Energy Systems as Objects of Hierarchical Modeling

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***Abstract* — The paper covers the trends in changing of the structure and properties of the energy systems of the future that are innovations-driven in their development. The role of intelligent technologies in the transformation of energy systems is analyzed. The main directions and findings of the published research on intelligent power systems are presented.**

***Index Terms* — Energy systems, innovative intelligent technologies, transformation of energy systems, substantiation of development, operating modes control.**

I. Introduction

By the middle of the 21st century, we should expect drastic changes in the appearance of the energy sector. These changes are related not only to the processes that are internal for the energy sector (intensive development of energy technologies, a qualitative shift in the scale of adoption of intelligent information and communication technologies and means of control of energy facilities and systems), but also to a fundamental change in the paradigm of development and functioning of energy systems as client-oriented infrastructure systems that provide reliable and efficient services to industries and the community. The energy infrastructure systems are primarily those of power, heating and gas supply systems with developed transportation and distribution network infrastructure. In a sense, the infrastructure includes oil and petroleum product supply systems, although they do not have developed distribution networks. Infrastructure systems also include water supply systems.

The patterns of changes in the conditions of development and operation of energy systems lead to the following substantial transformations in the structure of systems and their operating modes.

The scale of the energy systems and the expansion of the areas served by them keeps growing.

The development of urban agglomerations around large cities continues due to the establishment of public and business administration centers located therein, the concentration of high-tech production facilities, financial resources, the creatives, and the research and educational cluster. At the same time, the trend towards the de-urbanization of urban settlements continues, including the removal of industrial production facilities from urban areas and the development of individual low-rise residential buildings construction. Furthermore, the status and standard of living will continue to increase in medium and small towns. All this will lead to a growing dispersal of energy consumption across the territory in the process of deep electrification and gasification of the industrial and residential sectors to ensure the growth of quality of life and labor productivity [1-3].

The trend towards decentralization of energy supply is also developing on the energy generation side as a result of the increased adoption of distributed generation sources connected to distribution power and heat network hubs. This trend is due to the emergence of new highly efficient energy production technologies that enable energy supply systems to be flexible in their adjusting to the uncertainty of the demand for energy. Energy sources that make use of renewable energy resources also contribute to distributed generation.

New highly efficient technologies are increasingly being adopted for large energy sources as well. In fact, the makeup of the generation capacity of future energy supply systems should include relatively large generation sources to supply energy to large energy-intensive consumers and a rather high share of distributed generation. Let us consider in more detail the features and challenges of future energy systems.

II. Innovations-driven electric power systems of the future

The widespread adoption of distributed generation units in electric power systems is responsible for several distinctive features. Many small generating units that make use of gas turbine technologies operate at higher

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frequencies than the utility frequency and are connected to the system via rectifier-inverter units. Wind turbines have a similar connection while having the distinctly stochastic nature of the generated power. As a result, the frequency characteristics of generation in electric power systems change significantly, and the frequency-regulating effect of generation diminishes. Distributed generation units have small permanent rotor inertia if compared to conventional high-capacity generators and and also have simplified control systems, which is responsible for the challenges to be faced when ensuring the stability of power energy systems.

Connection of distributed generation units to the distribution power grid drastically changes its properties, leading to stability issues, underpinning the need for significant development and fundamental reconstruction of power-system protection systems at this level [2].

Due to the trends in the development and location of electric power generation and consumption, the power grid will also change significantly in the future. Taking into account new technologies in converters based on power electronics, cost reduction, reliability improvement, and high controllability of DC power transmissions, they will enjoy undergoing substantial development in the power transmission grid. At the same time, the widespread adoption of devices that form flexible AC power transmission systems (FACTS) on the basis of power electronics will radically increase the controllability of the AC transmission grid [4]. New technologies, including the use of FACTS devices, will significantly improve the reliability and controllability of the power distribution grid.

