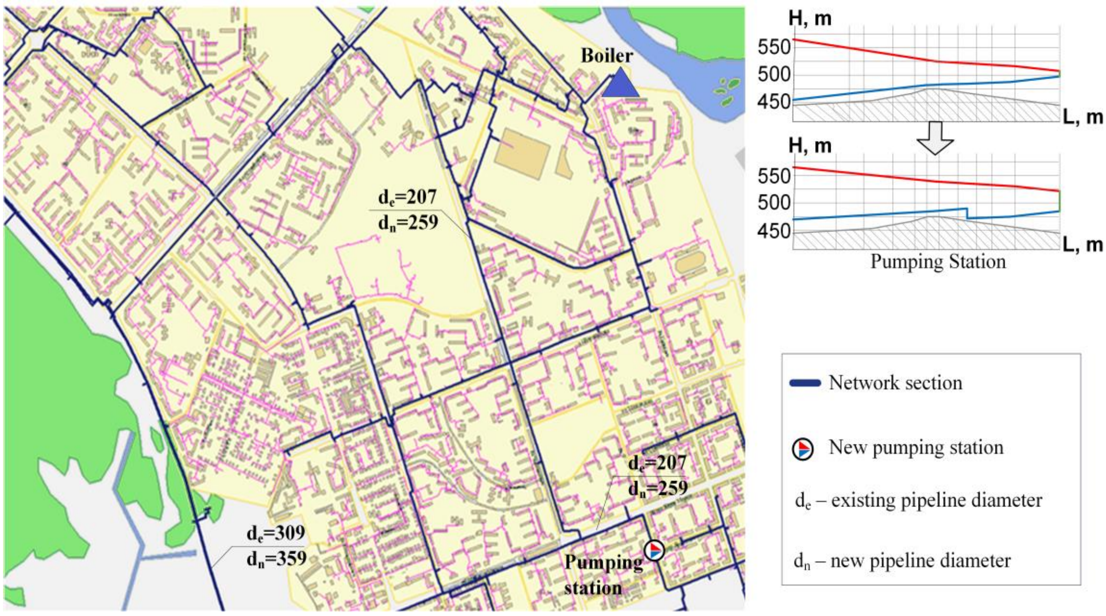

Figure 6. A fragment of Bratsk heating system with recommended reconstruction measures.

reconstruction and expansion of the heating systems in the Central and Admiralteisky districts of Saint Petersburg, the town of Bratsk (Fig. 6) and Magistralny urban-type settlement. The proposed recommendations on the reconstruction of the heating system ensure their adaptation to the growing heat loads and foster their optimal operation.

VII. Discussion And Conclusions

The paper proposes original methods for model-driven development of the SOSNA software aimed at determining optimal parameters of heating systems. These methods are based on the MDE conception that allows the development of sophisticated software packages in the context of an applied problem. The software takes into consideration the specific features of construction and makes recommendations on the equipment for the studied heating system. The software can be used by research, design and operation organizations dealing with heat supply. It makes it possible to generate reconstruction and expansion recommendations which can enhance heating system efficiency and provide the required quality of heat supply to consumers.

Acknowledgements

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Reduction and Equivalencing of Equations of Electrical Network based on Matrix Annihilators

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***Abstract*— This paper proposes an original method for the reduction of node voltage equations, aimed at equivalencing electrical network. The method is based on equivalent matrix transformations using matrix annihilators. The offered method, in comparison with the traditional one, makes it possible to improve the conditionality of the solved equations by an order of magnitude or more. This has a positive effect on the numerical stability of the resulting electrical network equivalents. The results of reduction of a small, large, and very large system of node voltage equations are presented.**

***Index Terms* — electrical network, nodal stress equations, reduction, matrix annihilator, equivalencing, conditionality, large and very large matrices.**

I. Introduction

It is well known that the calculation of electric power systems (EPS) conditions is multivariate. Solving the complete systems of equations covering all the nodes and connections of large power systems, even with simplified models, poses a serious problem, because of the lack of reliable information on all elements of the network. The problem is exacerbated by the need to accumulate and store large amounts of information [1] and the corresponding increase in the requirements for speed of computers [2].

The need to reduce the computation time arises mainly in multivariate and multimode calculations in operational control, and in EPS operation planning [3, 4]. Equivalencing makes it possible both to reduce the time of solving the node voltage equations (NVE), and to reconcile the amount of information and its error.

Equivalencing of EPS is the transformation (reduction) of a complex mathematical model into a simpler one while preserving the most important (required) properties within a given accuracy. This approach is widely used with the toolkit of Krylov subspaces [5]. There is one more approach to the calculation of EPS conditions, where equivalencing is reduced to the transformation of an equivalent circuit and its parameters to the one having a smaller number of nodes and branches and suitable for modeling of the initial EPS conditions.

The paper proposes an original NVE reduction method for equivalencing an electrical network. The method is based on the NVE matrix transformations with the help of algebraic objects, called annihilators of matrices.

This method, in comparison with the traditional algorithm based on the Schur complement, makes it possible to improve significantly the conditionality of the solved equations, especially for large (up to 10 000 equations) and very large (up to 100 000 equations) systems of NVE. It has a significant effect on the accuracy of the obtained electrical network equivalents and on the numerical correctness of numerical models.

II. The Traditional Approach To NVE Equivalencing

The procedure of equivalencing is given later as an example. Excluded nodes (set M) and nodes stored in equivalent units (set N) are given in [2].

The nodes were renumbered so that the first nodes were from the set N and the rest of the nodes were from the set M. In this case, the NVE were structurally divided into blocks (block matrices and subvectors)

$$\begin{bmatrix} \boldsymbol{Y}_{NN} & \boldsymbol{Y}_{MN} \\ \boldsymbol{Y}_{MN} & \boldsymbol{Y}_{MM} \end{bmatrix} \begin{bmatrix} \boldsymbol{U}_N \\ \boldsymbol{U}_M \end{bmatrix} = \begin{bmatrix} \boldsymbol{I}_N \\ \boldsymbol{I}_M \end{bmatrix}. \quad (1)$$

Here, $\boldsymbol{U}_N, \boldsymbol{U}_M$ – the voltage subvectors; $\boldsymbol{I}_N$, $\boldsymbol{I}_M$ – current sub-vectors in the vector

$$\begin{bmatrix} \boldsymbol{I}_N \\ \boldsymbol{I}_M \end{bmatrix}. \quad (2)$$

Submatrix $\boldsymbol{Y}_{NN}$ in the conductivity matrix

$$\begin{bmatrix} \boldsymbol{Y}_{NN} & \boldsymbol{Y}_{MN} \\ \boldsymbol{Y}_{MN} & \boldsymbol{Y}_{MM} \end{bmatrix} \quad (3)$$

is square and covers only the constraints on the set of nodes N, and the square submatrix $\mathbf{Y}_{\mathrm{MM}}$ corresponds to the

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connections on the set *M*. Note that $\boldsymbol{Y}_{NM}$ and $\boldsymbol{Y}_{MN}$ are rectangular matrices.

