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Contents

Development Issues of Systems for Automation and Digitalization of Power Distribution Networks

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***Abstract* — This paper studies 0.4 kV power distribution networks (PDNs) and automated systems for electricity monitoring and metering (ASEMM). As is known, a main task of ASEMMs is to digitalize PDNs, which is aimed at improving the efficiency and reliability of their operation. It is advisable that new models, methods, and intelligent technologies used for automation and informatization of distribution networks should also be focused on minimizing their power losses, which are currently fairly high and significantly compromise the technical and economic performance of automation systems employed and PDNs. Modern (conventional) ASEMMs, implemented at the facilities of utilities, do not have the appropriate technical, algorithmic, and software tools to reduce power losses in the PDN. This is due to the fact that conventional ASEMMs mainly collect remote data from the system meters and ensure their digital processing for the purpose of revenue metering of electricity. In this regard, the paper proposes methodological, algorithmic, and digital technologies to accomplish a set of new functional tasks in the conventional ASEMMs, aimed at reducing power losses in PDNs by optimizing their operating conditions.**

***Index Terms*: distribution network, power losses, automation issues.**

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I. Introduction

In the context of the energy crisis, the most important task is to save electricity through the introduction of new scientific methods and digital technologies at power sector facilities. Analysis of the operation of modern automated 0.4 kV power distribution networks (PDNs) shows that they lose more than 11–12% of electricity in the form of technical and commercial losses of the total amount supplied to the facilities of distribution utilities. By comparison, electricity losses in developed countries average 6–7%. Thus, there is significant potential for their reduction based on the new modern technologies that can back further improvement of the electricity monitoring and metering system in PDNs. As is known, the current automation and digitalization of information processes in PDNs involves active and wide adoption of new technologies in the form of automated systems for electricity monitoring and metering (ASEMM) [1, 2], which can be considered as elements of Smart Grid technology [3, 4]. The practice of their use has shown that they fail to adequately ensure the desired level of electricity losses, since these automated systems are mainly designed for electricity revenue metering. Analysis indicates that to significantly reduce electricity losses in the PDN it is necessary to additionally perform the optimization of operating conditions of facilities [5–8], diagnostics of critical states of distribution grids [9–11], including the identification of places of unauthorized consumption (theft) of electricity [12–14], and the monitoring of electricity losses [15, 16] in real time. The existing (conventional) ASEMMs do not address this set of tasks. This study aims to formulate proposals to improve conventional ASEMMs by incorporating new additional information subsystems in them, with the view to significantly reducing technical and commercial losses of electricity.

II. Structure and Tasks of Conventional ASEMMs

As is known, electricity losses in low-voltage distribution networks are caused by such main factors as: current and voltage unbalance [5, 17]; unauthorized electricity consumption (theft) in PDNs [14, 18]; non-linear properties of loads of network consumers [17, 19]; exceeded critical levels of wear of wires of backbone network lines. These factors cause the networks to deviate from their rated operating conditions. Unbalanced PDNs are a consequence of unbalanced loads and their unequal distribution over the phases of the three-phase network, which is one of the main factors that lead to increased losses of active power in networks and transformer substations. According to published research, in lines with distributed load with a relative deviation of phase currents from their average value in the range of 0.3–0.5, technical losses increase on average by 35%. The results of experimental studies conducted to determine electricity losses in power supply systems of single-family dwelling units show that technical losses due to the unbalance in transmission lines and transformer substations account for more than 6% of the total amount of electricity consumed in PDNs [20]. In this case, the quality of power deteriorates, and the probability of failure of household appliances and industrial plants increases. Some technologies [5, 21–23] proposed to solve the problem of voltage and current balancing in the distribution networks did not find wide practical application due to the complexity of their technical implementation. In particular, balancers with special transformers are practically not used in 0.4 kV networks, as they are the sources of technical electricity losses in networks, and they are rather expensive and complex engineering systems. The most promising way of combating the above undesirable factors is to use the potential capabilities of integrated hardware and software systems of ASEMM, developed on the basis of AIM, MDM, and APM technologies [24–26]. Such information systems have been developed by such companies as JSC "Systems and Technologies" Group, JSC "Electrotechnical factories "Energomera," Research and Production Corporation "Lianozovo Electromechanical Plant" (JSC LEMZ R&P Corp.), Research and Production Corporation "MIR" (Russia), ADD Grup (Moldova), Yitran (Israel), Hexing Electrical Co.Ltd. (PRC), SigmaTelas (Lithuania) [27–30].

The generalized structure of conventional ASEMMs is shown in Fig. 1. It includes the information subsystems for:

- revenue metering of electricity consumed by PDN consumers;
- automated data collection from the system's electricity meters and transfer of the necessary data to the upper control level;
- monitoring the condition of electricity meters and other technical facilities.

There is a shared database designed to store regulatory, reference, process, measurement, and other data in the ASEMM. Through this database the necessary information is exchanged between the indicated subsystems, whose main functions are:

- to remotely collect energy consumption data with a specified sampling rate (hour, week, month, etc.);
- to provide automated metering of electricity consumed by network consumers and multi-tariff options at the same time;
- to continuously monitor the use of energy;
- to control power and remotely disconnect/reconnect network consumers;
- to get up-to-date information about meter failures and malfunctions in the system;
- to calculate energy balance in the distribution network;
- to set up a shared database and prepare reports and other information materials;
- to exchange information with the upper control level.

Analysis of the functional structure of modern ASEMMs shows that the main function of these information systems is to ensure revenue metering of electricity in distribution networks. Their main advantages are:

1. automation of processes of measurement data collection, without involving inspectors (supervisors)

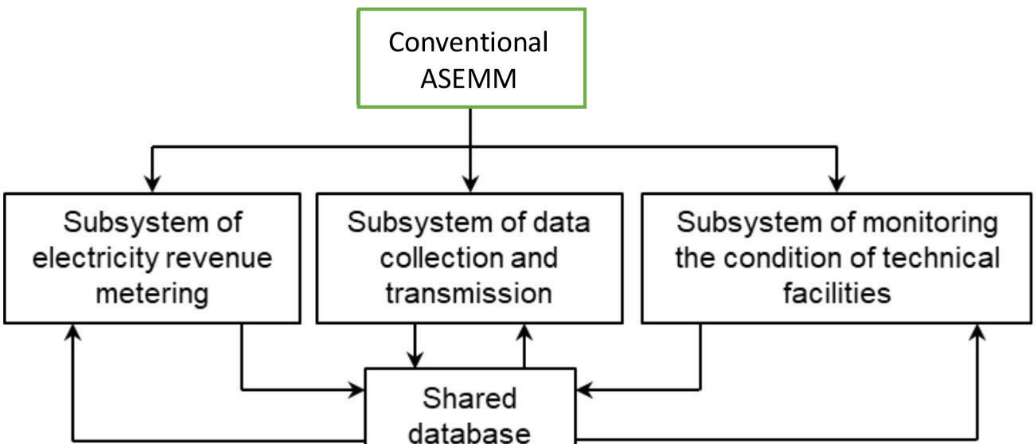

Fig. 1. Generalized structure of subsystems of conventional ASEMMs.

in charge of power supply and electricity metering;
2. elimination of the human factor in the collection of data on energy consumption, which ends corrupt practices;
3. automatic disconnection of the consumer in the case of late payment and exceeded limit on electric power consumption.

At the same time, analysis of the use of conventional ASEMMs shows that the existing set of functional subsystems does not focus on minimizing the technical and commercial losses of electricity in the PDN. In this regard, there is a need to develop new methods and digital technologies targeted at improving the conventional ASEMMs used in distribution networks. One possible way in this direction is to develop a modernized information and control system on the platform (basis) of conventional ASEMMs, designed to address optimization, diagnostic, and monitoring tasks in the PDN.

III. Structure and Tasks of the Modernized ASEMM

Our analysis shows that the conventional ASEMMs should address the following functional tasks:

- automatic control of technical losses of electricity to ensure optimization of distribution network operating conditions;
- detection and identification of the coordinates of unauthorized electricity consumption (thefts);
- diagnosis of the condition of the wires in the sections of the network backbone line that connect different consumers;
- on-line monitoring of technical and commercial electricity losses in the PDN.

Our analysis shows that performing these tasks within the ASEMM can significantly reduce technical and commercial losses of electricity, and improve power quality and reliability of power supply to consumers. In this regard, there is a need to develop new scientific methods and digital technologies focused on the modernization of conventional ASEMMs used in distribution networks. One of the possible ways in this direction is to create new additional information subsystems as part of conventional ASEMMs, to carry out the above optimization, diagnostic, and monitoring tasks. The structure of the proposed modernized ASEMM is shown in Fig. 2.

It includes conventional information subsystems of the ASEMM (Fig. 1) and new subsystems (IC, CSD, and ELM) designed to perform the above additional functional tasks. In this case, to build an IC subsystem we use the following objective function as the performance metric of the system:

$$E = J, \qquad (1)$$

Where J is the value of the effective current in the zero wire of the initial section of the network.

Minimization of the performance metric (1) is equivalent to the optimization of the operating conditions of the unbalanced PDN, which involves balancing the initial section of the network and provides the minimum imbalance of the values of total power consumed by each of the network phases. This can significantly reduce technical losses in the transformer power sources of the PDN and improve their reliable operation. In order to minimize the objective function E, we introduce the criterion function $F(p)$, which defines the measure of deviation of the desired state of the distribution network in terms of power p^* at its input from the actual state defined by the vector $p = [p_1, p_2, p_3]$, where p_k is the absolute value of the power consumed by the k-th network phase.

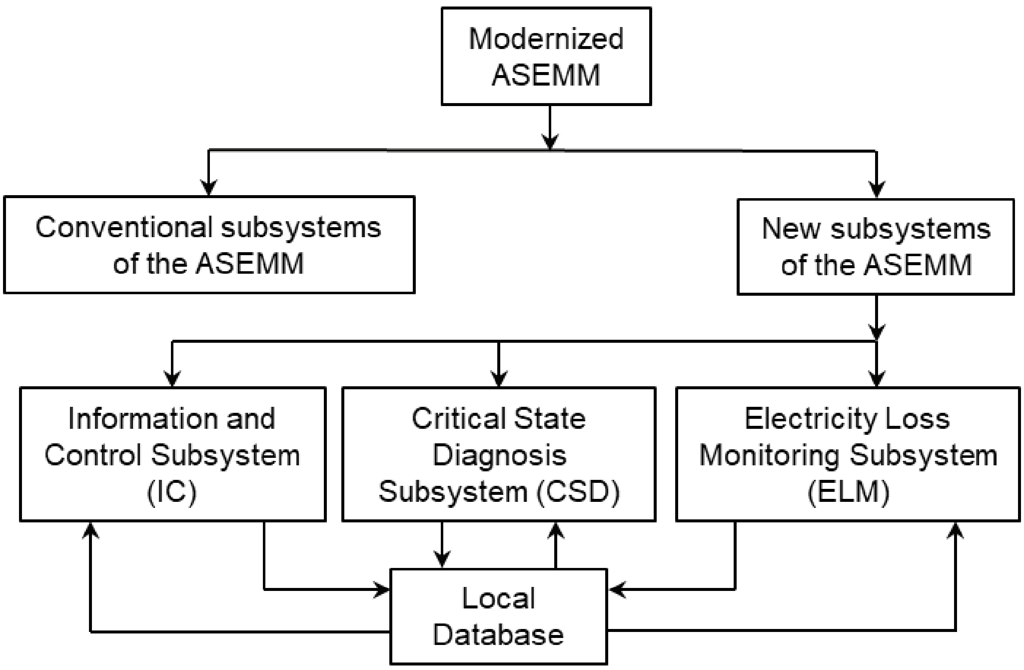

Fig. 2. Structure of additional subsystems of the ASEMM.

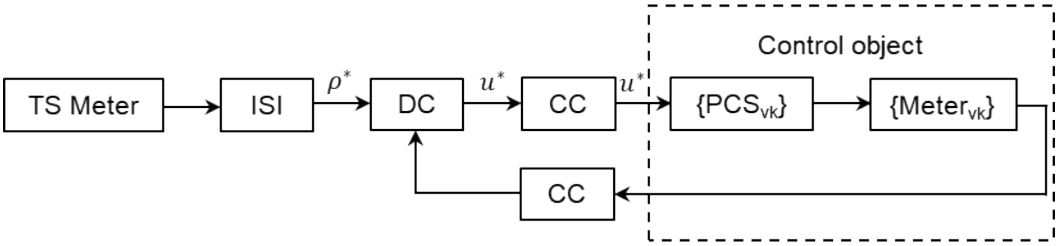

Fig. 3. Functional structure of the IC subsystem.

As a result, the optimization of the distribution network operating conditions is reduced to solving the following extreme-value problem:

$$\min_{p\in P} F(p) = F(p^*), \qquad (2)$$

where P is a discrete admissible subset; p^* is an optimal desired vector. An algorithm for solving the extreme-value problem (2) is proposed in [8].

From a technical perspective, the IC subsystem is implemented by means of a digital controller (DC) [8, 31], the structure of which is shown in Fig. 3.

It is assumed that a group of loads of network consumers, to which electricity meters $C\text{ч}_{vk}$ are connected, together with the actuators of the system, is a control object. The key functional unit of the system is the digital controller (DC) based on a microcontroller unit. The DC unit generates control actions u^* applied to the object based on a special algorithm (control rule). The program governing the operation of the DC is formed by the initial state identifier (ISI) of the automatic system in the form of the setting action ρ^*. The control signal u^* is a digital command code, which is formed as the vector $u^* = [\Phi_1, \Phi_2, \beta]$, where Φ_1, Φ_2 are numbers (names) of pairs of phases in which it is necessary to switch network consumers from a more loaded phase (Φ_1) to a less loaded one (Φ_2); β is a vector composed of the coordinates (addresses) of phase Φ_1 consumers to be switched. This control signal u^* is transmitted to the actuators of the system through the communication channel (CC). Such actuators are phase current switches (PCS) designed to carry out the required switching of loads of network consumers from one phase to another [7, 8]. The phase current switch (PCS) is implemented on the basis of a separate microcontroller unit. In conventional ASEMMs, various data transmission technologies (PLC, GSM, etc.) are used as CCs.

The procedure for synthesizing an algorithm of the functioning (control) of the digital controller includes the following main steps:

- 1. Formation of the initial data of the control task.
- 2. Situational analysis of the object.
- 3. Control algorithm synthesis.

Input data for the task is provided by reading the information recorded in the data concentrator (DC) of the ASEMM, and by writing it to the local database of the system. Such information, in particular, includes the active and reactive powers consumed by the phases and consumers of the network. The situational analysis is carried out to determine the structure of phase switching, i.e., to identify the names of the phases (Φ1, Φ2), in which it is necessary to perform the switching operations of the corresponding loads of the network consumers. The synthesis of the control rule u* is based on the found vector $p^* = [p_1^*, p_2^*, p_3^*]$. Methods, algorithms, and technologies for the construction of the IC subsystem are proposed in [7, 8].

The main functions of the Electricity Loss Monitoring (ELM) subsystem are the identification and continuous monitoring of technical and commercial electricity losses in the power distribution network. When there is unauthorized consumption (thefts) of electricity in the network, the balance of phasor powers is determined by the following relationships:

$$\dot{S}_k(\xi) = \dot{S}_k^a(\xi) + \dot{S}_k^T(\xi) + \dot{S}_k^x(\xi), \quad k = \overline{1,3},$$

where k is an index variable denoting the number of the corresponding phase (A, B, C), $k = \overline{1,3}$; $\dot{S}_k$ is the phasor power consumed by the k-th phase at a discrete moment of time $t = t_\xi$; $\dot{S}_k^a$ is total phasor power consumed by all consumers of the k-th phase; $\dot{S}_k^T$ is technical power losses in the k-th phase; $\dot{S}_k^x$ is uncontrolled power losses (UPL) in the k-th phase of the network. In this case, the powers $\dot{S}_k(\xi)$ and $\dot{S}_k^a(\xi)$ are known values. It should be noted that the existing ASEMMs do not determine technical $\dot{S}_k^T$ and commercial $\dot{S}_k^x$ losses, but only evaluate the values of total power $\dot{S}_k$ consumed by the network phases and electric power consumers $\dot{S}_k^a$. The main objective of the ELM subsystem is to identify the values $\dot{S}_k^T$ and $\dot{S}_k^x$ and to conduct continuous monitoring of uncontrolled power losses in the distribution network on their basis. At the same time, to effectively address the tasks of the ELM subsystem, models of virtual PDN are introduced for consideration, which describe the desired states of real-world networks in the absence of unauthorized consumers there. Methods and algorithms for solving the problems of the subsystem in question are proposed in [12, 13].