Growth of electricity consumption under scattered generating sources and consumers across the territory leads to an increase in the density of power transmission and distribution grids. In general, taking these factors into account, future electric power systems will increasingly acquire the functions and properties of infrastructure systems (think "the electric power Internet"), which will, in theory, be able to provide the consumer with electricity in the required location, having the necessary quality and reliability of electric power supply and being available at a reasonable price.

There is a tendency for the share of new electrical receivers with new load characteristics to grow. These receivers include all electrical installations powered through modern power supplies, that is rectifiers/stabilizers and rectifiers/inverters. They are the variable speed drive, all computer, office, and household appliances with pulse power supplies, LED lighting, etc. Their distinctive feature is the constant amount of the consumed active power immune to a wide range changes in the voltage of the power mains (some receivers ensure the same load even when the voltage level drops up to 30% of the rated voltage). While conventional consumers reduce their consumption when the supply voltage decreases, thus ensuring voltage-regulating effect of the load, new consumers increase the current consumption when the supply voltage decreases, while maintaining the same active power, and taking into account losses in the power distribution network, this leads to an increase in the active and reactive power of the load. Accordingly, with the growth of the total share of new electrical receivers, the voltage-regulating effect of the load in the electric power system will decrease.

The situation is aggravated by the widespread use of modern on-load tap changers (OLTCs) of transformers, including those used in the power distribution grid, which results in relatively stable voltage levels on the consumers' buses and the compliance with regulatory requirements, but in case of emergency in the mains and the power distribution grid instead of reducing the voltage on the consumers' buses (and, as a consequence, reducing the active and reactive load), there is a constant load, an increase in losses within the grid and a significant growth of reactive power consumption from the power supply grid.

Another problem is that an increasing number of receivers are keeping their power consumption constant when the frequency in the mains changes. Such receivers include not only the new consumers mentioned above, but also most of the heating elements used for electric heating. This reduces both the total power and the total share of the load directly connected to the AC mains (without frequency converters), which would ensure a frequency-regulating effect of the load for the entire electric power system.

Another important new factor for future electric power systems is the emergence of active consumers who independently manage their own electricity consumption, depending on the price terms as set in the retail electricity market, by transferring electricity consumption by some receivers from time intervals with high electricity prices to time intervals with low prices. Such load management independent of the dispatch schedule as practiced by active consumers challenges the control of the electric power system operating modes due to the uncertainty of power consumption by active consumers. Therefore, the interaction between the electric power system and consumers with respect to their joint control of the system's operating modes using the controlling capabilities of consumers is promising.

A significant change in the properties of future electric power systems will occur as a result of the ubiquitous spread of electric power storage systems, the technologies of which by now have already been adopted in the industrial sector [5]. Characteristically, system-wide electric power storage has high-efficiency and high-speed control systems based on power electronics that can contribute to the controllability of electric power systems. A large share of electric energy storage is expected to be based on electric vehicles, that, when used on a mass scale, will significantly change the appearance and operating modes of future electric power systems.

Taking into account the indicated tendencies of increasing adoption of electric receivers and electric power storage systems supplied with direct current through converter elements, one can expect transition to the establishment of electric power supplying DC distribution gridswith shared AC to DC converter units placed at supplying substations [6, 7].

The above new load characteristics of consumers, storage and generation of future electric power systems will significantly change the properties and controllability of the systems. The existing principles of the control over operating modes of conventional electric power systems are based on the use of voltage-regulating effect of the load and frequency characteristics of generation. Due to these effects, modern electric power systems have internal self-sustainability, while control systems intervene when the operating mode parameters go beyond certain limits. Due to changes in the properties of future electric power systems, their internal self-sustainability is essentially being challenged and, as a result, the traditional principles of control over the electric power systems operating modes will require significant modification and development.

Almost all countries around the world have declared the concept of the intelligent energy system (Smart Grid) as their national policy for the technological development of the electric power industry of the future. This concept is based on the integration of several innovative strands at all links of the chain ranging from production to electricity consumption, namely [8, etc.]:

- Innovative technologies and installations for the production, storage, transmission, distribution, and consumption of electricity;
- Highly efficient means and technologies for measuring, collecting, processing, storing, transmitting and presenting (visualizing) information;
- Advanced information and computer technologies, including the Internet;
- Highly efficient methods of monitoring and control based on modern approaches backed by the control theory;
- Active consumers.