Expanding equation (1) up to the selected blocks

$$\begin{aligned} \boldsymbol{Y}_{NN}\boldsymbol{U}_N + \boldsymbol{Y}_{NM}\boldsymbol{U}_M = \boldsymbol{I}_N, \\ \boldsymbol{Y}_{MN}\boldsymbol{U}_N + \boldsymbol{Y}_{MM}\boldsymbol{U}_M = \boldsymbol{I}_M, \end{aligned} \quad (4)$$

and expressing the voltage vector of the excluded nodes $\boldsymbol{U}_M$ from the second equation (4), we obtain the equation

$$\begin{aligned} \left(\boldsymbol{Y}_{NN} - \boldsymbol{Y}_{NM}\boldsymbol{Y}_{MM}^{-1}\boldsymbol{Y}_{MN}\right)\boldsymbol{U}_N = \boldsymbol{I}_N - \\ -\boldsymbol{Y}_{NM}\boldsymbol{Y}_{MM}^{-1}\boldsymbol{I}_M \end{aligned} \quad (5)$$

which with the introduction of new notations

$$\begin{aligned} \boldsymbol{Y}_{NN}^{э} = \boldsymbol{Y}_{NN} - \boldsymbol{Y}_{NM}\boldsymbol{Y}_{MM}^{-1}\boldsymbol{Y}_{MN}, \\ \boldsymbol{I}_N^{э} = \boldsymbol{I}_N - \boldsymbol{Y}_{NM}\boldsymbol{Y}_{MM}^{-1}\boldsymbol{I}_M, \end{aligned}$$

is reduced to the equivalent form

$$\boldsymbol{Y}_{NN}^{э}\boldsymbol{U}_N = \boldsymbol{I}_N^{э}. \quad (6)$$

Thus, the equivalencing procedure considered above, for the given excluded nodes (set *M*) preserves only the nodes of the set *N* in the resulting equivalent solution (equivalent).

From a formal point of view, the described equivalencing procedure is based on the well-known *Schur complement algorithm* [6, 7]. One of the drawbacks of this approach is the complexity and, often, the impossibility of preconditioning ("regulation" of the conditionality) of the solved equations.

The next section of the paper describes an original method. This method is an alternative to the *Schur complement algorithm*, and the equivalencing method is constructed on its basis.

This method, as was said earlier, makes it possible to effectively affect the NVE condition, and, as a consequence, reduce the computational errors and increase the correctness of the equivalent solutions obtained.

III. Mathematical Justification Of The Alternative Method

The following notations and definitions will be used: $\mathbf{0}_{n\times m}$ – $n\times m$ zero matrix; $\boldsymbol{E}_n$ – $n\times n$ unit matrix; $(\cdot)^{\mathrm{T}}$ –transposed matrix; $(\cdot)^{+}$ –pseudo-inverse matrix according to Moore-Penrose; $(\cdot)^{\perp}$ – maximal rank matrix annihilator; $\mathrm{rank}(\cdot)$ – rank of the matrix; $\mathrm{size}(\cdot)$ – dimensions of the matrix (vector dimension); $\mathrm{null}(\cdot)$ – basis of the null space of the matrix; $\mathrm{cond}(\cdot)$ – condition number of the matrix; $||\cdot||$ –given vector norm [6, 7].

In this paper, the so-called left annihilator of matrices is used, which is called the annihilator. Recall [8, 9], that the maximal rank matrix annihilator of $m\times n$ matrix $\boldsymbol{M}$ of rank r is called matrix $\boldsymbol{M}^{\perp}$, and $\boldsymbol{M}^{\perp}\boldsymbol{M} = \mathbf{0}_{(n-r)\times m}$, with $\mathrm{rank}\left(\boldsymbol{M}^{\perp}\right) = n-r$.

For simplicity, we shall assume that the annihilators of zero satisfy the orthogonality condition $\boldsymbol{M}^{\perp}\boldsymbol{M}^{\perp\mathrm{T}} = \boldsymbol{E}_{n-r}$.

Well-developed methods for computing the null space $\mathrm{null}(\boldsymbol{M})$ of a matrix $\mathbf{M}$ can be used for calculation of annihilator matrices [6, 10]. In this case $\boldsymbol{M}^{\perp} = \mathrm{null}\left(\boldsymbol{M}^{\mathrm{T}}\right)^{\mathrm{T}}$

We will consider the NVE in the following block decomposition:

$$\left[\boldsymbol{A}_1 \;\vdots\; \boldsymbol{A}_2\right]\begin{bmatrix}\mathbf{x}_1 \\ \mathbf{x}_2\end{bmatrix} = \mathbf{b}, \quad (7)$$

where $\boldsymbol{A}_1$, $\boldsymbol{A}_2$ – are rectangular submatrices of

$$\mathrm{size}\left(\boldsymbol{A}_1\right) = n\times n_1, \quad \mathrm{size}\left(\boldsymbol{A}_2\right) = n\times n_2, \quad (8)$$

in this case $n_1 + n_2 = n$. The decomposition (7), (8) is clearly shown in Fig. 1.

The statement: the solution of linear equation (7) for invertible block matrix $\left[\boldsymbol{A}_1 \;\vdots\; \boldsymbol{A}_2\right]$ is determined by the equivalent formulas [9]

$$\begin{cases} \mathbf{x}_1 = \boldsymbol{A}_1^{+}\left(\mathbf{b} - \boldsymbol{A}_2\mathbf{x}_2\right), \\ \mathbf{x}_2 = \left(\boldsymbol{A}_1^{\perp}\boldsymbol{A}_2\right)^{-1}\boldsymbol{A}_1^{\perp}\mathbf{b}. \end{cases} \quad (9)$$

$$\begin{cases} \mathbf{x}_1 = \left(\boldsymbol{A}_2^{\perp}\boldsymbol{A}_1\right)^{-1}\boldsymbol{A}_2^{\perp}\mathbf{b}, \\ \mathbf{x}_2 = \boldsymbol{A}_2^{+}\left(\mathbf{b} - \boldsymbol{A}_1\mathbf{x}_1\right), \end{cases} \quad (10)$$

here $\boldsymbol{A}_1^{\perp}$, $\boldsymbol{A}_2^{\perp}$ are the left annihilators of zero of the maximal rank submatrices $\boldsymbol{A}_1$, $\boldsymbol{A}_2$, respectively, $\boldsymbol{A}_1^{+}$, $\boldsymbol{A}_2^{+}$ are the pseudoinverse matrices of the submatrices $\boldsymbol{A}_1$, $\boldsymbol{A}_2$.

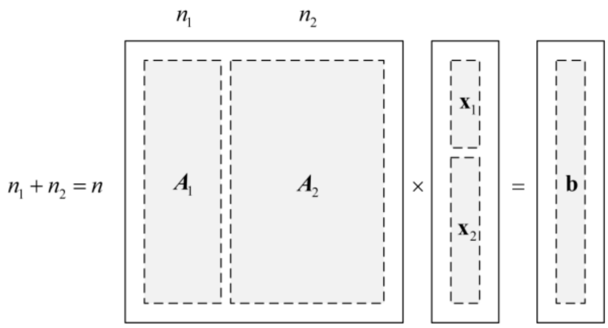

Figure 1. Block partition of matrices and vectors in the matrix equation.

IV. Reduction Of NVE Based On Matrix Annihilators

Considering NVE (1) in the division into blocks, as it is done in equation (7), we introduce the notations

$$\boldsymbol{Y}_N = \begin{bmatrix} \boldsymbol{Y}_{NN} \\ \boldsymbol{Y}_{MN} \end{bmatrix}, \quad \boldsymbol{Y}_M = \begin{bmatrix} \boldsymbol{Y}_{MN} \\ \boldsymbol{Y}_{MM} \end{bmatrix} \tag{11}$$

and write (1), taking into account (11). The obtained equation is

$$\begin{bmatrix} \boldsymbol{Y}_N & \boldsymbol{Y}_M \end{bmatrix} \begin{bmatrix} \boldsymbol{U}_N \\ \boldsymbol{U}_M \end{bmatrix} = \begin{bmatrix} \boldsymbol{I}_N \\ \boldsymbol{I}_M \end{bmatrix}. \tag{12}$$

Annihilator $\boldsymbol{Y}_M^{\perp}$ is introduced and it satisfies the following conditions:

$$\boldsymbol{Y}_M^{\perp}\boldsymbol{Y}_M = \mathbf{0}_{M\times M}, \quad \boldsymbol{Y}_M^{\perp}\boldsymbol{Y}_M^{\perp\mathrm{T}} = \boldsymbol{E}_{M\times M}. \tag{13}$$