The "Critical State Diagnosis of the Network" subsystem solves two problems:

- Detection and identification of unauthorized power consumption (thefts) in the PDN;
- Diagnosis of the condition of wires in the sections of the main power line connecting different consumers by their wear and tear level.

These problems are solved by identifying the PDN model with the numerical methods [32, 33] and the estimation of complex resistances of inter-consumer sections of the three-phase network [11]. At the same time, the level of wear and tear of the main power line wires can be assessed. Mathematical conditions for determining the critical states of the PDN are obtained. The solutions to the problems can be used to take appropriate organizational and engineering measures to eliminate the specified critical states of the PDN, which makes it possible to reduce electricity losses caused by unauthorized consumption of electricity and critical levels of wear and tear of wires in the sections of the main power line. Methods and technologies for building the CSD subsystem are outlined in [15, 16].

Data exchange between IC, ELM, and CSD subsystems can be done through the local database of the information system. Input data for addressing new functional tasks comes from the ASEMM data concentrator. In turn, the concentrator collects data by polling the electricity meters installed at the network consumers and at the transformer substation.

IV. Conclusion

Despite the active and widespread adoption of integrated hardware and software systems of ASEMMs in distribution networks, technical and commercial losses of electricity remain quite high. The paper presents several proposals to improve traditional systems of the network automation and digitalization. They are based on the development of new functional subsystems as part of conventional ASEMMs. Such subsystems are designed to carry out the following major functional tasks: automatic control of electricity losses, which ensures a reduction in technical losses in distribution networks (including losses in the transformer power sources); detection and identification of places of unauthorized consumption (theft) of electricity; real-time identification and monitoring of technical and commercial electric power losses in the network; diagnosis of the condition of wires in the inter-consumer sections of the main power line by their wear and tear level.

The creation and use of software of the new functional subsystems allow upgrading the conventional ASEMM into an information-and-control system. This can significantly improve the efficiency of ASEMM, the economic performance of distribution utilities, and the reliability of the transformer power supply sources of networks.

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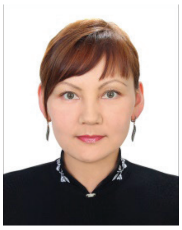

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A Technology for Predictive Estimation of Meteorological Parameters on the Basis of the Global Climate Model CFSv2

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***Abstract* — The paper presents a technology for predictive estimation of meteorological indicators based on the global climate model CFSv2. This technology provides continuous monitoring of current and prognostic indicators of the state of the atmosphere (temperature, pressure, humidity, precipitation, etc.) in the catchment basin of Lake Baikal. The monitoring and data analysis tasks are briefly described as well as the operation algorithms for the main software components intended to obtain predictive distributions of weather indicators for the average values of a given time period, predictive scenarios of the dynamics of their changes for a selected point or a separate basin. The technology involves adjusting the weights of individual ensembles of predictive data of the global CFSv2 system, which provides more reliable predictive estimates.**

***Index Terms*: prognostic estimates, monitoring and data analysis, climate forecast system, climate maps, ensemble approach.**

I. Introduction

Long-term prognostic estimates for 3 months or more are important to manage the operation of hydroelectric power plants (HPP). This affects the generation of electricity in a region with a high share of HPP (for example, for the Irkutsk region it is about 80%). Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS) has been developing long-term forecasting of nature-conditioned energy factors for a long time (for more than 60 years) [1–3]. The founders of this area of research are Academician I.P. Druzhinin and Professor A.P. Reznikov. The GIPSAR system, which was developed at the Institute and included various approximative and probabilistic methods [4, 5], made it possible to obtain sufficiently reliable prognostic estimates. Unfortunately, global climate change has disrupted many previously found patterns, which significantly reduced the reliability of prognostic results.

Modern global climate models make it possible to model and predict the climatic situation for various forecast horizons by considering many factors of the state of the atmosphere, ocean, and land. They allow producing long-term prognostic estimates based on the ensemble approach [6]. This approach suggests the technology for processing predictive ensembles and generates the most probable climatic conditions based on processing the data of the global climate model CFSv2 [7, 8].

II. Global Model CFSv2

Data processing of the global climate model *Climate Forecast System* (CFS) is implemented by separate components of the GeoGIPSAR information and climate system, which is a GIPSAR system extension, which includes the matrices of global data grid. This system was developed at the NCES Environmental Modeling Center [9]. The model is fully coupled and shows the interactions among the Earth's atmosphere, oceans, land, and sea ice. The main advantage of CFS is the openness of the data it provides.

The main purpose of the data analysis in CFSv2 is to create long-term global grid representations of atmospheric states generated by the model and the data assimilation system. The use of operational data has made progress in climate research by eliminating fictitious trends caused by model changes and data assimilation by second.

Data sets from the first version of CFS were collected and converted into the form required for the second version, which was a difficult and time-consuming task. This format was brought in line with international standards for the storage and exchange of observational data. Thousands of graphics editors of the model are generated automatically at the end of each reanalyzed month according to the first version and are displayed on the Climate Forecast System Reanalysis (CFSR) website in real time. In contrast to the first CFS version, CFSv2 has the following new features:

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- Analysing ocean parameters every 6 hours.
- Building an interactive ice model.
- Processing satellite signals received over 24 hours.

The main indicators of CFSv2 predictive ensembles, which are used in the GeoGYPSAR system, are precipitation intensity, surface air temperature, pressure above sea level, geopotential indicators on isobaric surfaces of 500 and 850 gpa, and atmospheric circulation rates [10].

Other models can also be used for forecasting, but most of them have commercial security.

III. The Main Components of Geoclimatic Data Processing

The GeoGIPSAR system is implemented in the form of various interconnected components that perform certain tasks. It includes the tools for adding new components and developing the existing ones. The main component aims to obtain the most probable distributions of atmospheric processes for an arbitrary time period [11, 12].

The system components are divided into 2 groups.

The first group includes:

1. Component for internet monitoring of new data of predictive ensembles in the CFSv2 Global Model Data Center [13].
2. Component for converting, aggregating, and writing to a data warehouse.

The second group of components includes:

1. Component for analysis and generation of prognostic indicators (averages for the period of climatic spatial distributions of indicators or their deviations from the norm).
2. Component for building prognostic scenarios of changes in meteorological indicators for a selected point or basin in comparison with the range of changes in actual data.
3. Component for visual representation of probabilistic distributions of the studied indicator for the selected point according to various sets (or weights) of individual ensembles.
4. Component for verification of prognostic indicators based on their comparison with actual data and refinement of the weighting coefficients of various ensembles.

After a reliable prognostic scenario of climatic parameters for the time period under study is obtained [14, 15], an algorithm for obtaining the inflow through the determination of the closest analogous years is applied. Such years are determined based on the spatial distribution over the past similar periods to minimize the proximity of comparative indicators in the following form:

$$\sigma(e,y,P)=\frac{\sum_{(p)} c_p\cdot\left(\sum_{(i,j)} d_{ij}(i,j)\cdot(p_{ij}^e-p_{ij}^y)^2\right)^{0.5}}{\sum_{(p)} c_p\cdot\sum_{(i,j)} d_{ij}(i,j)},\qquad(1)$$

$$c_p\geq 0,\ d_{ij}(i,j)\geq 0,\quad y=\overline{y_1,y_2},$$

where:

e, y denotes the studied periods of the season and those similar for other years (in a range of years);

$p\in P$ defines the type of parameter with a weighting factor c_p from a given set P;

$d_{ij}(i,j)$ is a specified weight function depending on the coordinates of the region i, j, with the maximum values in the area of the studied catchment basin;

p_{ij}^e, p_{ij}^y are aggregated indicators of the season period e and y years for each cell of the coordinate grid of the region.

An operatively formed set of the closest years with indicators $\sigma(e, y, P)\leq\sigma_0$ allows obtaining estimates of the dynamics of changes in water content for the nearest period.

IV. Description of the Technology for Predictive Estimation

The technology for predictive estimation of weather indicators based on the global CFSv2 model relies on an integrated approach, which allows considering weather indicators from different angles and to quickly make estimates of water content within the specified limits of the catchment basin. This approach makes it possible to increase the reliability of predictive estimates of water inflows into hydroelectric power plant (HPP) reservoirs. This is necessary for the effective management of HPP operating modes. The software components of the GeoGIPSAR technology perform the following tasks:

1. Internet monitoring allows downloading the necessary data of predictive ensembles of various weather indicators in a binary GRIB format, which has a complex structure with information compression.
2. Data conversion, aggregation, and recording in the GeoGYPSAR data warehouse in the form of specialized format files, which include daily averages.
3. Construction of prognostic maps based on absolute and relative weather indicators.
4. Generation of prognostic probable scenarios of a meteorological indicator for a point or a selected basin.
5. Estimation of the probabilistic distribution of the weather indicator component for the selected period with the calculation of the main statistical characteristics.
6. Determination of the weight coefficients of individual ensembles.
7. Verification based on comparison of prognostic and actual data.
8. Visualization of predictive maps and graphs.

Figure 1 shows the interaction of software components in the tasks of Internet monitoring, data conversion and recording in the of CFS ensemble storage. Daily automatic Internet monitoring provides new predictive ensembles periodically downloaded from the CFSv2 Data Center. Next, the downloaded GRIB format files with a complex binary structure are converted to a lighter and more flexible CFS format, which is necessary for further efficient

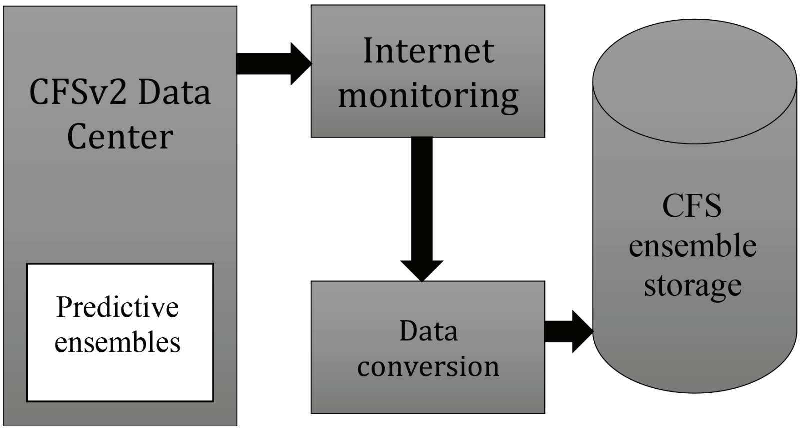

Fig. 1. Interaction of software components of the technology of forming predictive estimates.

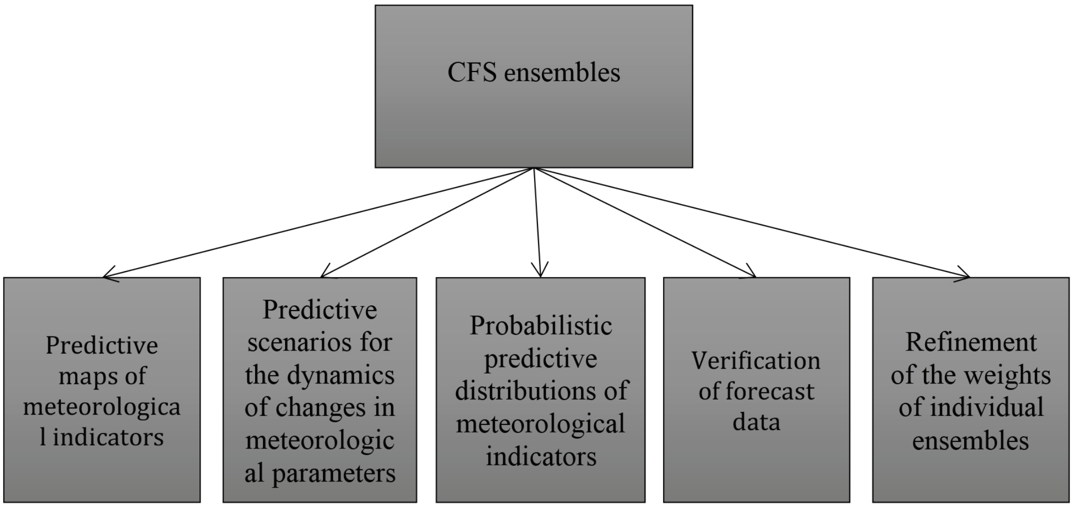

Fig. 2. Application of CFS ensembles within the technology for predictive estimation of meteorological indicators.

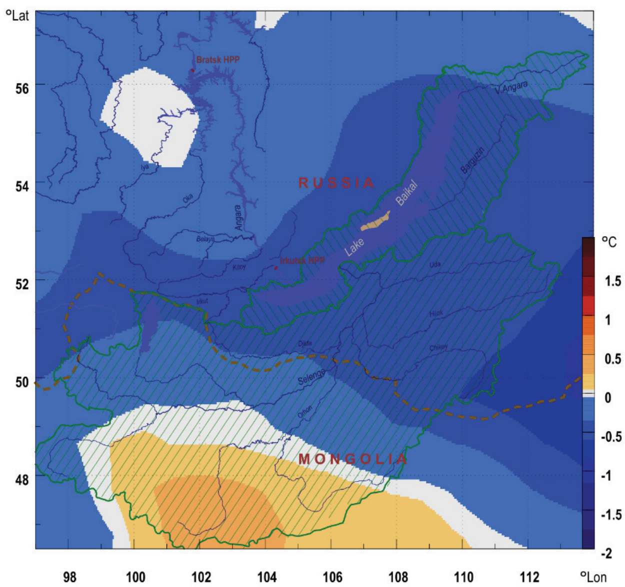

Fig. 3. The air temperature anomalies for June 2022.

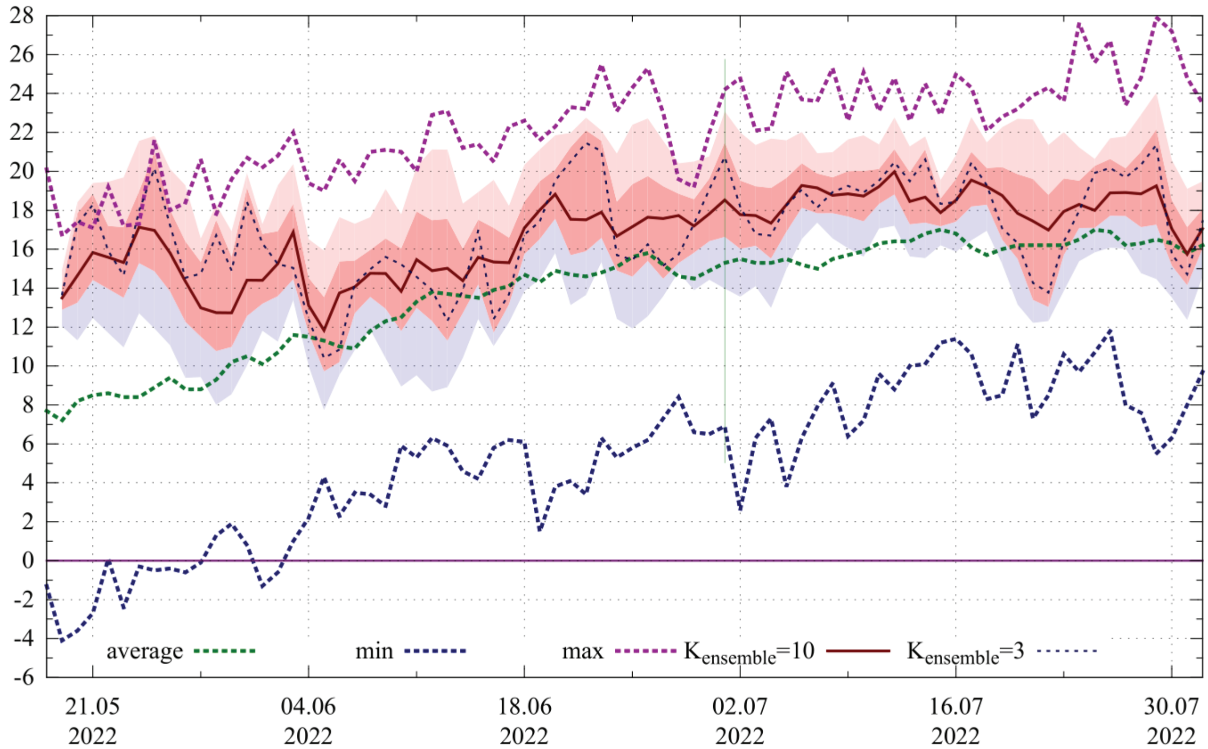

Fig. 4. A predictive scenario of the dynamics of temperature changes for the summer period for the village of Kyakhta.

processing. The converted files are accumulated in the CFS ensemble storage.