At the same time, a full-scale digitalization of all stages of the information and control subsystem will be carried out, ranging from measuring the current values of the operating mode parameters to the implementation of control actions.

The development of future electric power systems on the technological basis of the intelligent power system will make it possible to offset the above potentially negative tendencies in changing the properties of the electric power system in many respects. At the same time, new challenges are already emerging and will become more acute in the future in terms of the need to strengthen the coordination of the control over the operating modes of electric power systems at various levels, improve control efficiency, and ensure the reliability of the system of control over the operating modes of the electric power system itself. The issues of information security and cybersecurity in the monitoring and control of electric power systems are becoming particularly acute [9, 10, etc.].

III. Innovative technological transformations of future heat supply systems

Important conditions determining the development of heat supply at the present stage and in the oncoming future are the following [11]:

- Increased requirements for indoor comfort and heat supply quality aimed at expanding the range of services, including heating, cooling, ventilation, air conditioning, and hot water supply;
- Structural transformations in the economy, growth of the level of availability of amenities in the housing sector, changes in the territorial location of industrial production facilities and their transition to own energy sources will have a significant impact on the structure and demand for thermal energy, as well as on the makeup of generating capacity;
- Energy saving, application of energy efficient technologies in production, changes in the structure of industrial production, use of heat-saving structures of buildings, introduction of systems of metering and controlling of heat supply and consumption contribute to a significant reduction in the heat intensity of industrial products and total heat consumption in general;
- Decrease in the density of housing development, its expansion mostly within unoccupied areas, emergence of the market of efficient heat generating equipment of small capacity increase the role of decentralized (distributed) systems:
- Growth of the cost of electricity, higher prices for fuel and its transportation, more expensive equipment and materials, and, as a result, higher tariffs for heat energy, contribute to the adoption of energy-saving measures in the processes of production, transportation, and consumption of heat, as well as increase the share of secondary and renewable energy resources;
- Structural changes in the energy sector that increase the use of gas for heat supply as a result of gasification of regions contribute to the development of distributed, highly efficient, and competitive gas-fired heat sources;
- increased requirements for reliability and safety of heat supply and the need to comply with them in the context of contractual relations lead to increased costs in the heat network, which reduces the economic efficiency of large heat sources, limits the spans of heat supply, and increases the number of sources required;
- The increased community commitment of the population with regard to environmental issues will also support the trend of unbundling of systems and facilitate their technological improvement;
- Changes in the investment policy, lack of large public investments in heat supply, lack of interest on the part of private investors in financing the construction

of heat supply facilities and, effectively, transition of heat supply companies to self-financing with limited subsidies from local budgets, creation and strengthening of a competitive environment in all sectors of the economy, development of a free market for technologies and equipment significantly weaken the position of centralized heat supply and lead to a shift in the investment activity towards distributed generation, but do not deprive the former of its leading role;
- the diversity of ownership forms in the heat supply sector and the inevitable change in the relationship between the parties with the predominance of economic interests rule out measures of forcing consumers into using certain types of heat supply without providing economic incentives and encourage them to behave actively.

These conditions lead to the following changes:
1. decreased competitiveness of large centralized heat supply systems and reduction of per unit heat source capacities;
2. wider application of small distributed heat generation;
3. consumer interest in energy saving;
4. fuller use of secondary energy resources and the production waste suitable for obtaining heat energy;
5. increasing the use of renewable heat sources;
6. interest in making really optimal decisions on heat supply development.

The task of managing the development and operation of heat supply systems will be to adapt in a timely manner and respond adequately to changes in heat demand and other external challenges.

The new trends emerging in the heat supply industry will determine the technological transformation of heat supply systems. On the one hand, this is becoming strongly sought-after, but on the other hand, it is ensured by the emerging market of available innovative technologies and equipment.