Then, according to the first equation (10), from the theorem proved earlier we can write

$$\boldsymbol{Y}_M^{\perp}\boldsymbol{Y}_N\boldsymbol{U}_N = \boldsymbol{Y}_M^{\perp}\begin{bmatrix} \boldsymbol{I}_N \\ \boldsymbol{I}_M \end{bmatrix}. \tag{14}$$

Let us introduce new notations

$$\widehat{\boldsymbol{Y}}_{NN}^{\text{э}} = \boldsymbol{Y}_M^{\perp}\boldsymbol{Y}_N, \quad \widehat{\boldsymbol{I}}_N^{\text{э}} = \boldsymbol{Y}_M^{\perp}\begin{bmatrix} \boldsymbol{I}_N \\ \boldsymbol{I}_M \end{bmatrix}, \tag{15}$$

then, equation (14) can be rewritten in a generalized form

$$\widehat{\boldsymbol{Y}}_{NN}^{\text{э}}\boldsymbol{U}_N = \widehat{\boldsymbol{I}}_N^{\text{э}}. \tag{16}$$

Equations (6) and (16) are different, but they have the same solution $\boldsymbol{U}_N$. The principal difference of equation (16) is that it allows solving the problem of preconditioning in order to minimize computational errors simultaneously with equivalencing.

It is well known [6, 11, 12] that in order to reduce the influence of errors in the initial data, to increase the accuracy of the solution, and to accelerate the convergence of the iterative methods, various algorithms are used that usually consist of elementary transformations of rows (columns) of matrices in equation (7): scaling, regularization, balancing, change of conditioning (preconditioning, use of spectrally equivalent operators), etc.

With respect to matrix equation (16), the problem of reducing errors will consist in minimizing the ratio [11]

$$\tau = \frac{\left\|\Delta\boldsymbol{U}_N\right\| \cdot \left\|\widehat{\boldsymbol{I}}_N^{\text{э}}\right\|}{\left\|\boldsymbol{U}_N\right\| \cdot \left\|\Delta\widehat{\boldsymbol{I}}_N^{\text{э}}\right\|}. \tag{17}$$

However, the direct determination of the value τ in terms of the coefficients of the matrices of the original equation is difficult due to the nonlinearity of the valuation operation. Therefore, it is preferable to use a qualitative characteristic called the matrix condition number [6, 10, 11]. In the considered case, this number is

$$\operatorname{cond}\left(\widehat{\boldsymbol{Y}}_{NN}^{\text{э}}\right) = \left\|\widehat{\boldsymbol{Y}}_{NN}^{\text{э}}\right\| \cdot \left\|\left(\widehat{\boldsymbol{Y}}_{NN}^{\text{э}}\right)^{-1}\right\| \tag{18}$$

and it satisfies the inequality

$$\frac{\left\|\Delta\boldsymbol{U}_N\right\|}{\left\|\boldsymbol{U}_N\right\|} \le \operatorname{cond}\left(\widehat{\boldsymbol{Y}}_{NN}^{\text{э}}\right) \le \frac{\left\|\Delta\widehat{\boldsymbol{I}}_N^{\text{э}}\right\|}{\left\|\widehat{\boldsymbol{I}}_N^{\text{э}}\right\|}. \tag{19}$$

Given (15), the ratio (19) is transformed to the form

$$\frac{\left\|\Delta\boldsymbol{U}_N\right\|}{\left\|\boldsymbol{U}_N\right\|} \le \operatorname{cond}\left(\boldsymbol{Y}_M^{\perp}\boldsymbol{Y}_N\right) \le \frac{\left\|\Delta\left(\boldsymbol{Y}_M^{\perp}\begin{pmatrix} \boldsymbol{I}_N \\ \boldsymbol{I}_M \end{pmatrix}\right)\right\|}{\left\|\boldsymbol{Y}_M^{\perp}\begin{pmatrix} \boldsymbol{I}_N \\ \boldsymbol{I}_M \end{pmatrix}\right\|}. \tag{20}$$

The larger the condition number (18), the greater the impact of the original data errors on the solution to NVE.

Reduction of the condition number (18) can be achieved by further transformation of the NVE equivalent system (16) by introducing a new matrix $\boldsymbol{D}$, which should be [12] as close as possible to $\left(\boldsymbol{Y}_M^{\perp}\boldsymbol{Y}_N\right)^{-1}$, easily computable and easily invertible. In this case, the NVE will be replaced by the equation

$$\boldsymbol{D}\widehat{\boldsymbol{Y}}_{NN}^{\text{э}}\boldsymbol{U}_N = \boldsymbol{D}\,\widehat{\boldsymbol{I}}_N^{\text{э}},$$

where

$$\operatorname{cond}\left(\boldsymbol{D}\widehat{\boldsymbol{Y}}_{NN}^{\text{э}}\right) < \operatorname{cond}\left(\widehat{\boldsymbol{Y}}_{NN}^{\text{э}}\right).$$

V. Reduction Of A Small NVE System

Let us consider the computational example [9].

We analyze the electric network shown in Fig. 2 [2]. For convenience of calculation, we take all the line resistances to be the same $r_{ij} = 10\,\text{Ohm}$ ($Y_{ij} = 0{,}1$ S), except for the two lines $r_{13} = 20\,\text{Ohm}$ ($Y_{13} = 0{,}05$ S), $r_{24} = 5\,\text{Ohm}$ ($Y_{24} = 0{,}2$ S).

The basic mode corresponds to the NVE system

$$\begin{bmatrix} -0{,}25 & 0{,}1 & 0{,}05 & 0 \\ 0{,}1 & -0{,}4 & 0{,}1 & 0{,}2 \\ 0{,}05 & 0{,}1 & -0{,}25 & 0 \\ 0 & 0{,}2 & 0 & -0{,}2 \end{bmatrix} \begin{bmatrix} U_1^0 \\ U_2^0 \\ U_3^0 \\ U_4^0 \end{bmatrix} = \begin{bmatrix} -8{,}5 \\ 1 \\ -7 \\ -2 \end{bmatrix}, \qquad (21)$$

The results of the calculation are shown in Fig. 2.

Let us suppose that the set M of excluded nodes is 3 and 4. Then, matrix (3) has the following block decompositions:

$$\left[\boldsymbol{Y}_N \;\vdots\; \boldsymbol{Y}_M\right] = \left[\begin{array}{cc:cc} -0{,}25 & 0{,}1 & 0{,}05 & 0 \\ 0{,}1 & -0{,}4 & 0{,}1 & 0{,}2 \\ 0{,}05 & 0{,}1 & -0{,}25 & 0 \\ 0 & 0{,}2 & 0 & -0{,}2 \end{array}\right], \qquad (22)$$

considering that

$$\boldsymbol{Y}_M^{\perp} = \left(\text{null}\begin{bmatrix} 0{,}05 & 0 \\ 0{,}1 & 0{,}2 \\ -0{,}25 & 0 \\ 0 & -0{,}2 \end{bmatrix}^{\text{T}}\right)^{\text{T}} =$$

$$= \begin{bmatrix} 0{,}9646 & 0{,}0915 & 0{,}2295 & 0{,}0915 \\ -0{,}1837 & 0{,}6752 & 0{,}2333 & 0{,}6752 \end{bmatrix}$$

we have

$$\boldsymbol{Y}_M^{\perp}\boldsymbol{Y}_M = \begin{bmatrix} 0{,}9646 & 0{,}0915 & 0{,}2295 & 0{,}0915 \\ -0{,}1837 & 0{,}6752 & 0{,}2333 & 0{,}6752 \end{bmatrix} \cdot \begin{bmatrix} 0{,}05 & 0 \\ 0{,}1 & 0{,}2 \\ -0{,}25 & 0 \\ 0 & -0{,}2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Performing further calculations, we obtain

$$\widehat{\boldsymbol{Y}}_{NN}^{\text{э}} = \boldsymbol{Y}_M^{\perp}\boldsymbol{Y}_N = \begin{bmatrix} -0{,}2205 & 0{,}1011 \\ 0{,}1251 & -0{,}1301 \end{bmatrix},$$

$$\widehat{\boldsymbol{I}}_N^{\text{э}} = \boldsymbol{Y}_M^{\perp}\begin{bmatrix} \boldsymbol{I}_N \\ \boldsymbol{I}_M \end{bmatrix} = \begin{bmatrix} -9{,}8979 \\ -0{,}7473 \end{bmatrix},$$

$$\boldsymbol{U}_N = \widehat{\boldsymbol{Y}}_{NN}^{\text{э}\;-1}\,\widehat{\boldsymbol{I}}_N^{\text{э}} = \begin{bmatrix} 85{,}0 \\ 87{,}5 \end{bmatrix},$$

which exactly corresponds to the values indicated in Fig. 2.