The second group of the software components focuses on the use of CFS ensembles for various purposes (Fig. 2). The predictive maps of weather indicators are constructed using pluggable forecasting parameters (a selection of ensembles used, dates of the forecast period, the number of ensembles, connected GIS data, terrain coordinates, the predicted weather indicator, etc.).

The predictive scenario of the dynamics of changes in meteorological indicators is based on the forecast ensembles of CFS, given the range of its daily fluctuations according to the actual data of reanalysis [16].

Probabilistic prognostic distributions show the range and probabilities of the values of the studied meteorological indicator for a given period in comparison with the actual data for the given period.

V. Approach to Processing Predictive Ensembles

The components of processing the predictive ensembles allow constructing predictive maps of meteorological indicators (precipitation, temperature, pressure, etc.) for the studied catchment basins for a given period (up to 9 months); build predictive scenarios of changes in meteorological indicators for river basins; and generate probabilistic distributions of prognostic indicators for the studied period with operational calculation of the main statistical characteristics.

The generation of predictive indicators for a specific meteorological parameter for a certain coordinate grid (selected region) employs absolute and relative indicators, the general form of which is represented by formula:

$$P(k,t)=\left\{\overline{p_{ij}}(k,t),\ i=1,\ldots,N_x,\ j=1,\ldots,N_y\right\}. \quad (2)$$

To obtain predictive indicators with equal weights of ensembles, the formula (3) is used:

$$\overline{p_{ij}}(k,t)=\frac{1}{T}\sum_{t=1}^{T}\overline{p_{ij}}(k,t), \quad (3)$$

Formula (4) is used to determine predictive indicators given the weighting coefficients of ensembles c_k:

$$\overline{P_{ij}}(k,T)=\frac{\sum_{k=1}^{K}c_k\times p_{ij}(k,T)}{\sum_{k=1}^{K}c_k},\ 0\le c_k\le 1, \quad (4)$$

where:
p_{ij} – geoclimatic parameter;
t – time indicator;
N_x – latitude coordinate;
N_y – longitude coordinate;
c_k – weight of the ensemble;
K – number of predictive ensembles;
k – ensemble for a specific parameter;
i, j – spatial distribution indices (latitude, longitude).

The technology also involves the selection of the weighting coefficients of the influence of individual ensembles to obtain final indicators, and has procedures for verification based on actual data. The accuracy of forecasting weather indicators can be increased by

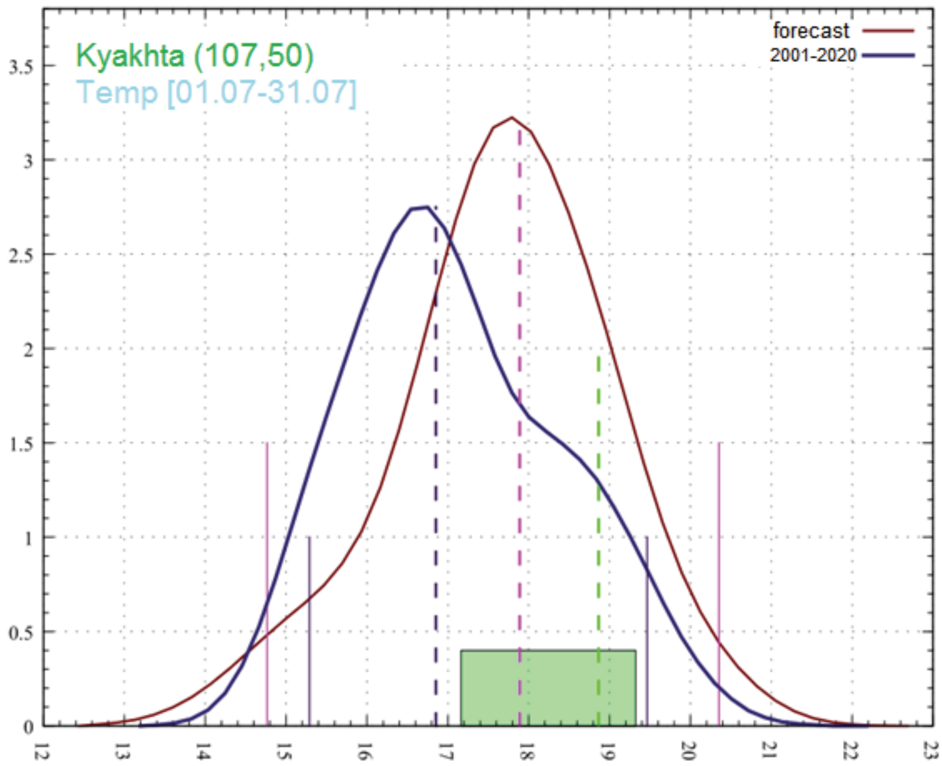

Fig. 5. Probabilistic prognostic and actual (for 2001-2020) distributions of the average temperature of July 2022 in the village of Kyakhta according to the data of prognostic ensembles for the period (01.03-30.04), 2022.

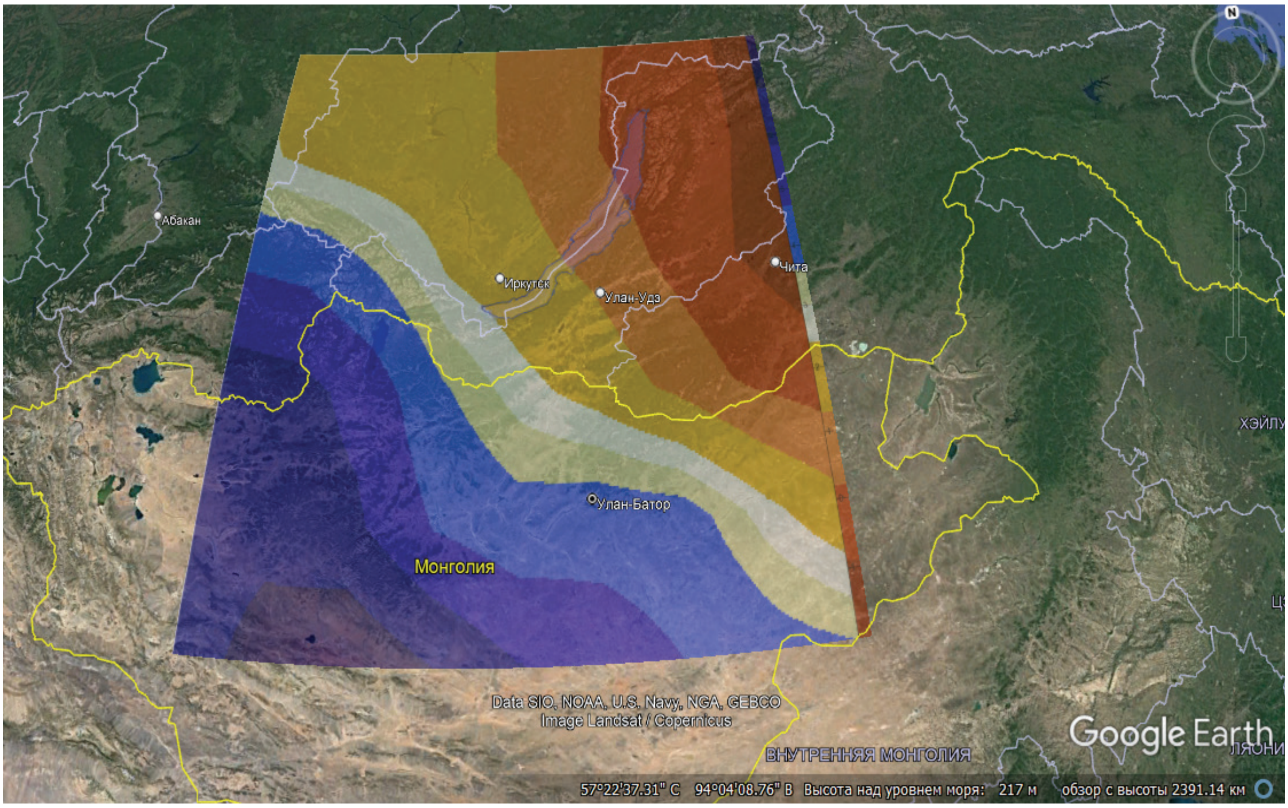

Fig. 6. An example of using a predictive map as a layer in Google Earth.

assigning a weight to an individual data ensemble and varying it depending on the importance. To assign a weight to the ensemble, it is necessary to analyze the degree of influence on the predicted time period.

VI. Examples of Using the technology to Predict Climate Indicators

The performance of the technology can be seen in Fig. 3. It shows a geoclimatic map for temperature anomalies for June 2022. The map is built by processing the data ensembles for the months of January–February. For more accurate results, it is necessary to periodically update the data of the forecast period and adjust the weighting coefficients of the influence of individual ensembles.

A set of accumulated ensembles can be used to build a predictive scenario of the dynamics of changes in the meteorological indicator for a given period. For example, Figure 4 shows the dynamics of temperature changes for the summer period for the village of Kyakhta. The red area highlights the most likely range, in which the air temperature indicator will be located. The solid red line shows the averaged most probable temperature based on processing 10 data ensembles. The blue and pink dashed lines show the lowest and highest possible average daily temperatures.

Figure 5 shows a graph of the probabilistic predictive and actual distribution of the average temperature of July 2022 in the village of Kyakhta according to the data of prognostic ensembles for the months of March and April. The green area is a refinement of the last 3 ensembles, the dashed lines on the graph are the medians of the actual (blue line) and predictive (pink line) values. At the same time, the data beyond 5–95% can be discarded. The actual data are taken into account for the period from 2001 to 2020, which is associated with global climate changes compared to the data of the 20th century.

The predictive indicators obtained are represented by geoclimatic maps, which can have various formats. The technology enables the transformation of maps to overlay a predictive indicator in the form of a layer in standard GIS systems in various services. For example, in Figure 6, a distribution in the form of a kml file is added as a separate layer to the standard GIS system Google Earth.

VII. Conclusion

The technology for predictive estimation of meteorological indicators based on the global climate model CFSv2 provides operational assessments of the state of the atmosphere in the studied catchment basin or at a desired point on the map by coordinates. The estimation at issue in combination with other methods employed in GeoGIPSAR allows experts to build the most probable prognostic picture. This approach, however, does not provide unambiguous prognostic estimates in the case of a long lead time and requires constant refinement (at least once a month) with the possibility of changing prognostic distributions. These data need to be coordinated with the data obtained using other approaches, such as neural network models, to adjust and refine the weighting coefficients of the influence of individual initial ensembles on the final result. The development of this technology in this direction will improve the accuracy of predictive estimates of meteorological parameters.

The proposed software components have a flexible structure and wide possibilities for their development. The technology also allows adding new methods of analysis and forecasting of energy-significant meteorological indicators.

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Prognostic Maps of Climatic Indicators Based on a Multivariate Neural Network

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***Abstract* — The paper is concerned with the construction of maps of climatic indicators using a multivariate neural network. The application of the k-means clustering method for processing input data entering a neural network is described. An alternative neural model is considered within the framework of the multivariate neural network evolution.**

***Index Terms*: neural networks, predictive maps, clustering, MNN, k-means, forecasting.**

I. Introduction

Predictive estimates of water inflow significantly affect the operating conditions of hydroelectric power plants associated with the alternation of extreme high-water and low-water years, which is especially important to factor in for such objects as Lake Baikal. The inflow of water into the reservoir is a determining factor for the operation of hydropower plants (HPPs). Hydropower accounts for 80% of the total electricity generated in the Irkutsk region. Efficient operation and planning of the power system requires long-term (from 3 months to several years) forecasting of the inflow into the reservoir [1–12].

A long-term forecast however cannot be guaranteed, only probabilistic estimates can be considered. One of the objectives of this research is to increase the probability of predictive estimates.

Over the long history of climate observations, various patterns of building the interrelated climatic indicators have been identified, and various methods of forecasting natural processes have been developed on their basis. Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences is engaged in developing an area of long-term forecasting associated with the construction of powerful hydroelectric power plants on the Angara and Yenisei rivers. However, due to the global climate changes observed over the past century, the results obtained with the methods relying on patterns may differ from actual indicators. The very task of long-term forecasting is difficult by definition and the developed global models cannot give a guaranteed result due to the incompleteness of available information and insufficient knowledge of natural processes. The Institute has developed the GeoGIPSAR system for the long-term predictive estimation of water inflow and the climatic situation, which relies on probabilistic, approximative, and other methods for long-term estimation. Recently, neural network approaches have been used to make a long-term forecast [13–15] considering the global climate changes. A multivariate neural network (MNN) with a variety of settings (changing the number of hidden layers and a set of neurons in a layer, the type of activation function in a neuron, etc.) has been developed as a separate component of the GeoGIPSAR system to build various models in different forms (from numerical indicators to interval estimates) [13]. The MNN factors in the climate change by searching for the most correlated predictors and generating interval estimates for a forecast period. The interval method involves dividing the entire observation range into intervals and calculating the probability that the value will fall into each interval when calculating the predictive estimate. Interval estimates can increase the probability of predictive indicators, but are not sufficient to obtain guaranteed results. To increase the probability, the paper presents an approach to the creation of predictive climate maps for precipitation, temperature and other conditions to eliminate disagreement with interval estimates and other methods, for example, forecasting based on global climate models (CFSv2) [11, 12, 15, 16].

II. MNN-Based Prediction of the Climatic Situation

The diagram of MNN use to generate predictive estimates of the climatic situation is shown in Fig. 1.

The input data for this approach is a set of predictors in the form of a matrix of daily indicators of geoclimatic data for different periods. The output is prognostic maps of the studied region in the form of spatial distributions of

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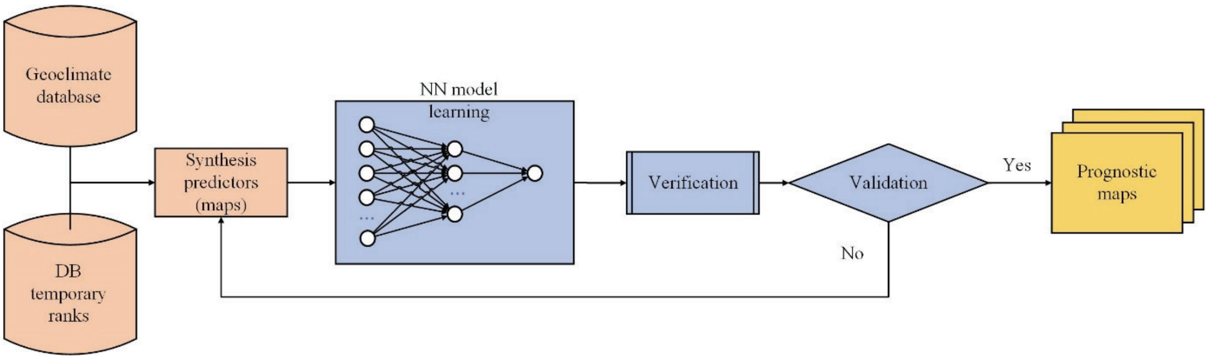

Fig. 1. The diagram of the MNN use for the generation of predictive estimates.