Availability of mini- and micro-sources of heat, having heat consumption systems equipped with smart meters, automatic regulation and control provide the necessary conditions for active consumer behavior. Such a consumer will have a significant impact on the technology of the operation of heat supply systems and will facilitate the transition from qualitative to quantitative regulation and differentiated control.

Technical re-equipment of heat supply systems is under way and is being developed in three main directions: changes in the structure of systems, systemic and technological changes, technical measures for the re-equipment of systems.

The main directions for changing the structure of heat and power systems are as follows:
a) Orientation towards hierarchical principles of the system design with separation of ring backbone and dead-end distribution networks by control nodes;
b) Adoption of generally independent connection diagrams for consumers and closed hot water supply systems;
c) Separation of heat sources, heat networks, and heat consuming installations into independent loops by means of heat exchangers, automation and regulation devices;
d) Creation of an automated control system for technological processes of production, transport, and consumption of the thermal energy.

Systemic and technological transformations are focused on new technologies of operation of heat supplying systems:
– Joint operation of heat sources, which actually meets the main purpose of large heat supply systems and ensures efficient supply of heat to consumers;
– Hybrid quantitative and qualitative as well as quantitative-only regulation of heat output and consumption, which contributes to the organization of joint operation of sources and ensuring that the amount of heat supplied and the demand for it match in real-time;
– Relatively low temperatures of the coolant, providing ample opportunities for involvement in joint operation for unified heat networks on the part of heat sources of different types and capacities, such as boiler-houses, cogeneration plants, sources that run on secondary energy resources and other non-conventional sources of heat; in addition, it makes it possible to use new materials in heat supply and will ensure extension of the working life of the equipment;
– Reduced coolant pressure due to the fact that in the independent circuits of heat and power system elements it is necessary to provide only coolant circulation, while leakage of coolant reduces and working life of equipment extends.

Technical re-equipment of the systems includes a set of measures without which it is impossible to implement the above-mentioned directions. Among them are the following:
- Application of the system of on-line monitoring, control and diagnostics of the condition of equipment and heat pipelines in heat networks, use of ball, disk and other shut-off and control valves that are motor-operated and remotely controlled;
- Introduction of automation, controlling, metering, and measuring systems and creation of an automated dispatcher control system on their basis;
- Wide-scale digitalization of all stages of operation of the information and control subsystem from measuring the parameters of the heat supply system operating mode to the implementation of control actions;
- Wide-scale application of the automated heat points with plate heat exchangers and control and regulation systems for sources, heat networks, and heat inputs of consumers.

A promising technological platform for the heat supply of the future, that is in line with the above mentioned changes in the principles of design and structure of heat supply systems, is the creation of an "intelligent" heat supply system that will unify, at a brand new technological level, sources, networks, and consumers into a unified automated system [12]. This will provide it with the necessary flexibility and adaptability to changing operating conditions, increase efficiency, reliability, and quality of heat supply, facilitate decrease in heat losses, and smooth out the unevenness of heat consumption schedules, etc. Availability of an opportunity to monitor and control in real-time the operating modes of all the participants of the process of generation, transmission, and consumption of heat, and to automatically respond to changes in various parameters in the heat supply system would allow for interactive ("here and now") behavior of consumers in the heat market. This will ensure bilateral and mutually coordinated interaction between the consumer and the heat and power system.

IV. Innovative trends in gas supply systems

The scale and complexity of gas supply systems continue to grow. The distance separating gas fields from the points of its consumption, the aspiration to diversify transport corridors and increase the possibility of adjusting the flow lead to an increase in the total length and growing complexity of the configuration of trunk gas pipeline systems. Active gasification of the regions, further urbanization of the country, the "overgrowth" of cities with townhouse villages and suburban settlements with the high degree of availability of amenities lead to the need for the development of centralized gas supply systems and gas distribution networks, and the broadening of the area covered by them.