It is worth noting, that the condition number of matrix (3) and the conductivity number of original matrix (22) is $\text{cond}\left[\boldsymbol{Y}_N \;\vdots\; \boldsymbol{Y}_M\right] = 15{,}9373$ for the original matrix, and

$$\text{cond}\,\widehat{\boldsymbol{Y}}_{NN}^{\text{э}} = \text{cond}\begin{bmatrix} -0{,}2205 & 0{,}1011 \\ 0{,}1251 & -0{,}1301 \end{bmatrix} = 5{,}5204,$$

for the equivalent, which is less by almost 3 times. This number can be further reduced if $\boldsymbol{Y}_M^{\perp}$ is

$$\boldsymbol{Y}_M^{\perp} = \begin{bmatrix} 6{,}6150 & 4{,}7836 & 3{,}2365 & 4{,}7836 \\ 3{,}5836 & 8{,}6518 & 4{,}1774 & 8{,}6518 \end{bmatrix} \qquad (23)$$

The use of annihilator (23) in the calculations provides

$$\widehat{\boldsymbol{Y}}_{NN}^{\text{э}} = \begin{bmatrix} -0{,}2205 & 0{,}1011 \\ 0{,}1251 & -0{,}1301 \end{bmatrix} \qquad (24)$$

$\text{cond}\,\widehat{\boldsymbol{Y}}_{NN}^{\text{э}} = 1{,}2444$, which is by more than an order of magnitude less than $\text{cond}\left[\boldsymbol{Y}_N \;\vdots\; \boldsymbol{Y}_M\right]$. In this case, the matrix

$$\boldsymbol{Y}_{NN}^{\text{э}} = \begin{bmatrix} -0{,}24 & 0{,}12 \\ 0{,}12 & -0{,}56 \end{bmatrix}.$$

calculated by the traditional method, has a 3,5 times greater condition number than matrix (24).

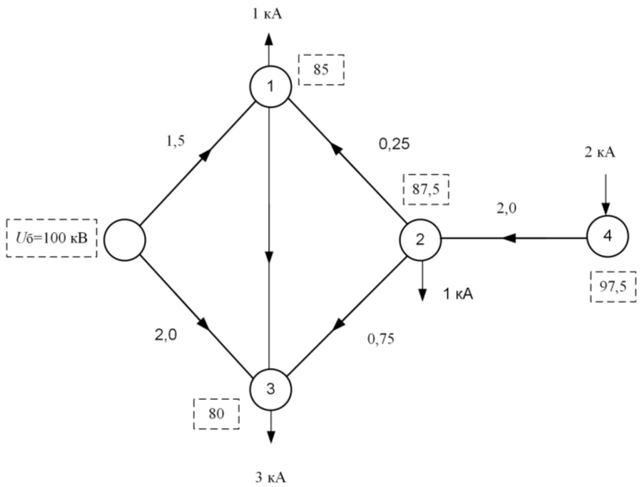

Figure 2. The scheme of the electrical network in the basic mode.

VI. Reduction Of A Large NVE System

Let us consider the reduction in a large NVE system, the basic mode of which corresponds to a matrix

$$\text{size}\begin{bmatrix} \boldsymbol{Y}_{NN} & \boldsymbol{Y}_{MN} \\ \boldsymbol{Y}_{MN} & \boldsymbol{Y}_{MM} \end{bmatrix} = 1000\times1000$$

and vector of

$$\text{size}\begin{bmatrix} \boldsymbol{I}_{N} \\ \boldsymbol{I}_{M} \end{bmatrix} = 1000 .$$

Matrix (3) and vector (2) for the basic mode are dense and their elements vary within the following limits: $-4,2; ...; 5,7$. The total number of non-zero elements of the matrix from (3) is $\sim 9,91\cdot10^5$.

Let the set M of excluded nodes be equal to 995, and, accordingly, the number of nodes $N = 1000 - 995 = 5$.

Calculation by formulas (11) – (16) in *Matlab*, using orthogonal annihilators leads to the following results:

$$\widehat{\boldsymbol{Y}}_{NN}^{э} = \begin{bmatrix} 1,8571 & -0,7800 & 1,4434 & 0,4049 & -0,4329 \\ -0,7242 & 0,6592 & 1,5200 & 0,5827 & 1,6713 \\ 0,2350 & -0,3492 & -0,6982 & 0,9702 & -1,3692 \\ -0,6484 & -0,6965 & 0,0061 & -1,1241 & 0,5262 \\ -0,8512 & 0,2244 & 0,1312 & 1,1808 & 1,2175 \end{bmatrix}, \quad (25)$$

$$\widehat{\boldsymbol{I}}_{N}^{э} = \left[0,7807; -0,1045; -1,4519; -0,2478; \ -0,1782\right],$$

$$\boldsymbol{U}_N = \left(\widehat{\boldsymbol{Y}}_{NN}^{э}\right)^{-1} \widehat{\boldsymbol{I}}_{N}^{э} = \begin{bmatrix} 1,6907 \\ 0,4469 \\ -0,8643 \\ -0,3758 \\ 1,4110 \end{bmatrix}. \quad (26)$$

In this case, the condition number of matrix (25) is 7,8019, and the Euclidean error rate of solution (26) with respect to the exact value of the solution vector is 3,825310^{-13}.

Calculations using conventional methods allow us to obtain the following matrix and vector

$$\boldsymbol{Y}_{NN}^{э} = \begin{bmatrix} 41,7122 & 19,8072 & -2,6691 & 84,1475 & -29,5413 \\ -55,6173 & -48,4439 & 9,7584 & -51,1095 & 43,1407 \\ -84,5763 & -19,1018 & 14,5854 & -42,1711 & 75,9152 \\ 87,8123 & 63,1374 & -21,0482 & 19,9958 & -59,6218 \\ 49,3494 & -8,4865 & 36,5263 & 64,3591 & -27,9839 \end{bmatrix} \quad (27)$$

$$\boldsymbol{I}_{N}^{э} = \begin{bmatrix} 8,3722 \\ -44,0346 \\ -41,1712 \\ 103,2302 \\ -15,6018 \end{bmatrix},$$

with more than 3,5 times the Euclidean norm of the error with respect to the exact value of vector 1,465110^{-12}. The condition number of matrix (27) is 39,4146 and it is almost 5 times higher than the condition number of matrix (25).

VII. Reduction In A Very Large NVE System

Let us suppose that a very large NVE system is given, whose dimension is 10^4. Matrix (3) has no zero elements, thus the number of non-zero elements is 10^8, that is one hundred million ($100\cdot10^6$). In this case, the elements in the matrix and vector (2) vary in the range from $-10,7$ to $11,5$. Suppose that the set of excluded nodes M is equal to $9\cdot10^3$, which means that the number of nodes left is $N = 10^4 - 9\cdot10^3 = 100$.