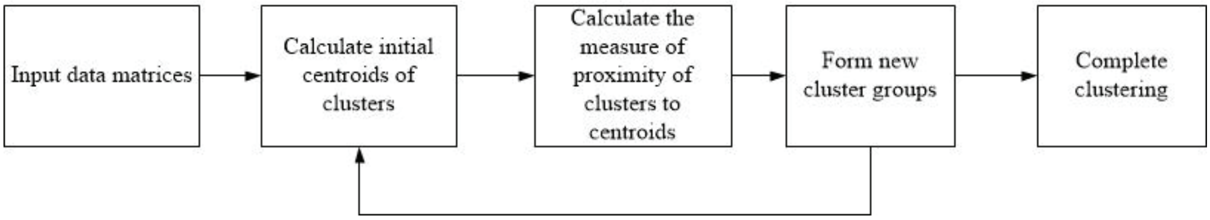

Fig. 2. A diagram of the k-means clustering algorithm.

meteorological indicators. A neural network with training and verification is an internal mechanism of the presented diagram. The criterion for the acceptability of the result in the verification sample is the following condition

$$\frac{\sum_{t=t_1}^{t_2}\sum_{i,j} c_{ij}\left(y_{ij}[t]-r_{ij}[t]\right)^2}{(t_2-t_1+1)\cdot\sum_{i,j} c_{ij}} \le \varepsilon \quad ,(1)$$

where $c_{ij} \in [0,1]$ is weighting coefficients of the weights of the significance of various sections of the studied area, which are set by the expert;

t is a discrete time period from t_1 to t_2;

y_{ij} is a predictive indicator for coordinates i, j;

r_{ij} is an actual indicator for coordinates i, j;

ε is a permissible average error of the prognostic values relative to the actual ones.

At each point, the forecast is compared with the fact. The formula is invariant with respect to the sample length. It allows building various neural network models that meet this criterion.

In fact, high or low water content is determined by a very few standard maps whose prediction can give a better result than numerical prediction of all indicators of grid data. One can distinguish N-types of maps from the set of all accumulated data on the selected meteorological indicator and reduce forecasting to the calculation of probability of belonging to these maps. To do this, it is necessary to perform cluster analysis by partitioning the accumulated data matrices into N clusters. To this end, the k-means method is used. [18–24].

The k-means method is a fairly popular clustering method due to its ease of implementation and high processing speed. The principle of this method is to minimize the total quadratic deviation of clusters points from their centers

$$m = \arg\min_{k\in[1,N]} \sum_{i,j}(x_{ij}-\mu_{ij}^k)^2, \quad \mu_{ij}^k = \sum_s x_{ij}^{ks}, \qquad (2)$$

where k is a cluster index;

μ_{ij} is a cluster centroid;

x_{ij} is a data matrix element.

The algorithm divides the complete set of data matrices into clusters (Fig. 2), which are the closest to the cluster's center, and clustering itself occurs due to the rearrangement of clusters, which involves:

1. Selecting a multidimensional space matrix for initial clustering;
2. Calculating the initial position of the centroid for each cluster;
3. Calculating a measure of proximity of the data matrices to the cluster centroids and assigning the cluster number to the matrix;
4. Repeating the cycle after new clusters are formed by changing the centroid;
5. Completing the clustering if the clusters do not change during the next cycle.

The performance of the method depends on the high sensitivity to noise and the dependence on the initial choice of cluster centers.

III. MNN-Based Methodology for Predicting Cluster Weights

In contrast to the generation of interval estimates for predicting a scalar value, for example, the inflow of a reservoir for a selected period of time, the use of cluster partitioning allows obtaining the probabilities of belonging to clusters.

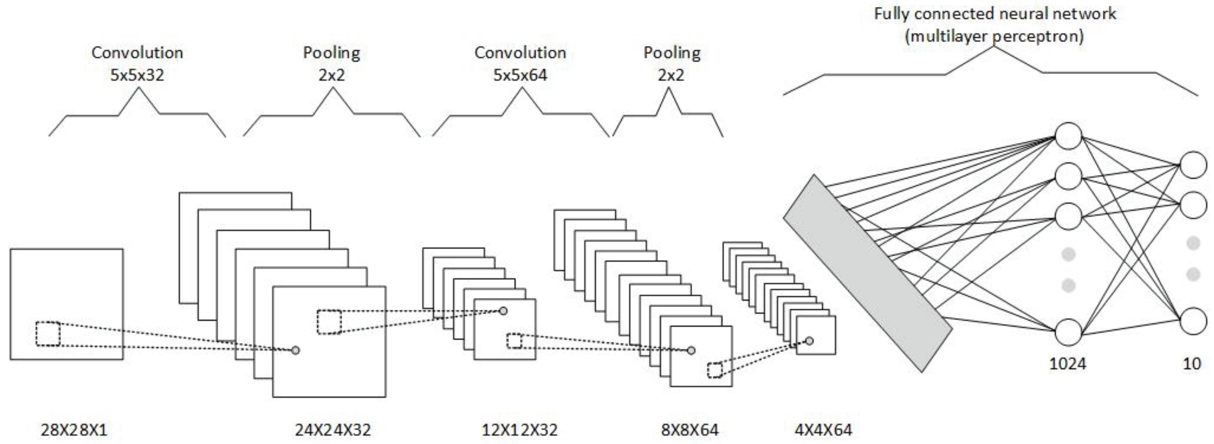

Fig. 3. The scheme of the convolutional neural network.

The use of MNN with the cluster method of distribution of weights involves assigning the value of a specific cluster to the forecast, thereby increasing the forecast accuracy. Whereas on the training sample, the values of the cluster are assigned to the probability of belonging to a particular cluster: 1 – belongs and 0 – does not belong, on the verification sample, the probabilities of the trained network are compared to the actual values of clusters. Acceptable results are considered to be the minimum deviation of prognostic indicators from actual ones according to the following criteria:

$$\frac{1}{T}\sum_{t=1}^{T}\sum_{k=1}^{N}| y_{k,t} - f_{k,t} | \leq \delta \qquad ,(3)$$

where T is the length of the verification sample;
δ is an average error across the entire verification sample;
$y_{k,t}$ is the weight of belonging to predictive clusters;
$f_{k,t}$ is weights of the actual data belonging to clusters.

The very process of the MNN operation to find out the membership to clusters is similar to the method of generating interval estimates. The only difference is that in the cluster method, the final value belongs to a specific cluster, whereas in the interval method, the value is only a set of probabilities of falling into a specific interval.

IV. Description of Software Tools for the implementation of the MNN-Based Cluster Assessment

The software components of the presented technology are implemented in the LuaISEM language (the standard Lua language with a set of libraries implemented at ESI). All the necessary input data and settings of the neural model are recorded in a single configuration file (SCF), which is subsequently input into the neural network model.

The MNN core is a multilayer perceptron with an inverse error propagation method. This model is chosen because the identification of all explicit and implicit patterns is a laborious process and sometimes impossible. This model solves this problem at a basic level and shows decent results. The multilayer perceptron is the simplest model of a neural network capable of performing tasks of small complexity. The inverse method of error propagation in the neural model identifies erroneous results of neurons and then decides on the reliability of intermediate results, while training the neural model "without a teacher" allows one to avoid interfering in the course of the MNN operation and is due to the unknown "correct answer."

The output matrices can be transformed into predictive maps by both using the Gnuplot graphical editor and superimposing the received data in the form of various layers in GIS systems (for example, Google Earth).

V. Prospects for the MNN Development

The process of the MNN operation is related to the use of a multilayer perceptron model. It has proven itself to be simple in the neural network model implementation, its setting, and showed the efficiency of calculations. In order to develop the MNN, the possibility of switching from the multilayer perceptron model to the convolutional neural network (CNN) model is considered [13, 14, 25–27].

The idea of convolutional neural networks comes from biology, namely from the visual cortex of the brain. The principle behind the model operation is the use of special (convolution) layers, using customizable filters, and pooling layers to identify the key features of the object. The CNN algorithm is a sequential application of convolution layers, where data is convoluted, and pooling layers, in which data is compressed. Further, the important features are identified with the algorithm and the feature vector is subsequently fed into a fully connected classification module, where it is assigned a class of the object under study. The larger the number of the consecutive convolution and pooling layers, the larger the output vector. With an excessively large number of convolution layers, the process of "retraining" the network occurs, and the resulting vector becomes incorrect. The process of CNN operation is schematically shown in Fig. 3.

The convolution operation itself is a sequential multiplication of an element of the original input values by an element of the receptive field filter matrix, which results in a matrix of new values, but of a smaller dimension. Each convolution layer generates an output matrix. If 4 filters are used in a layer, then the output matrix will consist of 4 layers. Each convolution layer forms more and more detailed features.

The pooling layer works on the principle of a convolutional layer, but with a view to reducing the size of the collapsed object in space. This must be done to reduce the computing power used in data processing. This process is useful for extracting dominant features. Two types of associations are distinguished: maximum and average. The first type returns the maximum value of the values covered by the receptive field, and the second type returns the average value. The maximum pooling also performs the function of noise reduction by discarding noisy activation values and eliminates noise by reducing dimensionality. The average pooling, in turn, simply reduces the dimension to suppress noise.

The input data for the convolutional neural network was a large database of accumulated data on the water inflow into Lake Baikal, as well as databases of various geoclimatic indicators. Further, the data for a particular year were synthesized into a single vector, which was transmitted to the convolutional neural network.

VI. Conclusion

The presented method of predicting spatial distributions of meteorological indicators (precipitation, temperatures in the catchment basins of hydroelectric power plant reservoirs) increases the reliability of predictive scenarios of water inflows into hydroelectric power plant reservoirs.

The effective refinement of the methodology requires a lot of research on the choice of predictors and acceptable estimates on verification samples, which is planned in the future.

The individual methods of convolutional neural networks are also considered promising to factor in the specific features of the influence of various areas of the data matrices used to increase the reliability of predictive estimates.

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Analysis of China and the World's Energy Security Issues

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Abstract — **Energy security is an important part of the national security system. Affected by global geopolitics and the spread of the novel corona virus pneumonia, China's energy security is facing severe challenges. Energy is the most basic driving force for the development and economic growth of the whole world, and it is the basis for human survival. The issue of energy security has arisen since the Industrial Revolution. With the increasing demand for energy in human society, energy security has been gradually getting closely linked with political and economic security. By the middle of the 21st century, or around 2050, oil resources will be exhausted, and prices will rise substantially, according to a common estimate by economists and scientists. If the new energy system is not established at this time, the energy crisis will sweep the world, especially the developed countries that strongly depend on oil resources. How to comprehensively and efficiently utilize domestic energy resources, control and reduce the scale of oil and gas imports, and ensure energy security are still urgent research issues for China's high-quality and sustainable development.**

Index Terms: **energy security, energy revolution, energy system.**

I. Introduction

Energy security is not only a simple atomic state-to-state relationship, but also a strategic issue concerning national stability, regional coordination, economic structure, and personal development. In today's world, energy has become the currency of political and economic power, a determinant of power hierarchies between nations, and even a new bargaining chip for success and material progress.

The energy security issues facing the world nowadays are characterized by new features, which are significantly different from those observed during previous oil crises [1]. Current issues of energy security embrace not only the security of energy supply, but also the security of energy demand, energy prices, energy transportation, energy use, and other security risks and threats. Both developed and developing countries regard energy security as the primary goal of their national energy strategies. The per capita energy consumption of developed countries is high, and substantial imports are required to cover the shortage of domestic energy resources. Therefore, in addition to domestic resource factors, energy development strategies pay great attention to the influence of international factors related to the development and utilization of foreign resources, and even give attention to changes in energy demand in other countries, the impact on the international energy market, and the degree of the impact. Developing countries are at a disadvantage in international competition and place more emphasis on establishing their national energy security system.

Studies have shown that stabilizing traditional energy production, ensuring the security of imported oil and gas supply, implementing multi-energy complementarity, increasing the proportion of renewable energy consumption, improving energy technology level, accelerating energy technology innovation cooperation, and improving energy development systems and mechanisms are necessary measures for the energy development in China [3].

As an important part of the national security system, energy security has always been an issue of high concern in the countries of the world. At present, China has become the world's largest primary energy consumer, but it is difficult for the domestic energy production to meet consumer demand. The limited space for increasing domestic fossil energy production is not only the core issue facing China's energy security, but also the main factor leading to a gradual decline in energy self-sufficiency rate.

Affected by resource constraints, some of China's energy products are highly dependent on the imported resources, such as oil, which reached 72.5% in 2019. Against the

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backdrop of increasingly complex global geopolitics and the spread of the novel coronavirus pneumonia, China's energy security has to deal with severe challenges.

At the same time, environmental protection and climate governance have also put forward higher requirements for China's energy industry. At present, although China's economic development has entered a new normal, and the growth of energy resource demand has slowed down, the total demand still remains at a high level. China's total energy consumption is estimated to be about 5.9×109 tce (peak). Studies have shown that there is still room for growth in natural gas production, but coal and oil production have reached or are close to their peaks [4]; wind and solar energy resources are abundant, but due to resource storage and development technology costs and other factors, China still needs to take a long-term view and make long-term plans. The balance brings challenges, and it is not enough to undertake the mission of the main energy in the short term. How to ensure energy security while controlling and reducing the scale of oil and gas imports is still a major issue facing China's high-quality and sustainable energy development.

China's domestic academic circles have carried out a lot of research on the concept of energy security, energy security evaluation index system, fundamental issues of energy security, and strategies to ensure energy security and cope with climate change. Based on the macro background of China's economic development entering a new stage, and considering the industry trends of gradually strengthening environmental protection and climate governance, this paper defines the energy security concept of China from multiple perspectives and proposes measures to ensure energy security. The research on the energy development strategy provides theoretical reference.

In order to avoid the above dilemma, many countries actively develop new renewable energy sources such as solar energy, wind energy, and ocean energy (including tidal energy and wave energy). They also focus their attention on new fossil energy sources such as seabed combustible ice (hydrated natural gas). At the same time, fuels such as hydrogen and methanol have also received extensive attention as substitutes for gasoline and diesel.

At present, some renewable energy utilization technologies have made great progress and found wide application in the world. The utilization technologies of biomass energy, solar energy, wind energy, hydroelectric power, and geothermal energy have been applied.

The International Energy Agency (IEA) has conducted a study on international electricity demand from 2000 to 2030, which shows that the average annual growth rate of total power generation from renewable energy will be the fastest. IEA research believes that in the next 30 years, power generation from non-hydro renewable energy will grow faster than power generation from any other fuel, with an annual growth rate of nearly 6%, and its total power generation will increase fivefold between 2000 and 2030.

The proportion of renewable energy in primary energy is generally low. On the one hand, this is related to the importance and policies of different countries. On the other hand, this is associated with the high cost of renewable energy technology, especially the high-tech solar energy, biomass energy, wind energy, and others. According to a forecast study by the IEA, the cost of electricity generation from renewable energy will drop significantly over the next 30 years, but its competitiveness will rise. The cost of renewable energy utilization is related to many factors, which is why the cost forecast has uncertainty. These forecasts however point to a downward trend in the cost of renewable energy technologies.

China is the world's largest energy producer and consumer. The continuous growth of energy supply in the country provides important support for its economic and social development. The rapid growth of China's energy consumption has also created a broad development space for the world energy market. Currently, China has become an indispensable and important part of the world energy market, and is playing an increasingly important and active role in maintaining global energy security.