The product range of hardware components used in the gas supply system is being improved and expanded:

- Pipelines made of new materials, including polymeric ones;
- New materials and technologies for heat- and waterproofing, mitigation of corrosion processes and building up of deposits on internal surfaces of pipes, etc;
- Energy efficient, compact, and low-noise compressor equipment with high efficiency in a wide range of capacities;
- Reliable and quality shut-off and control valves.

Possibilities of monitoring and identification of the inefficient use of gas in turn reinvigorates the processes of mass application of more efficient and higher quality gas dispenser valves, gas consuming devices, automatic means of control in the points of consumption. Increasingly active consumer behavior leads to a significantly more elaborate processes of the gas supply system operation, strengthened non-stationarity of gas supply system operation modes, and increased probability of the operating modes that are either non-standard or even beyond-design.

This in turn serves as an incentive for the following:

- Introduction of new highly adaptable energy-saving compressor and power equipment with adjustable speed of rotation in the gas supply system;
- Wider application of control and local automation means at the main facilities, automatic controllers of pressure, flow rate, etc. in gas transportation and gas distribution networks;
- Deployment of large-scale telemetry and fiscal metering systems to monitor consumption patterns and processes;
- Application of differentiated tariffs for consumers per day.

Worldwide and in Russia alike, the gas industry is following in the footsteps of the electric power industry in the upgrading of networks, utilities, metering devices, creating a variety of pilot projects, and all these actions are ultimately aimed at the deployment of remote data collection using the M2M (Machine-to-Machine) technology.

As early as 2020, Europe could become one of the largest regional markets for M2M devices, reaching the level of 13.5 million installed devices. According to the projection published by Pike Research [13], the total number of M2M-based monitoring devices installed in the gas industry across the globe will grow rapidly over the next few years, rising from 8.5 million in 2009 to 36.3 million by 2016. The M2M technology involves equipping gas metering units with telemetry systems. The equipment, as a rule, includes commercial metering complexes of of gas metering units and a cabinet to automate the telemetry system. The main task of the system of gas distribution facilities telemetry is to control technological parameters: inlet and outlet gas pressure, pressure drops on filters, shut-off valves, etc. Alarm generation should be carried out with minimum delays in order to continuously monitor the condition of the facility and respond promptly in case of any malfunctions. According to some estimates, the telemetry system will allow controlling about 80% of the supplied natural gas. Data transmission is possible via one of the four communication channels: GSM, a dedicated physical line, a switched telephone line, or a radio channel. GSM is used most often because of its unquestionable advantages: the cost and speed of deployment while maintaining acceptable values of quality indicators.

Today there is an urgent need to create so-called intelligent gas distribution networks on a digital basis. Here, the intelligent system is understood as such a system of transmission and distribution of gas flows that combines conventional components and the state-of-the-art technologies, integrated control and monitoring tools, as well as information technologies and means of communication that ensure higher efficiency of the gas distribution network and gas supply resources management.

Integral parts of this gas network are as follows:

- Automation and control (intelligent metering systems: gas meters and electronic control devices);

– Network communication infrastructure (process, instrument, and local networks);
– A dedicated case-based center that makes use of artificial intelligence methods.

Building an intelligent network involves the installation of intelligent metering stations that enable creating a primary information field.

The main module influencing gas supply modes of the region is the subsystem of control over operation of metering stations of gas distribution stations. This subsystem enables to see the status of the main parameters of the gas distribution station, such as gas pressure at the outlet, hourly gas flow rate, gas flow rate as accumulated over a given contractual day, and gas flow rate for the previous day with the transfer of relevant data to a dedicated case-based center in the mode of a periodic automatic request.

The next, as per the order of the process of gas transportation in the gas distribution system, is the subsystem of control over gas regulating points of the enterprise. This subsystem is built on the basis of a software and hardware system that allows online monitoring of the following gas regulating points parameters via radio communication channels:
– Inlet and outlet gas pressure;
– Temperature inside the gas regulating points room;
– Level of gas content in the gas regulating points process rooms and those of consumers within the gas regulating points service area.