As a result of the calculations, the 100×100 matrix was obtained and it had the condition number $\text{cond}\ \widehat{\boldsymbol{Y}}_{NN}^{э} = 47,3464$, while the condition number of matrix $\boldsymbol{Y}_{NN}^{э}$ with the same size, was $\text{cond}\ \boldsymbol{Y}_{NN}^{э} = 10390,4112$, that is more than 200 times higher.

We note that it is not possible to directly use the Schur complement algorithm for such a large matrix. In this case, the authors used the parallelization of the computation process.

VIII. Conclusion

An original equivalencing algebraic method is proposed to reduce the equations of electric network steady-state conditions on the basis of matrix annihilators. The method allows transformations of the equivalent circuit and its parameters to a form having a significantly smaller number of nodes and branches. Numerical procedures for computing matrix annihilators are well developed for large ($100 \le n \le 1000$) and very large ($10^3 \le n \le 10^5$) matrices, while the variation in the annihilators properties makes it possible to significantly (ten times and more) improve the conditionality of the resulting NVE equivalents and thereby reduce computational errors and improve the correctness of the solution.

Acknowledgment

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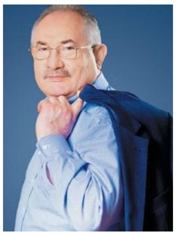

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A Reliability Analysis of State Estimation Software Based on SCADA and WAMS

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***Abstract* — The procedure of state estimation of electric power system (EPS) remains relevant for control of electric power facilities. Traditionally, the quality of state estimation results depends on the quality of input information, i.e. telemeterings and synchronized phasor measurements; proper design of equivalent circuit, specification of its parameters; and characteristics of communication channel. However, the quality of the applied SE software is normally not analyzed during its operation, while it is necessary to periodically check and assess whether or not it operates properly in real conditions. Moreover, timely updating of applied algorithms is also very important to increase the reliability of software operation. The paper proposes an analytical approach to the assessment of SE software operability based on the fault tree technology. The focus is made on various aspects of improvement in reliability of power system SE software during its operation.**

***Index Terms* — State Estimation, Fault Tree, SCADA, WAMS, Reliability of SE software.**

I. Introduction

There are universal indicators including those based on the queuing theory for software reliability that can reveal the level of its working capacity in terms of functionality and delivery of result. Application packages, different libraries of standard algorithms, and operating systems belong to this software type. SE software is specialized, and it is intended to provide quality results (based on a deep analysis of the input data) affecting the control of a technological process. It is extremely important to know how the SE software behaves under real conditions. Therefore, it is crucial to develop such indicators for software fault tolerance that would enable the protection of weak components of program blocks, and, thereby, increase the SE software operability in any hostile environment.

Being a complex property, reliability in general includes fault-free operation, durability, maintainability, and storability [1]. The software reliability level features the probability of its fault-free operation over a certain time interval. In [2], the authors propose the following reliability indicators: the average number of correctly solved problems over a certain time interval Δt1, the mean number of errors for that interval, the probability of solving a set number of problems for the time interval Δt2, the probability of emergence of a set number of errors for that interval, etc. Such indicators may be used for any software.

In [2], to analyze the software reliability the authors enumerate the factors leading to software faults: errors in the program, use of non-optimal and imperfect algorithms (for example, heuristics use), restricted real-time operation (the system state changes faster, than the computing cycle lasts). Interaction of several factors and hardware problems in the computing system may also lead to software faults.

For the software designed for on-line control of EPS to be as less vulnerable to various failures as possible, it should be based on:

- Accurate mathematical models of computational schemes and equipment applied in them;
- Highly redundant measurement system, provided by backup measurement devices;
- Robust algorithms for initial data verification (a priori, a posteriori, robust);
- Repeated testing of software, firstly on simulation and then on real-world data.

Failure of software operating in control system can lead to serious consequences for the process of control.

Knowing well the SE software object domain, we will try to develop other reliability indicators that account for the specific features of the solved problems and feature the fault tolerance of this very software.

In this paper, we propose a fault tree to analyze the consequences of technical failures and faults in the data acquisition and data processing systems (SCADA and WAMS) and in the SE software. Based on the analysis of the measurement information and on the SE results, we

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determine the reliability level for SE software, and propose some measures to increase its reliability

II. Electric Power System State Estimation Software And Computing Environment

A. *EPS data processing by State Estimation software*

The effectiveness of the EPS control is largely determined by reliability and quality of data on state variables of EPS.This information, coming to EPS Control centers, represents telemeasurements, telesignals, PMU measurements, pseudo measurements (zero injections at transit nodes, nodal loads from dispatcher records, etc.), a priori data on the accuracy of measurements (variances) and parameters of the EPS network. The available information is normally insufficient to control the state of the entire system. Random errors in the initial data as well as bad data can lead to wrong control decisions. This explains the need to solve the SE problem within the software for on-line control of optimal conditions of the Unified Power System of Russia.

An analysis of EPS observability [3] in state estimation determines if it is possible to estimate the power system state based on a set of available measurements. Considerable corruption in the SE results can be avoided by including a Bad Data Detection (BDD) algorithm in the SE software. EPS SE is performed for an equivalent circuit of network, and, normally, in real time. Errors in telesignals can lead to a wrong topology of the computational scheme.

SE software calculates steady state, using the measurements for the current computational scheme of the EPS. The obtained steady state is used as a reference state for solving various on-line control problems. Therefore, the obtained estimates of the state variables should lie within a feasibility region, i.e. meet the equality and inequality constraints. The estimates going beyond the feasibility region generate the need to consider constraints directly during performance of each individual control function, which can cause a considerable delay in decision making. Therefore, the program intended for the consideration of inequality and equality constraints specified for both measured and unmeasured state variables should be included in the real-time SE software [4, 5, 6].

The EPS SE software is intended to obtain the EPS current state model from telemetery and telesignals arriving from SCADA and phasor measurements from WAMS.

For the SE software to operate with WAMS, a traditional algorithm of linear SE (LSE) is used on the basis of state vector in rectangular coordinates [7]. The linear state estimation is also successfully performed using the test equation (TE) method developed at the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences [4, 8]. This method has a number of advantages over the traditional non-linear approach, the main of them being a possibility of a-priori bad data detection.

B. *Supervisory Control and Data Acquisition (SCADA) fault tolerance*

SCADA system includes: remote telemetry units (RTUs) installed at EPS substations to take telesignals on the switching equipment state and measurements of the state parameters, communication channels, database (DB), systems of on-line display of the state parameters, as well as the software (EMS-application) to process the measurement and to form control commands for dispatching management objects. Figure 1 presents the structure of a SCADA installed at the control center of a regional network company.

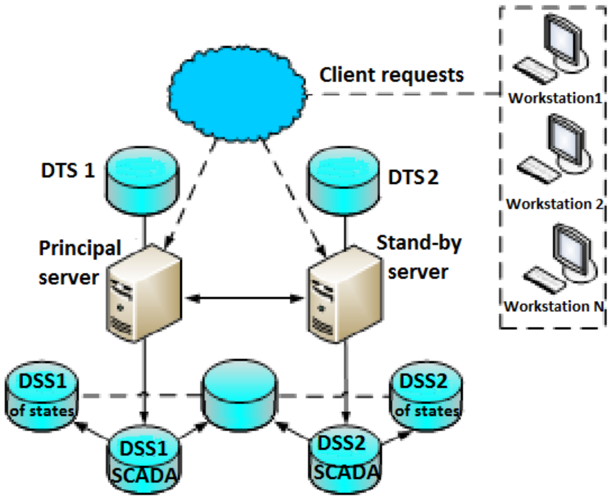

Figure 1. SCADA structure.

The SCADA operates at two independent servers, Principal (1) and Standby (2). The servers constantly exchange requests. For each server, their own data transmission system (DTS) and data storage system (DSS) are provided. Herewith, DSS 1 and DSS 2 constantly synchronize their data. Every 30 minutes, the data are transmitted to the historic server, at which reservation is provided continuously.