II. Energy Strategies of Different Countries

With the changes in the development needs over time, the concept of energy security has been continuously enriched and improved. In the 1970s, the fourth Middle East war triggered the oil crisis, and the world's major oil consuming countries established the International Energy Agency (IEA) and put forward the concept of national energy security for the first time. Early energy security research focused on energy supply and energy price stability, and focused on a relatively single energy type and dimension.

Since the 1980s, the energy security concept has gradually developed in various directions such as supply stability, cost-effectiveness, diversity of energy types, and safety of use. The dimensions of environmental security and economic security have been added. In the 21st century, the world's energy security will expand in the direction of broader social, economic, environmental, climate, and consumer security, covering more dimensions such as energy availability, affordability, sustainability, energy governance, and international cooperation. Since different countries have different resource storage, economic, and environmental needs, the priorities and measures of their energy security strategies are also different. Therefore, we should study and define the energy security concept in various countries according to their actual development stage and following the requirements of economic and social development, and environmental capacity.

Let us consider energy security strategies of different countries.

The national energy security strategy formulated by the United States mainly includes energy conservation, improvement of mechanisms, flexible financial support, and maximum utilization of renewable energy. The core of the recent strategy is to provide energy self-supply and reduce external dependence. For example, in January 2017, the United States issued an “Energy Independence” executive order and the “America First Energy Plan,” which was launched to reduce energy costs and maximize the use of domestic energy resources, especially traditional fossil fuels [2].

Most of Japan’s oil and gas supply relies on imports, and has always attached great importance to cooperation with oil and gas producing countries and use of local oil and gas reserves. The long-term goal of the Japanese energy strategy is to achieve energy transformation and build clean, low-carbon, high-efficiency, and smart new models of systems for energy supply through various channels to ensure sustainable development.

Germany’s energy security strategy is centered on renewable energy and supported by improving energy efficiency. In September 2010, the German Federal Ministry of Economics and Technology released the long-term strategy of the “Energy Plan,” which clearly states that the development of renewable resources is the primary target before 2050, and the corresponding strategic goals are economic feasibility, supply security, and environmental friendliness [3].

At present, the world economy, science and technology, culture, security, and politics are undergoing adjustments, changes in the development environment are also occurring in China. The country has proposed promoting a new development pattern with the domestic cycle as the main body, and the domestic and international dual cycles to promote each other. Energy is the source of power for economic development, and its field development should implement the new energy security strategy of “four revolutions and one cooperation” (i.e., consumption, supply, technology, institutional revolution, and international cooperation). In other words, the concept of China’s energy security can be divided into the following five aspects.

Sustainable Development:

The CO_2 and pollutants emitted from energy production and utilization have caused global warming, climate problems, and air pollution problems. In China, the extensive economic growth in the past brought serious environmental problems and increased social governance costs. In the future, energy security must pay close attention to the environment and sustainable development. On the one hand, China has to undertake the obligation to peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060. On the other hand, the country must ensure that residents enjoy their due rights in energy development and meet the growing needs for a better life. Then, China should focus on the carbon emissions per unit of gross domestic product (GDP), energy consumption, per capita carbon emissions under the carbon emission reduction target, and make policy adjustments and changes based on these values.

Guaranteed Supply:

Energy supply security suggests improving the availability of energy; establishing a diversified energy source system, diversified energy import channels, and reliable energy transportation methods; and providing a better replacement and coordinated development mechanism between traditional energy and new energy. This can ensure sufficient and continuous energy supply to the greatest extent, reduce the risk of energy supply failures, and ensure the smooth development of economic activities. The major influencing factors of energy supply security include the degree of resource security, energy import channels, and energy strategic emergency reserves.

Technological Support:

Research shows that scientific and technological progress is the fundamental driving force for promoting energy efficiency, improving energy structure, and reducing energy and environmental conflicts. Science and technology security refers to the scientific and technological capabilities required to formulate and implement the national energy security strategy involving energy production, transportation, consumption and other links, including energy conservation, the ability to popularize and apply mature technologies, the research and development of short-circuit technologies, high-end technology reserves and cooperation capabilities, corresponding standard systems, energy information collection and application capabilities, and others.

Affordability:

China needs to consider the coordinated development of the economy and energy. Important indicators to measure China’s energy and economic security include the impact of energy industry and energy prices on the national economy, the impact of energy imports on international trade, and the ratio of per capita energy consumption to income.

Guaranteed System:

Energy system and mechanisms are an important part and institutional guarantee of energy security. In the context of China’s energy revolution and energy transformation, the energy system mainly involves energy diversification management and supervision and incentive mechanism, energy market and price mechanism, reform mechanism, energy-related laws and regulations, management regulations, and global new energy governance system.

III. China’s energy security situation

A. Sustainable Security

At present, China ranks first in the world in terms of total energy production, total consumption, and coal output. Although energy utilization efficiency has been continuously improved and energy structure has been optimized, there are still great environmental and climate governance pressures. In 2019, the total energy production in China was 3.97×109 tce, of which coal accounted for 69.2%; the total energy consumption was 4.86×109 tce, of which coal accounted for 57.7%.

Although China's current energy intensity is relatively high, and the carbon emissions and energy consumption per unit of GDP are much higher than those of developed countries and regions such as the United States, Europe, and Japan, the per capita carbon emissions and energy consumption levels are far lower than those of developed countries, and there is greater room for improvement. Thus, under the circumstance of environmental capacity constraints and the global response to climate change requiring low-carbon energy development, China should make major adjustments to the future energy utilization direction and consumption structure.

B. Supply Security

The distribution of fossil energy resources in China is very uneven: most of the energy resources and production are concentrated in the western region, while energy consumption is concentrated in the economically developed regions along the eastern coast, and is inversely distributed with the resource-bearing areas [5]. The current evaluation of domestic fossil energy resources shows that, while there is room for growth in natural gas production, coal and oil production have both approached or reached their peaks, which is the main reason for the annual decline in self-sufficiency.

Data shows that in 2019, China's dependence on foreign crude oil exceeded 70%, and its dependence on natural gas was close to 45%. Compared to developed countries, China has fewer oil and gas strategic reserves and emergency reserve facilities, and its emergency reserve system is weak. This results in China's weak ability to adjust to fluctuations in the international oil and gas market, which also has a significant impact on the safe and efficient operation of the pipeline network.

C. Technology Security

China's energy industry has accumulated relative advantages in the field of engineering science and technologies, some of which have reached or approached the world's top level, but the overall technological level of the industry is not enough to support the needs of energy structure transformation and upgrading. There is still a gap in some directions between China and developed countries. Therefore, the country has a lot of room for development in the independent research, enhancement of core technologies, and the introduction and absorption of external technologies.

Some of the problems that still exist in the field of engineering science and technology in China are summarized as follows:

1. The technology is not advanced enough in the coal industry, where most of the geophysical technology and equipment, including the manufacturing process, materials, assembly, sealing, machining accuracy, automation technology, coal quality improvement, and processing of mining equipment, require upgrading;
2. In the oil and gas industry, the accumulation of cutting-edge technologies such as deep water, shale oil and gas, tight oil, and natural gas hydrate ones is insufficient, and the technical level of oil and gas development and large-scale liquefied natural gas (LNG) development under low temperature environment still need to be improved;
3. In the field of electric power, the manufacturing capacity of key components of high-end power equipment is relatively weak, and the technology for application of offshore wind power system, intelligent distributed power supply and micro-grid still needs to be improved.

In the free trade environment, China can solve the above problems through the global industrial division system and industrial chain formed by the exchange of goods and the comparative advantage, but it is relatively easy to be influenced by geopolitics, and China is experiencing unprecedented challenges. In other words, China needs to strengthen the independent research and development of core technologies and products in the energy industry, gradually reduce and eventually get rid of the dependence on imported technologies and products, and effectively enhance the key supporting role of science and technology in the energy industry.

D. Economic Security

The energy industry plays an important role in China's GDP and international trade, and energy imports affect economic security. In recent years, China's energy has included mature categories such as coal, oil, natural gas, electricity, and renewable energy, and has built a relatively complete energy supply system.

For a long time, energy trade has had a great impact on China's international trade. Since China is a net energy importer, and energy trade is mainly related to oil and natural gas imports, based on the historical total trade data published by the General Administration of Customs, an autoregressive model is used to predict China's long-term net exports of goods, and based on the international long-term forecast of China's energy trade according to 2018 World Energy Outlook released by the IEA, it can be found that China's energy imports offset the surplus in trade in goods [3].

Compared to developed countries such as the United States, the United Kingdom, Germany, and Japan, China's current per capita GDP is still relatively low, and comprehensive energy prices are also relatively low. In the future, with the development of China's economy and the continuous improvement in per capita GDP, the domestic affordability of comprehensive energy prices will also exhibit an upward trend. In addition, due to China's high dependence on foreign oil and gas, "black swan" and "grey rhino" events such as the normalization of the new coronavirus pneumonia epidemic also have a certain impact on energy security.

IV. Key Measures of China's Energy Security Strategy

A. Stabilizing the traditional energy production

Although China is rich in coal resources, it is still necessary to scientifically plan production capacity, increase the proportion of production capacity of large mines, and meet the basic needs of domestic demand for coal. At the same time, it is also necessary to maintain the basic stability of coal import volume and import sources, and focus on meeting the coal consumption needs of the southeast coastal areas.

In terms of oil, China needs to intensify the exploration and development of marine and unconventional oil, improve the recovery rate, and slow down the rate of decline in the production capacity of old oil fields. It is also necessary to strengthen the technical reserve and transformation of shale oil development, and build production capacity as soon as possible. Internationally, China needs to deepen international cooperation to make up for the operating pressure of domestic inefficient production capacity on oil and gas companies.

Driven by the dual driving effects of air pollution prevention and low-carbon and clean energy transformation, China's natural gas consumption will continue to grow. China should attach equal importance to conventional gas and unconventional gas; implement technical research and technical transformation in tight gas, shale gas, natural gas hydrate, and others; and maintain stable growth of domestic natural gas production.

B. Enhancing the level of energy technology

To ensure the security of energy supply, the key is to rely on scientific and technological progress. China should strengthen the research and development of cutting-edge energy technologies, promote the development and application of advanced and applicable energy technologies, and improve the development capabilities of major energy technologies and equipment. China should accelerate the development of new and clean energy such as solar energy, wind energy, and biomass energy through scientific research and innovation; increase the research and development of future new energy sources such as ocean energy and nuclear fusion energy; and establish a new energy structure for China's sustainable development.

The most important point is that China must find a path that suits its development and continue to increase the promotion and application of mature technologies such as industrial energy conservation and building energy conservation; strengthen the research and development of new energy-saving technologies for energy production and utilization; and improve energy utilization efficiency.

C. Improving the energy development system

Promoting China's energy market-oriented reform and increasing the degree of openness of the energy market, promoting energy price reform, further improving the construction of a market mechanism conducive to the development of new energy, and improving a long-term stable system to provide the advancement of renewable energy are the tasks China should do now.

Many developed countries such as Europe and the United States have formulated relevant laws and regulations on energy supply and storage in order to ensure the safety of energy economic operation. There are still many deficiencies in China's current energy legislation. In order to cope with the increasingly severe international energy security situation, it should actively learn from foreign energy legislation experience.

D. Strengthening international cooperation

The current international environment is relatively complex. China must correctly study the impact of geopolitical conflicts on global energy security and avoid risks to ensure the national energy security.

In terms of scientific and technological innovation cooperation, it is necessary to rationally increase investment, strengthen the integration of the energy industry with advanced information technologies such as artificial intelligence and big data, optimize energy development and utilization methods, and promote the transformation of traditional "advantageous production capacity" to "new production capacity" of scientific and technological innovation.

China should actively participate in the international energy market price system and increase the right to speak in pricing. With the further expansion of demand for oil in China, being a major global oil consumer, and the improvement in its participation in the international market, China's position in the international oil pricing power still has a lot of room for improvement.

V. Conclusion

In terms of energy security factor, there are significant differences in the sustainability indicators of energy development across provinces. The indicators of resource-based provinces in China are significantly higher than those of other regions such as Inner Mongolia, Shanxi, Shaanxi, and Xinjiang. These provinces are rich in energy reserves, stand out in energy production capacity, account for a large proportion of their energy, have a high degree of energy security, and are less affected by the energy situation in other regions. However, most provinces in China lack energy resources and have to rely on energy supply from other regions to meet their demand. This dependence makes these provinces potentially risky in terms of energy, therefore, their energy development has low sustainability indicators in terms of security factors.

From the perspective of social factors, Chinese provinces have a relatively good level of sustainable energy development. There are no major differences among regions. The country is in a period of rapid social development, and social construction has achieved phased results. The implementation of national policies in all regions is generally consistent and certain results have been achieved.

In terms of ecological factors, the sustainable development index has a good national average value, but there are significant differences among regions. Inner Mongolia, Ningxia, Shanxi, Shaanxi, Xinjiang and other resource-based provinces have very low ecological indices. The ecological issue of resource-based provinces has become a problem that cannot be ignored. In China, the use of clean energy is relatively small, and the main energy source is coal, which causes high CO_2 emissions. This makes ecological issues crucial for China's energy sector.

Chinese provinces are already well placed in terms of the social aspects of energy sustainability. On the premise of ensuring a stable energy supply across the country, the production and emission of carbon dioxide will be strictly controlled.

The following recommendations can be made based on these investigations:

1. Adjust the industrial structure and promote the optimization and upgrading of the industrial structure. When the government and energy production departments formulate energy consumption and production plans, they must follow the laws of the market and fully consider the impact of changes in industrial structure on energy consumption.
2. Increase investment in science and technology to improve energy utilization. Adhere to the policy of prioritizing energy conservation, strive to reduce energy consumption and improve energy utilization efficiency.
3. Optimize the energy consumption structure and increase the development and utilization of new energy. At the same time, it is necessary to increase capital and technical investment in new energy, especially clean and renewable energy.
4. Strengthen the government's macro-control. The government must not only invest in energy-saving and new energy technologies, but also strengthen administrative legislation.

In the context of global response to climate change, low-carbon economy has become the general trend of world economic development. Clean utilization of traditional fossil energy and increase in the proportion of non-fossil energy in a country's energy consumption structure have become an inevitable choice. As a growing developing country, China needs not only to ensure a stable energy supply at a reasonable price to support rapid economic development, but also to reduce energy consumption and carbon emissions related to economic development, and increase the proportion of clean energy use to combat climate change.

In terms of economic security and energy development, energy security under low carbon economy requires the country to improve its energy structure (increase the proportion of renewable energy, use coal cleanly, and vigorously develop unconventional natural gas), promote energy conservation and emission reduction. Briefly, the arrival of the low-carbon era actually brings about a new context for the national energy strategy and energy security. China will face pressure from traditional energy security and challenges from non-traditional energy security, and it is unlikely that all energy security goals will be achieved at the same time.

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On the Problem of Optimal Control of the Motion of Two-Link Planar Manipulator with Nonseparated Multipoint Intermediate Conditions

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***Abstract* — The study focuses on the problem of optimal control of the motion of a two-link planar manipulator on a fixed base with given initial and final conditions, nonseparated conditions for the values of the phase vector at intermediate times, and with a quality criterion given over the entire time interval. It is assumed that absolutely rigid links of the manipulator are interconnected by an ideal cylindrical hinge, and the similar hinge is used to attach the first link to the base. The optimal rules of changing the control moments are constructed, which allow the manipulator to move from a given initial state to a final one, satisfying nonseparated multipoint intermediate conditions. An application of the proposed approach is exemplified by constructed control functions and the corresponding motion with given nonseparated conditions for the values of the phase vector coordinates at some two intermediate times.**

Index Terms: **two-link manipulator, optimal control, nonseparated multipoint conditions, phase constraints.**

I. Introduction

Problems of control and optimal control of dynamical systems with given constraints on the values of the coordinates of the phase vector at intermediate times arise in a number of problems important for applications. Similar problems, in particular, are encountered in the case of control and optimal control of manipulation robots, aircraft, technological processes, energy-saving control of thermal devices, and others [1–3]. Such a wide demand requires the development and design of modern (highly efficient) optimal control methods, which easily implement the control of the manipulator, leading to the desired movement. When studying the movements of manipulators and designing control systems, a mechanical model of a manipulator is usually used in the form of a system of absolutely rigid bodies (rods), which are connected with each other in series using ideal hinges [7–13]. Some important applied problems involve solving the problems of control and optimal control of the movement of manipulators as dynamic systems with nonseparated multipoint intermediate conditions. A characteristic feature of these problems is, along with the classical boundary (initial and final) conditions, the presence of nonseparated (nonlocal) conditions at several intermediate points of the considered interval. The study of these problems is of great importance for both theory and applications. Some issues of control and optimal control of linear dynamical systems with nonseparated multipoint intermediate conditions are examined, in particular, in [1–6].