Thus, the use of intelligent support apparatus or smart technologies in the gas industry is directly related to gas distribution networks, is close to the consumer and allows online redistribution of gas flows in the gas distribution network, optimizing (to the necessary and possible extent) the gas flows through its branches.

V. General trends in the development and operation of future energy systems

The covered innovative tendencies in electric power, heat supplying and gas supplying systems are in many respects characteristic of water supply systems, and also, of oil supplying systems when it comes to the process and transportation infrastructure. Generalizing these trends enables us to formulate a number of statements that apply equally to all of these systems.

1. Increase in the scale of the energy systems under consideration, expansion of the territories served by them.
2. Increasingly complex structure of power systems due to increased diversity of power elements in a wide range of technologies and capacities, including distributed generation, and increased complexity of the network infrastructure configuration.
3. Strengthening of interaction and interdependence of different energy systems within the energy sector, especially so under emergency conditions, and thereby aggravation of energy security problems in the country and its regions.
4. Wide use of innovative technologies in production, transport, distribution, and consumption of energy resources and final energy types.
5. The active nature of consumer behavior in terms of managing their own energy consumption at the pace that matches that of the process, using time-differentiated prices for consumed energy resources.
6. Wide use of information and communication technologies for measuring the state of energy systems, transmission, processing, and presentation of current information for monitoring and control of operating modes.
7. Active use of the ideology of intelligent energy systems as a technological platform for future energy systems.
8. Significant change in the properties of future intelligent energy systems as objects of monitoring of their condition and control of their operating modes.
9. Creation of conditions for the making up of integrated intelligent energy systems as unified technological complexes with a shared control system due not only to conventional integration factors at the level of energy production (e.g., that of CHPPs that produce electricity and heat when using gas as their fuel), but also due to the availability of alternative technologies for the use of different types of energy for the same purpose on the consumer side (e.g., heating that comes either from a district heating system or an electric heater) [14].

The listed general tendencies of development and operation of future energy systems predetermine the directions of their research.

VI. The current state of the research in the field of intelligent energy systems

Over the past 10-15 years, experts have been actively discussing and developing the agenda of creating intelligent electric power systems, that is Smart Grids [15-19, etc.]. Under the auspices of international organizations, international conferences are held annually on the problems of intelligent electric power systems. For example, the Institute of Electrical and Electronic Engineers (IEEE) annually holds dedicated international conferences titled "Innovative Smart Grid Technologies" in Europe, Asia, Africa, North and South America. The subject of intelligent technologies and intelligent electric power systems is also covered to a significant extent by the general electric power conferences held by the IEEE, that is IEEE PES General Meeting, IEEE Power Tech, IEEE Power Con, and the like. Intelligent technologies and adding intelligent capabilities to the control of electric power facilities and electric power systems are actively discussed at international conferences, congresses, symposiums, seminars held by the International Federation of Automatic Control (IFAC), as well as at the International Conference on Large Electric

Systems (CIGRE), International Conference on Electricity Distribution (CIRED), and by a few other international associations and organizations. The top-of-the-agenda challenges of intelligent technologies are also dealt with at international conferences held in Russia and CIS countries in Russian language, such as "Contemporary directions in the development of the systems of power-system protection", "Electric power engineering through the eyes of the youth", "Methodological issues of research of reliability of large energy systems", and a number of others.

The strong interest in the ideology of intelligent electric power systems as a technological platform for the power industry of the future has well-justified grounds. In many countries, this is due to several major factors: the expected widespread use of highly fluctuating renewable energy sources, the additional demand for electricity due to the gradual transition to electric vehicles, and the development of information technologies that enable to create a game-changing highly efficient monitoring and control systems of the electric power system. At the same time, approaches and priorities vary from country to country due to the different profiles of the electric power industry and electric power systems, and differences in preferences.