An absence of response from Principal Server 1 is considered as a fault, and the system switches to Standby Server 2. This occurs at minimal delays not noticeable for the user.

There can be two types of failures: 1) hardware failures, and 2) software failures. After a failure at the Principal Server, the software is restarted (in case, it was a program failure), or it is switched to a Standby Server. Client requests go to the Principal Server, and, in case of its failure, they are redirected to the Standby Server with no request latency change.

In case of the DSS1 failure, the Principal Server switches to DSS2 with minimal delays. In case of the DTS1 failure, the incoming data stream is directed to DTS2. As practice shows, failures seldom arise in such systems. Software failures occur once a month, on average, hardware failures occur once a year.

C. WAMS Data Acquisition (DA) Automatic System (AS) fault tolerance [9]

In 2009-2011, to solve the problems in acquiring and storing the WAMS information, a WAMS Data Acquisition Automatic System (WAMS DA AS) shown in Fig.2 was created and put into industrial operation.

PMU, being the lowest hardware level transmits phasor measurements (PMs) to the system under Protocol C37.118-2008/2011 to phasor data concentrators (PDCs) for further use in calculations. PMs are relayed to a higher level of dispatching control to the super-PDC corresponding to the control hierarchy. This architecture is simple, reliable, and perfectly suitable to solve problems in the absence of restrictions for the computing and telecommunication infrastructure. The measurements are kept in the DB of own design [9]. The system servers are connected in a cluster operating synchronously: they interact with each other and exchange the information with data sources and clients.

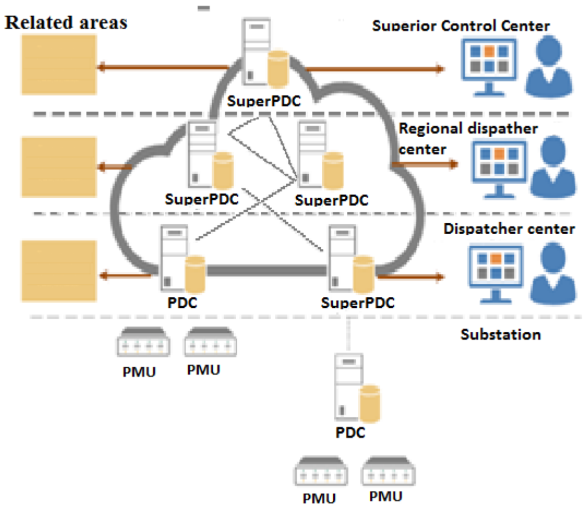

Figure 2. Structure of WAMS Data Acquisition Automatic System [9].

The DBs included in the cluster are synchronized among themselves. The facilities ensuring fault tolerance within the system allow us to create clusters of 2 and more servers. The storage is scaled over almost unlimited number of servers (up to 65535). Failure of any two servers will not lead to information loss.

On the one hand, the DA AS architecture is hierarchical, because the servers are at all the levels of the dispatcher control; on the other hand, the cloudy technology is used, when the places of data storage and their traffic routes are not anchored rigidly. This increases the DA AS fault tolerance.

III. Block Diagram Of The SE Software For The Reliability Analysis

SE software will operate correctly, as long as all three elements are operable: measurements, the network, and SE algorithms:

- analyze the network observability;
- identify and detect gross errors in PM and telemetry (TM);
- filter random TM errors, i.e., to receive their estimates and to finally calculate non-measured parameters.

Let us represent the SE software, a program tool, as a technical system that is to operate safely and properly. For the initial analysis, we make a block diagram (Fig.3). As the Figure demonstrates, most of the SE software components are reserved.

Measurements: when there are no PMs, the SCADA measurements are used; if there are no both PM frame and SCADA snapshot, SE software can operate with archival snapshot. Moreover, the incoming measurements are recorded in the real-time DB (RT DB) that is also reserved;

Network: the data on the diagram are stored on the DB server of constant information; at computer centres of major power facilities, a standby server and a standby DB are provided; a special algorithm forms the current (operational) network based on the basic scheme from telesignals;

Algorithms: algorithms for the observability analysis (OA), for the measurement validation, and for the SE are reserved by alternative blocks.The SE software produces the fastest solution, when the LSE algorithm functions. Therefore, the OA program should determine, whether the network is PMU-observable. If the OA answer is negative and LSE is impossible to run, OA is performed by a set of SCADA measurements (here is the example of the OA algorithm redundancy) for non-linear SE (here is the example of the SE redundancy). Redundancy for the algorithm of the a-priori validation by test equations is represented by a-posteriori validation by SE remainders. When analyzing the reliability of complex systems, however, it is necessary to find which of the elements are critical and whose serious faults affect the system operability to a greater extent, in general. Typical criticality indicators [2] are the fault probability, the severity of consequences, the element tolerance to malicious activities, the risk value due to a fault, the possibility of fault localization, the controllability of the element state during the operation, reserving, etc. Ranging the elements by the criticality degree is possible at different levels of structuring the system objects. Critical elements may be visually provided by the Fault Tree technology

IV. Fault Tree Technology

For the first time, the term "fault tree" in Russian literature was mentioned in Yu. Guk's book [10]. Known since 1960s, the Fault Tree Analysis technology applied by expert systems in military aviation, then in nuclear power, and in some other industries [11, 12], appeared a convenient means to analyze the operation capacity (fault tolerance) of any technical system or its separate complex nodes. The fault tree is presented in the form of a hierarchical structure:

- Level 1 - tree root - is the addressed technical system;

- Level 2 is the system indicators featuring this system;
- Level 3 - system elements - is the details of system indicators;
- Level 4 - tree leaves - is the events leading to a fault of the system operability (technological problems);
- Level 5 – the lowest level is the measures to suppress the fault causes.

procedures etc.). Basic elements are exposed to these or those failures or technical faults which are on the forth level of Fault Tree. At the tree lowest level, there are counter-measures written in italics. The set of counter-measures enables the calculation of the indicators for the EPS SE algorithm operation efficiency and fault tolerance.

Figure 4 shows the block "Analyzing program", the program determining the most vulnerable SE software components in terms of fault tolerance. This determination is based on the statistic block that stores the calculated indicators for a certain period of time (both blocks are given in bold).

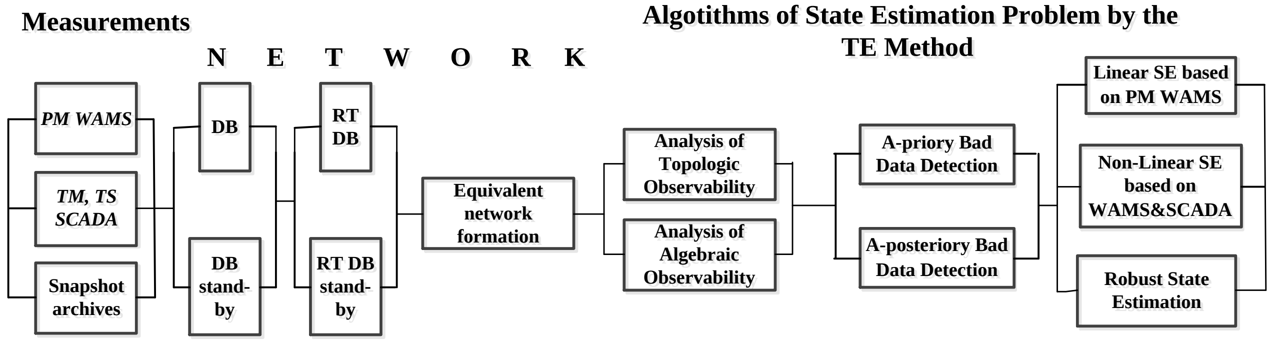

Figure 3. State Estimation Software block diagram.