This paper considers the problem of optimal control of the motion of a two-link planar manipulator on a fixed base with given initial and final conditions, nonseparated conditions for the values of the phase vector at intermediate times, and with a quality criterion given over the entire time interval. Based on the mathematical model of a two-link planar manipulator in the form of Lagrange equations of the second kind [14], in which the main moments are controls, we have constructed explicit forms of the optimal control action and the corresponding motion using the method of moment problems [15].

II. Mathematical Model of the Manipulator and Problem Statement

We consider a two-link manipulator (see Fig. 1) consisting of two absolutely rigid bodies (links) G_1, G_2 connected by hinge O_2. Body G_1 is connected with a fixed base by means of hinge O_1. The hinges are ideal, cylindrical, and their axes are parallel to each other. The

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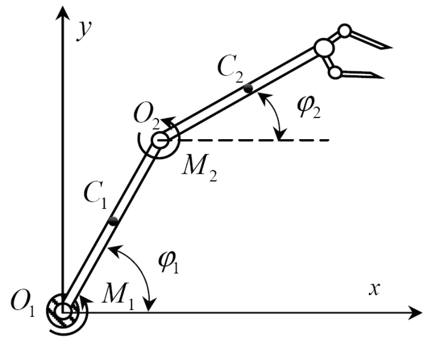

Fig. 1. Two-link manipulator.

system moves in a horizontal plane perpendicular to the hinge axes O_1, O_2.

Each link of the manipulator is an absolutely rigid homogeneous rod of length L. It is assumed that link G_2 includes the executive body (grip), i.e., the mass of the gripper is neglected and the dynamic characteristics are not considered separately. Manipulator is controlled by two independent drives D_1, D_2. Drive D_1 carries out the interaction of body G_1 with the base, and drive D_2 carries out the interaction between link G_1 and link G_2 of the manipulator. The main force vectors generated by drives D_1, D_2 are equal to zero, and the main moments relative to the hinge axes O_1, O_2 are equal to M_1, M_2, respectively. Values M_1, M_2 are taken as control functions in the considered model of the manipulator. It is also assumed that control functions belong to the class of piecewise continuous functions. We do not take into account the action of other forces.

Let us introduce a fixed Cartesian coordinate system O_1XY with the origin on the hinge axis O_1 in the considered plane. Let us denote by φ_1, φ_2 the angles between the horizontal axis and the first and second links, respectively; I_1, I_2 are the moments of inertia of bodies G_1, G_2 relative to the corresponding axes; $L_1 = |O_1O_2|$ is the distance between hinge axes, $L_2 = |O_2C_2|$ is the distance from axis O_2 to the center of gravity C_2 for link G_2.

The kinetic energy of the two links is equal to

$$K = \frac{1}{2}\left(I_1 + m_2L_1^2\right)\dot{\varphi}_1^2 + \frac{1}{2}\left(I_2 + m_2L_2^2\right)\dot{\varphi}_2^2 + \\ + m_2L_1L_2\cos\left(\varphi_1 - \varphi_2\right)\dot{\varphi}_1\dot{\varphi}_2.$$

The equations of motion of the considered manipulator in the form of Lagrange differential equations of the second kind have the form:

$$\begin{aligned} &\left(I_1 + m_2L_1^2\right)\ddot{\varphi}_1 + m_2L_1L_2\cos\left(\varphi_1 - \varphi_2\right)\ddot{\varphi}_2 + \\ &+ m_2L_1L_2\sin\left(\varphi_1 - \varphi_2\right)\dot{\varphi}_2^2 = M_1 - M_2, \\ &(I_2 + m_2L_2^2)\ddot{\varphi}_2 + m_2L_1L_2\cos\left(\varphi_1 - \varphi_2\right)\ddot{\varphi}_1 - \\ &- m_2L_1L_2\sin\left(\varphi_1 - \varphi_2\right)\dot{\varphi}_1^2 = M_2. \end{aligned} \tag{1.1}$$

It is assumed that the center of mass of the second link is located on the axis of hinge O_2, connecting with the first link, which corresponds to the static balance of the second link of the manipulator. In this case, assuming that $|O_2C_2| = L_2 = 0$, equation (1.1) has the form

$$\dot{x}_1 = x_2,\ \dot{x}_2 = u_1,\ \dot{x}_3 = x_4,\ \dot{x}_4 = u_2, \tag{1.2}$$

where

$$x_1 = \left(I_1 + m_2L_1^2\right)\varphi_1,\ x_2 = \left(I_1 + m_2L_1^2\right)\dot{\varphi}_1,$$

$$x_3 = \left(I_2 + m_2L_2^2\right)\varphi_2,\ x_4 = \left(I_2 + m_2L_2^2\right)\dot{\varphi}_2.$$

Control functions u_1 and u_2 have the form

$$u_1 = M_1 - M_2,\ u_2 = M_2,$$

where M_1, M_2 are the main moments relative to the hinge axes.

Let the initial and final states of system (1.2) be given

$$x(t_0) = (x_1(t_0), x_2(t_0), x_3(t_0), x_4(t_0))^T,$$
$$x(T) = (x_1(T), x_2(T), x_3(T), x_4(T))^T, \tag{1.3}$$

and, at some fixed intermediate time instants

$$0 \le t_0 < t_1 < t_2 < t_3 = T,$$

nonseparated (nonlocal) multipoint intermediate conditions

$$\sum_{k=1}^{2} F_k x(t_k) = \alpha \tag{1.4}$$

be given, where α is a two-dimensional column vector, F_k are (2×4)-dimensional matrices ($k = 1, 2$), whose elements are real numbers [4].

In general, for some cases, it can be assumed that at intermediate times t_k (k = 1, 2) not all values of the coordinates of the phase vector $x(t_k)$ are present in (1.4), but only some of them. In such cases, we will assume the corresponding elements of the matrix F_k to equal zero.

System (1.2) with multipoint intermediate condition (1.4) on the time interval $[t_0, T]$ is completely controllable [2, 14].

The optimal control problem for system (1.2) with nonseparated multipoint intermediate conditions (1.4) can be formulated as follows.

Find the optimal control actions $u_1^0(t)$ ***and*** $u_2^0(t)$, $t \in [t_0, T]$***, which transfer the solution to system (1.2) from the initial state*** $x(t_0)$ ***to the final state*** $x(T)$***, thereby ensuring satisfaction of the nonseparated multipoint intermediate condition (1.4) and having the smallest possible value of the quality criterion*** æ$[u^0]$**:**

$$æ[u] = \left(\int_{t_0}^{T} (u_1^2 + u_2^2)dt\right)^{\frac{1}{2}}. \tag{1.5}$$

III. Solution to the Problem

To solve the problem, we write the solution to Eq. (1.2) following from the initial state $x(t_0)$, and by substituting the values $x(t_k)$ into (1.4) for the time instants $t = t_k$ (k = 1, 2), obtain the following relations:

$$\sum_{k=1}^{2} F_k X[t_k, t_0]x(t_0) + \sum_{k=1}^{2}\int_{t_0}^{t_k} F_k X[t_k, \tau]Bu(\tau)d\tau = \alpha. \tag{2.1}$$

For a finite time $t = T$, we have

$$x(T) = X[T, t_0]x(t_0) + \int_{t_0}^{T} X[T, \tau]Bu(\tau)d\tau, \tag{2.2}$$

where $X[t, \tau]$ denotes the normalized fundamental matrix of the solution to the homogeneous part of equation (1.2). The matrices B and $X[t, \tau]$ have the following form:

$$B = \begin{pmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix},$$

$$X[t,\tau] = \begin{pmatrix} x_{11}(t,\tau) & x_{12}(t,\tau) & 0 & 0 \\ 0 & x_{22}(t,\tau) & 0 & 0 \\ 0 & 0 & x_{33}(t,\tau) & x_{34}(t,\tau) \\ 0 & 0 & 0 & x_{44}(t,\tau) \end{pmatrix},$$

where

$$x_{11}(t, \tau) = x_{22}(t, \tau) = x_{33}(t, \tau) = x_{44}(t, \tau) = 1;$$
$$x_{12}(t, \tau) = x_{34}(t, \tau) = t - \tau. \quad (2.3)$$

Using the approaches given in [2, 4], from (2.1) and (2.2) we obtain the following integral relation

$$\int_{t_0}^{T} H[t]u(t)dt = \eta(t_0, ..., T), \quad (2.4)$$

where the following notation

$$H[t] = \begin{pmatrix} F(t)B \\ X[T,t]B \end{pmatrix},$$

$$\eta(t_0, ..., T) = \begin{pmatrix} \alpha - Fx(t_0) \\ x(T) - X[T,t_0]x(t_0) \end{pmatrix},$$

$$F(t) = \sum_{k=1}^{2} F_k[t] = \sum_{k=1}^{2} F_k X[t_k, t],$$

$$F = \sum_{k=1}^{2} F_k X[t_k, t_0] = F(t_0),$$

$$F_k[t] = \begin{cases} F_k X[t_k, t], \text{ for } t_0 \le t \le t_k, \\ 0 \quad , \quad \text{ for } t_k < t \le t_{m+1} = T, \end{cases} \quad k = 1, 2, \quad (2.5)$$

is accepted. Here $H[t]$ is a (6×2) block matrix, the known matrices $F(t)$ and F have dimension (2×4), and η is a (6×1)-dimensional known column vector.

For system (1.2) with nonseparated multipoint intermediate condition (1.4) to be completely controllable on the interval $[t_0, T]$, it is necessary and sufficient that the column vectors of the matrix $H[t]$ be linearly independent on this interval.

Let nonseparated intermediate values (1.4) have the form:

$$x_1(t_1) + x_3(t_1) + x_1(t_2) + x_3(t_2) = \alpha_1,$$
$$x_2(t_1) + x_4(t_1) + x_2(t_2) + x_4(t_2) = \alpha_2, \quad (2.6)$$

i.e., $\alpha = (\alpha_1, \alpha_2)^T$, $F_1 = F_2 = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}$.

Substituting the expressions for matrices F_1, F_2 and the fundamental matrix of solution $X[t, \tau]$ into formula (2.5), we have

$$F(\tau) = F_1 X[t_1, \tau] + F_2 X[t_2, \tau] = $$
$$= \begin{pmatrix} f_{11}(\tau) & f_{12}(\tau) & f_{13}(\tau) & f_{14}(\tau) \\ f_{21}(\tau) & f_{22}(\tau) & f_{23}(\tau) & f_{24}(\tau) \end{pmatrix}, \quad (2.7)$$

where

$$f_{11}(\tau) = x_{11}(t_1,\tau) + x_{11}(t_2,\tau);$$
$$f_{12}(\tau) = x_{12}(t_1,\tau) + x_{12}(t_2,\tau);$$
$$f_{13}(\tau) = x_{33}(t_1,\tau) + x_{33}(t_2,\tau);$$
$$f_{14}(\tau) = x_{34}(t_1,\tau) + x_{34}(t_2,\tau);$$
$$f_{22}(\tau) = x_{22}(t_1,\tau) + x_{22}(t_2,\tau);$$
$$f_{24}(\tau) = x_{44}(t_1,\tau) + x_{44}(t_2,\tau);$$
$$f_{21}(\tau) = f_{23}(\tau) = 0.$$

Therefore, matrix $H[t]$ will be presented in the form:

$$H[\tau] = $$
$$= \begin{pmatrix} x_{12}(t_1,\tau) + x_{12}(t_2,\tau) & x_{34}(t_1,\tau) + x_{34}(t_2,\tau) \\ x_{22}(t_1,\tau) + x_{22}(t_2,\tau) & x_{44}(t_1,\tau) + x_{44}(t_2,\tau) \\ x_{12}(T,\tau) & 0 \\ x_{22}(T,\tau) & 0 \\ 0 & x_{34}(T,\tau) \\ 0 & x_{44}T(t_2,\tau) \end{pmatrix}.$$

According to (2.4)–(2.6), we will have the following integral relations:

$$\int_{t_0}^{T} \left[h_{11}(\tau)u_1 + h_{12}(\tau)u_2 \right] d\tau = \eta_1,$$

$$\int_{t_0}^{T} \left[h_{21}(\tau)u_1 + h_{22}(\tau)u_2 \right] d\tau = \eta_2,$$

$$\int_{t_0}^{T} h_{31}(\tau)u_1 d\tau = \eta_3, \quad \int_{t_0}^{T} h_{41}(\tau)h_1(\tau)d\tau = \eta_4,$$

$$\int_{t_0}^{T} h_{52}(\tau)u_2 d\tau = \eta_5, \quad \int_{t_0}^{T} h_{62}(\tau)u_2 d\tau = \eta_6, \quad (2.8)$$

where the following notation

$$h_{11}(\tau) = x_{12}(t_1,\tau) + x_{12}(t_2,\tau);$$
$$h_{12}(\tau) = x_{34}(t_1,\tau) + x_{34}(t_2,\tau);$$
$$h_{21}(\tau) = x_{22}(t_1,\tau) + x_{22}(t_2,\tau);$$
$$h_{22}(\tau) = x_{44}(t_1,\tau) + x_{44}(t_2,\tau);$$
$$h_{31}(\tau) = x_{12}(T,\tau); \; h_{41}(\tau) = x_{22}(T,\tau);$$
$$h_{52}(\tau) = x_{34}(T,\tau); \; h_{62}(\tau) = x_{44}(T,\tau);$$
$$\eta_1 = \alpha_1 - 2[x_1(t_0) + x_3(t_0)] -$$
$$- (t_1 + t_2 - 2t_0)[x_2(t_0) + x_4(t_0)]; \quad (2.9)$$
$$\eta_2 = \alpha_2 - 2[x_2(t_0) + x_4(t_0)];$$
$$\eta_3 = x_1(T) - x_1(t_0) - (T - t_0)\, x_2(t_0);$$
$$\eta_4 = x_2(T) - x_2(t_0);$$
$$\eta_5 = x_3(T) - x_3(t_0) - (T - t_0)\, x_4(t_0);$$
$$\eta_6 = x_4(T) - x_4(t_0)$$

is accepted.

For a given performance criterion æ$[u]$, the optimal control problem with integral condition (2.4) is a conditional extremum problem, where the minimum of the functional æ$[u]$ must be determined under conditions (2.4).