In Europe, the United States, and a host of other countries, the focus is on the electric power distribution grid and consumer activity [15, 16]. In China, emphasis is placed on the high-voltage transmission grid in terms of equipping it with high-precision PMU-based systems of synchronized vector measurements, modern systems of collection, transmission, processing, and presentation of information that serve as the backbone for creation of large-scale systems of monitoring (WAMS) and control (WACS) of the operating modes of electric power systems [20, 21]. In Russia, the concept of the active and adaptive grid is being developed, referring, first of all, to the transmission electric power grid, but also to the distribution grids [17, 18]. Active and adaptive grid, being a counterpart to Smart Grid, assumes a wide use of modern systems of metering, collection, processing, transmission and visualization of data, active elements that change the topology of the grid and influence the generation and consumers, real-time control systems that allow to respond adequately to the changing situation in the electric power system, systems of real-time monitoring and forecasting of the state of the electric power system.

In 2010-2012, at the initiative and with the support of Federal Grid Company of the Unified Energy System (FGC UES), the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences, the Institute of Control Sciences, RAS of the Russian Academy of Sciences, and the Scientific and Technical Center of the Federal Grid Company (FGC UES), with the participation of a number of organizations and experts, developed the Concept of the intelligent electric power system of Russia with an active and adaptive grid [22]. On the basis of this concept, the above organizations have developed and systematized theoretical foundations, methods, and models of control of intelligent power systems [23]. In 2008-2011, within the framework of the 7th framework program of cooperation between the European Union and Russia in the field of energy under the State Contract of the Ministry of Education under the coordination of the Melentiev Energy Systems Institute, SB RAS, and with the participation of the Institute of Control Sciences, RAS, and a number of other organizations, the project "Knowledge-based coordination of operational and emergency control of interconnected power utilities of the European Union and Russia" was implemented [24]. These fundamental works have served as a methodological basis for the development of research in Russia in the field of intelligent technologies and intelligent electric power systems.

In 2011-2013, Irkutsk National Research Technical University (INRTU) with the methodological support provided by the Melentiev Energy Systems Institute, SB RAS, implemented the project titled "The Intelligent Energy System for the Efficient Electric Power Industry of the Future", supported by the grant of the Ministry of Education and Science of the Russian Federation in accordance with the Resolution of the Government of the Russian Federation dated April 9, 2010 No. 220 "On Measures for Recruiting Leading Researchers for Russian Institutions of Higher Professional Education". The visiting scholar was Prof. Dr. Z.A.Styczynski, Otto von Gehrike University of Magdeburg, Germany. The letter of intent was signed between Irkutsk National Research Technical University, Otto von Gericke University, Melentiev Energy Systems Institute SB RAS, Fraunhofer Institute (Magdeburg), Irkutskenergo JSC, and Siemens, according to which INRTU established an advanced research infrastructure within the framework of the project. On the basis of this infrastructure, the studies planned for the project were carried out.

The Smart Grid ideology is beginning to be adopted in gas supply systems [25-27 et al]. The main research and their findings focus on gas distribution networks and more specifically on intelligent metering, processing, and presentation of up-to-date information to the consumer. This field is pioneered by Japan. Relevant work is being done in European countries, although the attitude to this problem is rather cautious [27]. In Russia, the process of using the Smart Grid ideology is still at its infancy [28, 29].

Heating systems have significant methodological, technological, and information potential to take advantage of the adoption of the Smart Grid ideology. This is facilitated by the successfully developing market of affordable modern technologies for adding intelligent capabilities, systems of control and metering of heat energy, telecommunications, and data support, small generation based on non-conventional and renewable energy sources, etc. They ensure the active behavior of consumers, handling of the storage and their own production of the thermak energy to create the most comfortable conditions indoors. A large-scale pilot project "Combined Efficient Large Scale Integrated Urban Systems" (CELSIUS) for the development of intelligent electricity, heat, and cooling systems is being implemented in five major European cities: Gothenburg, Geneva, Cologne, London, Rotterdam [30]. The greatest progress has been made in Gothenburg, where not only new technologies for energy production, but also integrated transport technologies in the form of a single structure for simultaneous transmission of electric power, heat and gas are employed. The first projects that deal with building intelligent heat supply systems are being implemented in a number of other European cities, such as Marstal and Copenhagen (Denmark) [31, 32, 33] Bietigheim-Bissingen and Crailsheim (Germany) [30], Malmö (Sweden) [34], Delft and Heerlen (Netherlands) [34, 35], etc. These projects are carried out on the basis of the existing systems with the inclusion of renewable energy sources, heat storages, and the involvement of consumers in the active management of their heat consumption, taking into account their individual characteristics and requirements.