Figure 4 presents the SE software fault tree to analyze the reliability of its operation. At the top level, there is SE software itself. The system indicators (measurements, network, algorithms) is the second level. Those indicators contain basic elements (measurements types, databases,

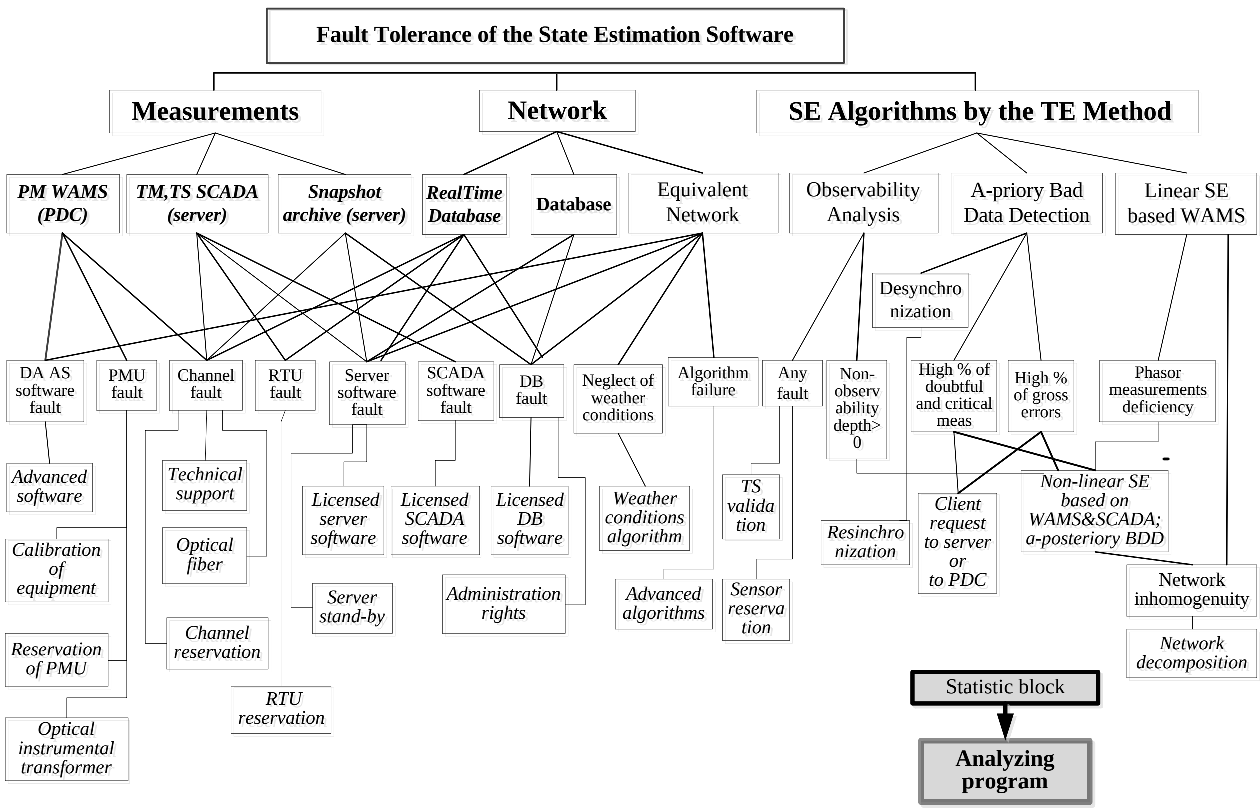

Figure 4. Electric Power System State Estimation Software Fault Tree.

Unlike the known term "decision tree" [13], the fault tree suggests that the total of possible options to solve a problem decreases up to the number of options obviously threatening the operability of the addressed technical system. In fact, the fault tree is a diagnostic method offering a way out of a specific problem situation.”

V. Fault Probabilities For The Fault Tree elements

The Analyzing program is run several times per day after a certain time, in which N runs of the SE software are executed. Due to series connections of basic components (“Measurements” - “Network” - “Algorithms”, see Fig.3) the probability for the SE software fault tolerance is calculated as follows [14]:

$$P_{SE\_soft} = P_{meas} \times P_{network} \times P_{alg}, \qquad (1)$$

in any other case, the SE software is non-operative, i.e.,

$$Q_{SE\_soft} = 1 - P_{SE\_soft}. \qquad (2)$$

In turn, due to parallel connections of elements, the probability for the basic component “Measurements” fault is calculated as follows

$$Q_{meas} = Q_{PM} \times Q_{TM} \times Q_{archive}, \qquad (3)$$

where Q_{meas} is the fault probability of the measuring part, $Q_{PM}, Q_{TM}, Q_{archive}$ are the faults of phasor measurements, telemeasurements and pseudomeasurements, respectively; $Q_{meas} = 1$ means that no measurements are available for the SE software.

Equivalent circuit (current network) formation is switching of the network elements, which imposes telesignals on the basic scheme, integrating the adjacent nodes into one node at the switched-on bus-tie switch, and substituting several parallel lines with a single equivalent line. The procedure of equivalent circuit formation can fail only if the algorithms for its construction contain errors. Fault tolerance of some elements can be improved by their reservation [15] (see Fig.3 – DB stand-by and RT DB stand-by):

$$Q_{network} = 1 - (1 - Q_{TS})(1 - Q_{DB}^2)(1 - Q_{alg\_forming\_network}) \qquad (4)$$

Procedure for the observability analysis (OA) initially checked if the number and structure of measurements in the SCADA snapshots corresponded to the network graph. A special algorithm was used for allocation of SCADA sensors to improve the quality of network observability. This algorithm indicated the sites poorly equipped with sensors and provided recommendations on placement of sensors and measuring channels [3]. At present, along with SCADA measurements, phasor measurements are also used in EPS. Therefore, now, the algorithms for the WAMS sensor allocation are developed considering possible failures of individual connections, sensors, and loss of measurements [16].

Observability analysis enables the detection of the observable and unobservable fragments in the network. It is known that, voltage phasor measurements at a node and current phasor measurements in the adjacent line can be used to obtain a calculated PM value at a node on the other end of this line. Such a sensor location in the network (area), when all the absent nodal measurements may be calculated by the available PMs, is called "non-observability depth equal to 0" [17]. If the available real and calculated PMs do not provide a completely PM-observable network, we consider the network "unobservability depth" equal to 1 and more (which implies measurement insufficiency for the LSE operation) as a failure of the OA procedure for the LSE.

$$Q_{OA} = \frac{n_{stop\_unobserv \ge 1}}{N_{run\_SE\_software}}. \qquad (5)$$

If the LSE cannot be performed, the procedure of nonlinear SE is run based on the SCADA and WAMS data.

A failure of the OA procedure for the nonlinear SE is practically impossible due to special options supporting observability in up-to-date nonlinear SE software, $Q_{OA\_for\_nonlinearSE} = 0.0001$. Thus, for LSE or nonlinear SE the failure is:

$$Q_{OA} = Q_{OA\_LSE} \times Q_{alg\_OA}, \quad \text{or} \quad Q_{OA} = Q_{OA\_SE} \times Q_{alg\_OA}. \qquad (6)$$

The procedure of the a-priori BDD based on the test equation method is performed before the SE procedure. It shows: the number of reliable and non-reliable measurements received by the SE software, the number of critical measurements which when excluded lead to non-observable parameters whose errors cannot be detected; and the groups of doubtful measurements, in which it is impossible to detect the erroneous measurements. The measurements with the detected gross errors (bad data) are replaced with specified ones during the algorithm operation. Thus, their variance values increase, which reduces the trust in such measurements. It is much worse, if the measurements contain critical ones that do not belong to test equations, and doubtful ones, whose quality cannot be checked at a given set of test equations. Therefore, we will consider a high percent of the doubtful and critical measurements in the incoming snapshot as a failure of the a-priori validation procedure:

$$Q_{apriori\_doubt} = \frac{n_{run\_SE\_with\_high\%\_doubt\_meas}}{N_{run\_SE}} \qquad (7)$$

$$Q_{apriori\_critical} = \frac{n_{run\_SE\_with\_high\%\_critical\_meas}}{N_{run\_SE}} \qquad (8)$$

Herewith, the SE software operation does not stop, because, further, the algorithms for the robust SE and for the a-posteriori BDD are started. Correspondence between the SCADA snapshot time tags and those of WAMS is a strict requirement for the BDD procedure.