The left-hand side of condition (2.4) is a linear operation generated by function $u(t)$ on the time interval $[t_0, T]$, and the functional is the norm of a normed linear space. Then the optimal control action $u^0(t)$, $[t_0, T]$, minimizing the functional æ$[u]$ and satisfying condition (2.4) must be constructed according to the algorithm for solving optimal control problems using the moment problem method [15]. To solve the problem of moments (1.5) and ((2.8)), following [15], we need to find the quantities l_i, $i = 1,\ldots,6$, related by condition

$$\sum_{i=1}^{6} l_i \eta_i = 1, \tag{2.10}$$

for which

$$(\rho_0)^2 = \min_{(2.9)} \int_0^T \left[h_1^2(\tau) + h_2^2(\tau) \right] d\tau, \tag{2.11}$$

where

$$h_1(\tau) = l_1 h_{11}(\tau) + l_2 h_{21}(\tau) + l_3 h_{31}(\tau) + l_4 h_{41}(\tau),$$
$$h_2(\tau) = l_1 h_{12}(\tau) + l_2 h_{22}(\tau) + l_5 h_{52}(\tau) + l_6 h_{62}(\tau), \tag{2.12}$$

To determine the quantities l_i^0, $i = 1,\ldots,6$, minimizing (2.11), we apply the method of indefinite Lagrange multipliers. Let us introduce the function

$$f = \int_{t_0}^{T} \left[\left(h_1(\tau)\right)^2 + \left(h_2(\tau)\right)^2 \right] d\tau + \lambda \left[\sum_{i=1}^{6} l_i \eta_i - 1 \right],$$

where λ is the indefinite Lagrange multiplier. Based on this method, calculating the derivatives of function f with respect to l_i, $i = 1,\ldots,6$ and equating them to zero, we obtain the following system of integral relations:

$$\int_{t_0}^{T} \left[h_{11}(\tau) h_1(\tau) + h_{12}(\tau) h_2(\tau) \right] d\tau = -\frac{\lambda}{2} \eta_1,$$

$$\int_{t_0}^{T} \left[h_{21}(\tau) h_1(\tau) + h_{22}(\tau) h_2(\tau) \right] d\tau = -\frac{\lambda}{2} \eta_2,$$

$$\int_{t_0}^{T} h_{31}(\tau) h_1(\tau) d\tau = -\frac{\lambda}{2} \eta_3, \quad \int_{t_0}^{T} h_{41}(\tau) h_1(\tau) d\tau = -\frac{\lambda}{2} \eta_4, \tag{2.13}$$

$$\int_{t_0}^{T} h_{52}(\tau) h_2(\tau) d\tau = -\frac{\lambda}{2} \eta_5, \quad \int_{t_0}^{T} h_{62}(\tau) h_2(\tau) d\tau = -\frac{\lambda}{2} \eta_6.$$

Given the notation (2.12), equations (2.13) can be written in the form of the following algebraic equations:

$$\begin{aligned}
&a_{11}l_1 + a_{12}l_2 + a_{13}l_3 + a_{14}l_4 + a_{15}l_5 + a_{16}l_6 = -(\lambda/2)\eta_1,\\
&a_{21}l_1 + a_{22}l_2 + a_{23}l_3 + a_{24}l_4 + a_{25}l_5 + a_{26}l_6 = -(\lambda/2)\eta_2,\\
&a_{31}l_1 + a_{32}l_2 + a_{33}l_3 + a_{34}l_4 = -(\lambda/2)\eta_3,\\
&a_{41}l_1 + a_{42}l_2 + a_{43}l_3 + a_{44}l_4 = -(\lambda/2)\eta_4,\\
&a_{51}l_1 + a_{52}l_2 + a_{55}l_5 + a_{56}l_6 = -(\lambda/2)\eta_5,\\
&a_{61}l_1 + a_{62}l_2 + a_{65}l_5 + a_{66}l_6 = -(\lambda/2)\eta_6.
\end{aligned} \tag{2.14}$$

The following notation is used here:

$$a_{11} = \int_{t_0}^{T} \left[\left(h_{11}(\tau)\right)^2 + \left(h_{12}(\tau)\right)^2 \right] d\tau =$$

$$= \int_{t_0}^{t_1} \Big[\left(x_{12}(t_1,\tau)\right)^2 + 2x_{12}(t_1,\tau)x_{12}(t_2,\tau) +$$
$$+ \left(x_{34}(t_1,\tau)\right)^2 + 2x_{34}(t_1,\tau)x_{34}(t_2,\mathrm{t}) \Big] d\tau +$$
$$+ \int_{t_0}^{t_2} \left[\left(x_{12}(t_2,\tau)\right)^2 + \left(x_{34}(t_2,\tau)\right)^2 \right] d\tau,$$

$$a_{12} = a_{21} = \int_{t_0}^{T} \left[h_{11}(\tau) h_{21}(\tau) + h_{12}(\tau) h_{22}(\tau) \right] d\tau =$$

$$= \int_{t_0}^{t_1} \Big[x_{12}(t_1,\tau) x_{22}(t_1,\tau) + x_{12}(t_1,\tau) x_{22}(t_2,\tau) +$$
$$+ x_{12}(t_2,\tau) x_{22}(t_1,\tau) + x_{34}(t_1,\tau) x_{44}(t_1,\tau) +$$
$$+ x_{34}(t_1,\tau) x_{44}(t_2,\tau) + x_{34}(t_2,\tau) x_{44}(t_1,\tau) \Big] d\tau +$$
$$+ \int_{t_0}^{t_2} \left[x_{12}(t_2,\tau) x_{22}(t_2,\tau) + x_{34}(t_2,\tau) x_{44}(t_2,\tau) \right] d\tau,$$

$$a_{13} = a_{31} = \int_{t_0}^{T} h_{11}(\tau) h_{31}(\tau) d\tau =$$

$$= \int_{t_0}^{t_1} x_{12}(t_1,\tau) x_{12}(T,\tau) d\tau + \int_{t_0}^{t_2} x_{12}(t_2,\tau) x_{12}(T,\tau) d\tau,$$

$$a_{14} = a_{41} = \int_{t_0}^{T} h_{11}(\tau) h_{41}(\tau) d\tau =$$

$$= \int_{t_0}^{t_1} x_{12}(t_1,\tau) x_{22}(T,\tau) d\tau + \int_{t_0}^{t_2} x_{12}(t_2,\tau) x_{22}(T,\tau) d\tau,$$

$$a_{15} = a_{51} = \int_{t_0}^{T} h_{12}(\tau) h_{52}(\tau) d\tau =$$

$$= \int_{t_0}^{t_1} x_{34}(t_1,\tau) x_{34}(T,\tau) d\tau + \int_{t_0}^{t_2} x_{34}(t_2,\tau) x_{34}(T,\tau) d\tau,$$

$$a_{16} = a_{61} = \int_{t_0}^{T} h_{12}(\tau) h_{62}(\tau) d\tau =$$

$$= \int_{t_0}^{t_1} x_{34}(t_1,\tau) x_{44}(T,\tau) d\tau + \int_{t_0}^{t_2} x_{34}(t_2,\tau) x_{44}(T,\tau) d\tau,$$

$$a_{22} = \int_{t_0}^{T} \left[\left(h_{21}(\tau)\right)^2 + \left(h_{22}(\tau)\right)^2 \right] d\tau =$$

$$= \int_{t_0}^{t_1} \Big[\left(x_{22}(t_1,\tau)\right)^2 + 2x_{22}(t_1,\tau)x_{22}(t_2,\tau) +$$
$$+ \left(x_{44}(t_1,\tau)\right)^2 + 2x_{44}(t_1,\tau)x_{44}(t_2,\tau) \Big] d\tau$$
$$+ \int_{t_0}^{t_2} \left[\left(x_{22}(t_2,\tau)\right)^2 + \left(x_{44}(t_2,\tau)\right)^2 \right] d\tau,$$

$$a_{23} = a_{32} = \int_{t_0}^{T} h_{21}(\tau) h_{31}(\tau) d\tau =$$

$$=\int_{t_0}^{t_1} x_{22}(t_1,\tau)x_{12}(T,\tau)d\tau+\int_{t_0}^{t_2} x_{22}(t_2,\tau)x_{12}(T,\tau)d\tau,$$

$$a_{24}=a_{42}=\int_{t_0}^{T} h_{21}(\tau)h_{41}(\tau)d\tau=$$

$$=\int_{t_0}^{t_1} x_{22}(t_1,\tau)x_{22}(T,\tau)d\tau+\int_{t_0}^{t_2} x_{22}(t_2,\tau)x_{22}(T,\tau)d\tau,$$

$$a_{25}=a_{52}=\int_{t_0}^{T} h_{22}(\tau)h_{52}(\tau)d\tau=$$

$$=\int_{t_0}^{t_1} x_{44}(t_1,\tau)x_{34}(T,\tau)d\tau+\int_{t_0}^{t_2} x_{44}(t_2,\tau)x_{34}(T,\tau)d\tau,$$

$$a_{26}=a_{62}=\int_{t_0}^{T} h_{22}(\tau)h_{62}(\tau)d\tau=$$

$$=\int_{t_0}^{t_1} x_{44}(t_1,\tau)x_{44}(T,\tau)d\tau+\int_{t_0}^{t_2} x_{44}(t_2,\tau)x_{44}(T,\tau)d\tau,$$

$$a_{33}=\int_{t_0}^{T}\left(h_{31}(\tau)\right)^2 d\tau=\int_{t_0}^{T}\left(x_{12}(T,\tau)\right)^2 d\tau,$$

$$a_{34}=a_{43}=\int_{t_0}^{T} h_{31}(\tau)h_{41}(\tau)d\tau=\int_{t_0}^{T} x_{12}(T,\tau)x_{22}(T,\tau)d\tau,$$

$$a_{44}=\int_{t_0}^{T}\left(h_{41}(\tau)\right)^2 d\tau=\int_{t_0}^{T}\left(x_{22}(T,\tau)\right)^2 d\tau,$$

$$a_{55}=\int_{t_0}^{T}\left(h_{52}(\tau)\right)^2 d\tau=\int_{t_0}^{T}\left(x_{34}(T,\tau)\right)^2 d\tau,$$

$$a_{56}=a_{65}=\int_{t_0}^{T} h_{52}(\tau)h_{62}(\tau)d\tau=\int_{t_0}^{T} x_{34}(T,\tau)x_{44}(T,\tau)d\tau,$$

$$a_{66}=\int_{t_0}^{T}\left(h_{62}(\tau)\right)^2 d\tau=\int_{t_0}^{T}\left(x_{44}(T,\tau)\right)^2 d\tau.$$

Adding condition (2.10) to the obtained equations (2.14), we obtain a closed system of seven algebraic equations for the same number of unknown quantities l_i, $i = 1,\ldots,6$, and λ. Let the quantities l_i^0, $i = 1,\ldots,6$, and λ_0 be the solution to this closed system of algebraic equations. Then, according to (2.11), (2.12), we have

$$h_1^0(\tau)=l_1^0h_{11}(\tau)+l_2^0h_{21}(\tau)+l_3^0h_{31}(\tau)+l_4^0h_{41}(\tau),$$

$$h_2^0(\tau)=l_1^0h_{12}(\tau)+l_2^0h_{22}(\tau)+l_5^0h_{52}(\tau)+l_6^0h_{62}(\tau), \quad (2.15)$$

$$(\rho_0)^2=\int_{t_0}^{T}\left[\left(h_1^0(\tau)\right)^2+\left(h_2^0(\tau)\right)^2\right]d\tau.$$

Following [15], the optimal control actions can be represented as:

$$u_1^0(t)=\frac{1}{\rho_0^2}h_1^0(t)\,;\; u_2^0(t)=\frac{1}{\rho_0^2}h_2^0(t)\,.$$

Taking into account the notation (2.15), the optimal control actions are represented as follows:

$$u_1^0(t)=\begin{cases}\frac{1}{\rho_0^2}[l_1^0\left(x_{12}(t_1,\tau)+x_{12}(t_2,\tau)\right)+l_2^0\left(x_{22}(t_1,\tau)+x_{22}(t_2,\tau)\right)+ \\ +l_3^0x_{12}(T,\tau)+l_4^0x_{22}(T,\tau)], & t\in[t_0,t_1),\\ \frac{1}{\rho_0^2}\left[l_1^0x_{12}(t_2,\tau)+l_2^0x_{22}(t_2,\tau)+l_3^0x_{12}(T,\tau)+l_4^0x_{22}(T,\tau)\right], \\ & t\in[t_1,t_2),\\ \frac{1}{\rho_0^2}\left[l_3^0x_{12}(T,\tau)+l_4^0x_{22}(T,\tau)\right], & t\in[t_2,T],\end{cases}$$

$$u_2^0(t)=\begin{cases}\frac{1}{\rho_0^2}[l_1^0\left(x_{34}(t_1,\tau)+x_{34}(t_2,\tau)\right)+l_2^0\left(x_{44}(t_1,\tau)+x_{44}(t_2,\tau)\right)+ \\ +l_5^0x_{34}(T,\tau)+l_6^0x_{44}(T,\tau), & t\in[t_0,t_1),\\ \frac{1}{\rho_0^2}\left[l_1^0x_{34}(t_2,\tau)+l_2^0x_{44}(t_2,\tau)+l_5^0x_{34}(T,\tau)+l_6^0x_{44}(T,\tau)\right], \\ & t\in[t_1,t_2),\\ \frac{1}{\rho_0^2}\left[l_5^0x_{34}(T,\tau)+l_6^0x_{44}(T,\tau)\right], & t\in[t_2,T],\end{cases}$$

or, given (2.3), they can have the form:

$$u_1^0(t)=\begin{cases}\frac{1}{\rho_0^2}\left[l_1^0(t_1+t_2-2\tau)+2l_2^0+l_3^0(T-\tau)+l_4^0\right], \\ & t\in[t_0,t_1),\\ \frac{1}{\rho_0^2}\left[l_1^0(t_2-\tau)+l_2^0+l_3^0(T-\tau)+l_4^0\right], & t\in[t_1,t_2),\\ \frac{1}{\rho_0^2}\left[l_3^0(T-\tau)+l_4^0\right], & t\in[t_2,T],\end{cases}$$

$$u_2^0(t)=\begin{cases}\frac{1}{\rho_0^2}\left[l_1^0(t_1+t_2-2\tau)+2l_2^0+l_5^0(T-\tau)+l_6^0\right], \\ & t\in[t_0,t_1),\\ \frac{1}{\rho_0^2}\left[l_1^0(t_2-\tau)+l_2^0+l_5^0(T-\tau)+l_6^0\right], & t\in[t_1,t_2),\\ \frac{1}{\rho_0^2}\left[l_5^0(T-\tau)+l_6^0\right], & t\in[t_2,T].\end{cases}$$

Substituting the expression for the optimal control action into (1.2) and integrating these equations, we obtain the optimal motion on each time interval.

IV. Example

Let some fixed intermediate times $0 \le t_0 < t_1 < t_2 = T$, and $t_0 = 0$; $t_1 = 2$; $t_2 = 3$; $T = 4$ be given. The initial and final states for phase vector $x = (x_1, x_2, x_3, x_4)^T$ will be $x(0) = (0, 0, 0, 0)^T$, $x(4) = (5, 0, 4, 1)^T$.