Methodological developments published abroad on the subject of intelligent heat supply systems are primarily related to the definition of their properties, the shaping of the technological concept of the intelligent heat supply system (smart thermal grids) [36, 37], a general mathematical description of such systems, taking into account the storage and alternative production of thermal energy on the consumer side [38, 39]. The mathematical model of optimal control of the system operation that ensures reconciling energy balances at the minimum cost of heat production is proposed [39], the problem of optimizing the system operating modes at the minimum fuel consumption for heat production were stated and solved [40, 41]. The problems of real-time forecasting of the demand for heat and its distribution among sources, including renewable ones, were formulated [42]. The main feature of these projects is that they focus on the application in systems with a high degree of automation of technological processes. However, they do not cover the entire range of new challenges that arise. In Russia, the issue of "smart thermal grids" have made it only to the stage of discussion. Having said that, the technological backbone has been prepared for its implementation, and there is scientific and methodological progress made with respect to managing development and operation. These are the works on solving the problems of optimal distribution of heat loads between heat sources [43, etc.], on the ideology, principles of design, and control of operating modes [44, etc.]. They can lay the methodological foundation for intelligent heat supply systems.

On the basis of the analysis of problems of designing and operation of pipeline systems of heat, water, oil and gas supply, as well as current trends of innovative development of energy systems the tasks of construction and control of intelligent pipeline systems were formulated at the Melentiev Energy Systems Institute, SB RAS [12, 45]. A new content was elucidated for the problems of analysis and synthesis of hydraulic circuits, which are the theoretical basis of intelligent pipeline systems. Methods were developed to quantify the controllability and identifiability of these systems.

In connection with the mainstreaming of research within the framework of the concept of Smart Grid, studies were carried out on the subject of analysis of integrated energy supply systems, taking into account the activity of consumers in the management of their own energy supply, the use of energy storage devices, modern information and communication technologies, etc.[46-48, etc.]. Specific applications to the various integrated energy supply systems are discussed: those of electricity and heat; electricity, water, and gas; electricity and gas; electricity, heat and cold; etc.

In the European Union countries, the issues of equipping residential and public buildings with smart meters are being studied. The European Commission has formulated the problem of standardization of smart meters of electricity, gas, heat, water (Mandate M/4416, 2009) [26, 27]. The smart metering system is considered a key link in the implementation of integrated intelligent power supply systems. In connection with the standardization of smart meters and the active use by consumers of their own micro-sources of energy (solar photovoltaic panels and collectors, micro-turbines, micro-storage of electricity and heat, etc.), as well as alternative devices that record energy use, there is ongoing work on the creation and operation of micro-energy systems at the level of consumers [49,50].

VII. Conclusion

The above analysis of the state of research in this subject area attests to the availability of elaborate developments in building and studying intelligent energy systems. At the same time, the quality of the findings that apply to individual directions and various energy systems varies. In addition, the state of development in Russia appears to be inadequate if compared to the practices adopted abroad. All this requires revitalizing and incorporating basic research into the problems of intelligent energy systems and ways of solving them.

The complexity of energy systems, their interaction and interdependence, the complexity of substantiating the development of these systems as stand-alone systems and as part of the energy sector as well as integrated energy systems, the complexity of the processes that take place in energy systems - all this predetermines the relevance of the application of hierarchical modeling to substantiating the development and management of the operation of energy systems.

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