The LSE procedure is solved non-iteratively. An indispensable condition for its start is the observability of the entire equivalent network through PMs. Therefore, the LSE algorithm fault is:

$$Q_{LSE} = Q_{OA} \times Q_{a\lg\_OA} \quad (9)$$

In our Fault Tree, the algorithms for nonlinear SE, robust SE and for the a-posteriori BDD are presented as the counter-measures against the SE software operability faults (see Fig.4). Given the series connection of blocks of the system indicator "Algorithms", we obtain

$$Q_{a\lg} = 1-(1-Q_{OA})(1-Q_{BDD})(1-Q_{SE}) \quad (10)$$

VI. CASE STUDY

We apply the Fault Tree Technology (2)-(10) to calculate the fault tolerance probability value of SE software (1)

a) The block "**Analyzing program"** based on block "**Statistica"** is run 4 times per day, 1 time every 6 hours.
b) SE software is executed 3 times per 2 min (1 time per 40 s or 2/3 min). This is equal to 540 runs every 6 hours c) The initial probability of any algorithm failure is

$$Q_{a\lg\_OA} = Q_{a\lg\_BDD} = Q_{a\lg\_SE} = 0.0001.$$

d) SCADA software failures occur, on average, once a month, hardware (server) failures occur ones a year

$$Q_{SCADA\_software} = \frac{4}{30\times 24\times 60}\times\frac{2}{3} = 6.17\times 10^{-5};$$

$$Q_{server} = \frac{4}{365\times 24\times 60}\times\frac{2}{3} = 5.07357\times 10^{-6};$$

e) The number of SCADA snapshot failures is 3, the number of telesignal failures is 7, so

$$Q_{TM} = 3/540 = 0{,}00555; \quad Q_{TS} = 7/540 = 0{,}01296$$

As a result, **for SCADA** we obtain:

$$Q_{TM\_SCADA} = 1-(1-0.00555)(1-5.07357\times 10^{-6})(1-6.17\times 10^{-5}) = 0.0056$$

$$Q_{TS\_SCADA} = 1-(1-0.01296)(1-5.07357\times 10^{-6})(1-6.17\times 10^{-5}) = 0.0130$$

f) There are 6000 WAMS frames per 2 min (1 per 20 ms), but only 3 frames are available for SE software (for SCADA). Totally 540*6000=3240000 frames come to PDC during 6 hours. We consider averaged phasor values on a small time interval when phasor angle is insignificantly changed. Thus, we have 540 accurate frames because we consider systematical errors as faults of communication channels and assume that

$$Q_{PM\_snapshot} = 0.0$$

g) Research [18] on the data transmission from a measurement point to a PMU device, considering communication channel and instrumental transformer errors result in the fault probability:

$$Q_{PMU} = 0.0879 \ [17]$$

h) Reliable transfer of PMs from PDC to dispatcher center suggests sending 50x60x60 packages per hour, but with the leased WAMS channels some packages can be lost. Minimal losses of packages per 1 channel are estimated at about 500-1000, consequently,

$$Q_{WAMS\_channel} = \frac{500}{50\times 60\times 60} = 0.0028$$

i) PDC fault probability depends on fault probabilities of PMU and communication channels:

$$Q_{PDC} = 1-(1-0.0879)(1-0.00555) = 0.0904$$

j) Let DA AS faults occur 2 times per month:

$$Q_{DA\_AS\_soft} = \frac{2\times 4}{30\times 24\times 60} = 1.2346\times 10^{-4}$$

Thus, **for WAMS** we obtain

$$Q_{PM} = 1-(1-0.0)(1-0.0904)(1-1.2346\times 10^{-4}) = 0.0905$$

The system indicator "Measurements" (3). Assuming $Q_{BD} = Q_{SCADA\_software}$, we calculate

$$Q_{meas} = 0.0905\times 5.07\times 10^{-6}\times 0.0056 = 5.9854\times 10^{-9}$$

The system indicator "Network" (4) is

$$Q_{network} = 1-(1-0.0130)(1-5.07357\times 10^{-5})*(1-0.0001) = 0.0131$$

k) The fault probability of Observability Analysis Algorithm (6), assuming $Q_{OA\_LSE} = Q_{PM}$ is:

$$Q_{OA\_LSE} = 1-(1-0.0905)(1-0.0001) = 0.0906$$

l) The fault probability of a-priori BDD algorithm (7), (8). 15 SCADA snapshots with doubtful measurements and 5 SCADA snapshots with critical TM were detected during 6 hours:

$$Q_{apriori\_doubt} = 15/540 = 0.028;$$

$$Q_{apriori\_critical} = 5/540 = 0.00926;$$

$$Q_{apriori\_BDD} = 1-(1-0.028)(1-0.00926)(1-0.0001) = 0.0369$$

$$Q_{aposteriori\_BDD} = 1-(1-0.00926)(1-0.0001) = 0.0094$$

The system indicator "Algorithms" for LSE (9) is:

$$Q_{ALG\_LSE} = 1-(1-0.0905)(1-0.0369)(1-0.0001) = 0.1243$$

The system indicator "Algorithms" for nonlinear SE and robust SE (here $Q_{OA\_nonlinearSE} = 0$) is:

$$Q_{ALG\_nonlinearSE} = Q_{ALG\_robustSE} =$$
$$= 1-(1-0.0)(1-0.0094)(1-0.0001) = 0.0096$$

m) We obtain the fault tolerance of the SE software based on Q_{meas}; $Q_{network}$; Q_{alg} and approach (2):

$$P_{meas} = 1 - 5.9854 \times 10^{-9}; \ P_{network} = 1 - 0.0131;$$
$$P_{ALG\_LSE} = 1 - 0.1243; \ P_{ALG\_nonlinearSE} = 1 - 0.0096;$$

As a result, **the SE software fault tolerance probability** is (1):

$$P_{LSE\_software} = 0.8642; \quad P_{nonlinearSE\_software} = 0.9774$$

The fault probability of the SE software with reserved algorithms (see Fig.3) is:

$$Q_{alg} = 1 - (1 - 0.0906 \times 0.0)(1 - 0.0369 \times 0.0094)(1 - 0.0001^2)$$
$$= 3.5417 \times 10^{-4}$$

Finally, **the SE software fault tolerance probability when the algorithms are reserved** is:

$$P_{SE\_software\_when\_reserved} = 0.9865$$

VII. Conclusion

Development of any program product is determined by an urgent need to accelerate the processing of raw data and obtain calculation results in the form of tables, plots, diagrams, diagnostic and expert evaluation. The program product (software) implementation is based on the selection of adequate processing algorithms and appropriate programming languages (environments). Testing of the program product on reference samples and its application to a real object are the final stages of its design. Acceptance of the program product (software) is performed according to the established state standards [19, 20, etc.].

Further, the program product operation starts and whether or not it is successful depends on the quality of initial data and possibility of its processing by reliable algorithms. In [19], the authors claim, for example, that "the software tools and programs included in the program product cannot reach the state when their control by user is impossible, and the data should be neither corrupted or lost". In the real-time operation of the state estimation software, however, the cases of data losses (underdelivery) are commonplace. Therefore, for the failure-free operation of the applied program product it is necessary to have adaptive algorithms that can solve a problem depending on the composition and quality of the initial information. Thus, a fault tree analysis, one of the analytical approaches, is proposed in this paper to the personnel working with the state estimation software in real time.

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