According to formula (2.9), assuming that $\alpha_1 = 3$, $\alpha_2 = 2$, we obtain the following value for the constant vector η:

$$\eta = (\eta_1, \eta_2, \eta_3, \eta_4, \eta_5, \eta_6)^T = (3, 2, 5, 0, 4, 1)^T.$$

Further, carrying out the corresponding calculations of the integrals for the coefficients of the system of equations (2.14), we obtain

$$a_{11} = 42,\ a_{12} = a_{21} = 25,\ a_{13} = a_{31} = a_{15} = a_{51} = 121/6,$$
$$a_{14} = a_{41} = a_{16} = a_{61} = 13/2,\ a_{22} = 18,$$
$$a_{23} = a_{32} = a_{25} = a_{52} = 27/2,\ a_{24} = a_{42} = a_{26} = a_{62} = 5,$$

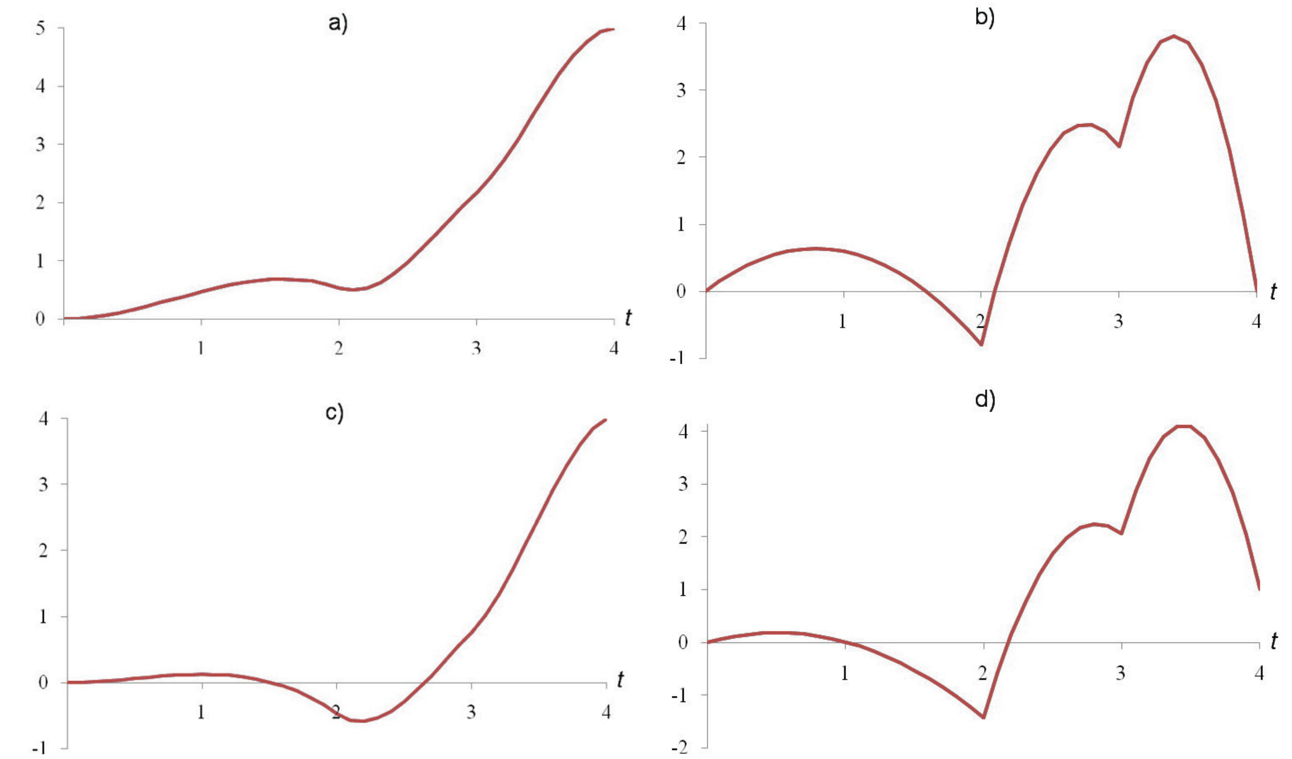

Fig. 2. Graphs of the vector function of the optimal movement $x^0(t)$ ***at*** $t\in[0,4]$ ***by coordinates: a)*** $x_1^0(t)$ ***; b)*** $x_2^0(t)$ ***; c)*** $x_3^0(t)$ ***; d)*** $x_4^0(t)$ ***.***

$$a_{33}=64/3,\ a_{44}=4,\ a_{34}=a_{43}=a_{56}=a_{65}=8,$$
$$a_{55}=64/3,\ a_{66}=4.$$

Solving the system of algebraic equations (2.14) with the obtained numerical values of the coefficients for l_i^0, $i=1,\ldots,6$, and λ_0, we obtain the following values:

$$l_1=-\frac{18528}{243299},\ l_2=-\frac{21696}{243299},\ l_3=\frac{40965}{243299},$$

$$l_4=-\frac{24702}{243299},\ l_5=\frac{39867}{243299},$$

$$l_6=-\frac{22018}{243299},\ \lambda=-\frac{3904}{243299}.$$

Based on the notation (2.5), the optimal functions $h_1^0(\tau)$, $h_2^0(\tau)$, $\tau\in[t_0,T]$ are represented as follows:

$$h_1^0(\tau)=\begin{cases} l_1^0\left(t_1+t_2-2\tau\right)+2l_2^0+l_3^0\left(T-\tau\right)+l_4^0, \\ \qquad\qquad\qquad\qquad t\in\left[t_0,t_1\right), \\ l_1^0\left(t_2-\tau\right)+l_2^0+l_3^0\left(T-\tau\right)+l_4^0,\ t\in\left[t_1,t_2\right), \\ l_3^0\left(T-\tau\right)+l_4^0, \qquad\qquad t\in\left[t_2,T\right], \end{cases}$$

$$h_2^0(\tau)=\begin{cases} l_1^0\left(t_1+t_2-2\tau\right)+2l_2^0+l_5^0\left(T-\tau\right)+l_6^0, \\ \qquad\qquad\qquad\qquad t\in\left[t_0,t_1\right), \\ l_1^0\left(t_2-\tau\right)+l_2^0+l_5^0\left(T-\tau\right)+l_6^0,\ t\in\left[t_1,t_2\right), \\ l_5^0\left(T-\tau\right)+l_6^0, \qquad\qquad t\in\left[t_2,T\right]. \end{cases}$$

Now, calculating the value of $(\rho_0)^2$ according to formula (2.15), we obtain

$$(\rho_0)^2=\frac{1952}{243299}.$$

Further, for the components of the vector of optimal control action $u^0(t)$, $t\in[t_0,T]$, we will have explicit expressions in the following form:

$$u_1^0(t)=\begin{cases} 1.6014-2.0026t, & t\in[0,2], \\ 31.6998-11.4944t, & t\in(2,3], \\ 71.2899-20.9862t, & t\in(3,4], \end{cases}$$

$$u_2^0(t)=\begin{cases} 0.7264-1.4401t, & t\in[0,2], \\ 30.8248-10.9319t, & t\in(2,3], \\ 70.4149-20.4237t, & t\in(3,4]. \end{cases}$$

If we substitute the obtained expressions for the optimal control into (1.2) and integrate these equations, then we obtain the optimal motion on each time interval in the following form:

$$x_1^0(t)=\begin{cases} 0.8007t^2-0.3338t^3, & t\in[0,2], \\ 15.8499t^2-1.9157t^3+34.8852-41.2131t, & \\ & t\in(2,3], \\ 35.6449t^2-3.4977t^3+127.6147-117.2705t, & \\ & t\in(3,4], \end{cases}$$

$$x_2^0(t)=\begin{cases} 1.6014t-1.0013t^2, & t\in[0,2], \\ 31.6998t-5.7472t^2-41.2131, & t\in(2,3], \\ 71.2899t-10.4930t^2-117.2705, & t\in(3,4], \end{cases}$$

$$x_3^0(t)=\begin{cases} 0.3632t^2-0.2400t^3, & t\in[0,2],\\ 15.4124t^2-1.8219t^3+34.8852-41.2131t, & \\ & t\in(2,3],\\ 35.2075t^2-3.4039t^3+127.6147- & \\ \quad -117.2705t, & t\in(3,4], \end{cases}$$

$$x_4^0(t)=\begin{cases} 0.7264t-0.7200t^2, & t\in[0,2],\\ 30.8248t-5.4659t^2-41.2131, & t\in(2,3],\\ 70.4149t-10.2118t^2-117.2705, & t\in(3,4]. \end{cases}$$

Figure 2 shows a graphical view of the vector-function of the optimal movement $x^0(t)$ at $t\in[0,4]$ by coordinates $x_1^0(t)$, $x_2^0(t)$, $x_3^0(t)$, $x_4^0(t)$.

Note, by direct substitution, we can verify that the obtained optimal motions satisfy condition (1.4), i.e.,

$$F_1x^0(t_1)+F_2x^0(t_2)=\begin{pmatrix}3\\2\end{pmatrix}.$$

Thus, we have obtained explicit expressions for the optimal control and the corresponding optimal motion for system (1.2) with given initial and final values of the phase vector and nonseparated intermediate conditions (1.4).

V. Conclusion

The problem of optimal control of the motion of a two-link planar manipulator on a fixed base with given initial and final conditions and nonseparated conditions for the values of the phase vector at intermediate times is solved. The application of the proposed approach is exemplified by the construction of the functions of optimal control and the corresponding optimal motion with given nonseparated conditions for the values of the phase vector coordinates at some two intermediate times. The constructed corresponding graphs for the coordinates of the phase vector of the manipulator confirm the results obtained.

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Reengineering the "Oil and Gas of Russia" Software to Meet the Requirements of Current Resilience Studies in the Gas Industry

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***Abstract* — Research into energy models often has to rely on the functionality provided by legacy software that cannot correctly satisfy the needs of the researcher due to the request to perform tasks that were not provided by the developer during the creation of these products. To solve these problems, reengineering of legacy software is used. In particular, it was decided to reengineer software to solve the problem of flow distribution in the gas transmission system (GTS) and find bottlenecks in it with the aid of geographic information technology. The main disadvantages of the legacy software were the inability to add a new calculation scheme or modernize it, and the inability to use geocode. The reengineering methods applied involve: 1) analysing legacy software for module connectivity; 2) choosing a framework with the capability to develop geographic information systems; 3) reworking the architecture of the software module to implement the function of adding objects of the calculation model; 4) integrating software with an embedded database management system for compactness and the ability to save changes made. These solutions made it possible to update the software and give the researcher a convenient tool for creating and correcting calculation schemes using geographic information technologies for help. Geocoding support enables the expansion of the existing energy models by adding objects based on the data provided by geographic information services for the requested tag and the research to determine new optimal solutions for transporting energy resources.**

***Index Terms*: geographic information system, energy system, resilience, vulnerability.**

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I. Introduction

The resilience of an energy system (ES) is its property to withstand large disturbances by preventing their cascade development with a massive disruption of energy supply to consumers and to restore the initial state of the system or bring the system close to its initial state [1–3].

The modern scheme for studying the ES resilience [4], (Fig. 1) is based on the investigation and analysis of systemic capabilities for adaptation to large disturbances and recovery after their impact [5, 6], quantitative assessment of the ES resilience [7], and the development of strategies for its increase [8–14].

As seen in Figure 1, analysis of vulnerability [15] and risks [16] plays a central role in the study of ES resilience. Resilience (Figure 1) characterizes the size and scale of negative consequences for the entire system because of the impact of a particular disturbance [17].

The initial data for the analysis of vulnerability are: information on the functioning and expansion of ES, classes of disturbances, and measures to improve resilience.

Information on the ES functioning and expansion, which includes natural-climatic and socio-economic data from monitoring energy facilities, is the result of traditional general energy research [18].

Disturbances are divided into the following classes:

- Natural disasters such as floods, earthquakes, hurricanes, etc. [19];
- Technogenic disasters caused by failures of components or subsystems [20];
- Deliberate (intentional) violations such as terrorist acts, cyber-attacks, etc. [21];

The main purpose of the ES vulnerability analysis is to identify deficiencies in the design and control mechanisms of the system, which can contribute to the spread of a large disturbance over the systems under study [17].

Vulnerability analysis of ES [24] begins with building a set of possible states of energy systems, which reflect the most representative or characteristic combinations of external conditions of their expansion and functioning in the time interval at issue. Also, disturbance scenarios describing their impact on the ES are formed according to the specified classes. Further, vulnerability analysis is divided into types, such as an analysis of global

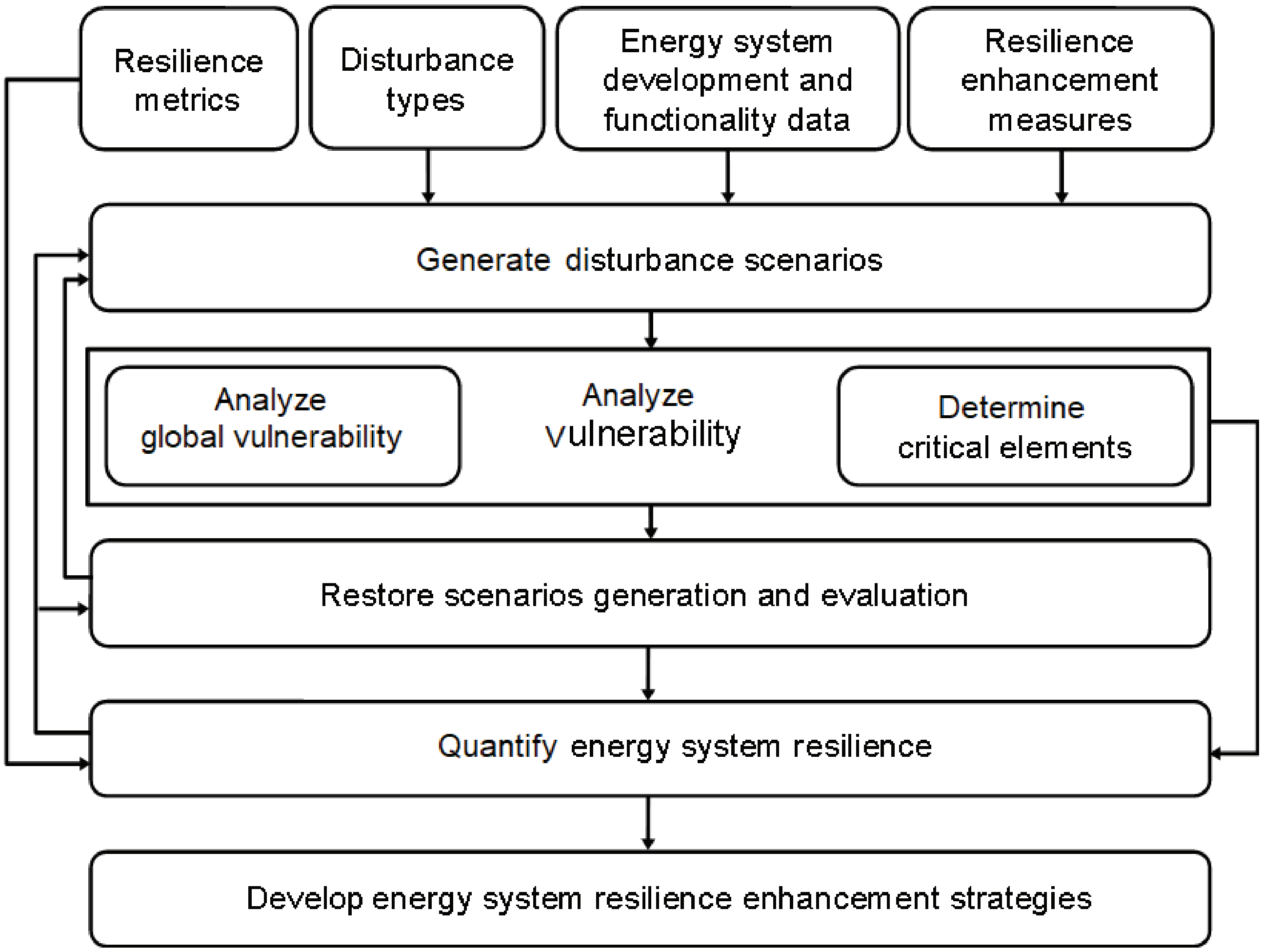

Fig. 1. General scheme of the ES resilience research.

vulnerability and a search for critical components [15, 20].

Global vulnerability analysis aims to obtain general information about the impact of disturbances on the ES performance and is carried out by modeling a series of disturbances with a gradually increasing degree of impact and, accordingly, an increasing number of consequences for the system. Such computational experiments will make it possible to determine the threshold values of the impact for certain classes of disturbances, the excess of which will cause the considered ES to split into unrelated parts [15, 20].

The search for critical components focuses on identifying the components, whose single or group failure causes the greatest decrease in the efficiency of the entire ES. The key point here is to detect all, even unexpected, sets of critical components [20].

To analyze the survivability of a unified gas system in emergency situations, the L. A. Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences has developed the “Oil and Gas of Russia” software, which includes models that simulate the behavior of the unified gas system (UGS) and oil products systems (OPS).

II. Software “Oil and Gas of Russia”

The software is based on a flow distribution model designed to assess the production capabilities of the UGS under various types of disturbances. These studies aim to minimize possible gas shortages for consumers, identify sections of the network with insufficient capacity, which occurs under given conditions.

To solve these problems, the distribution flow in the model follows the Basaker-Gowan algorithm as a minimum cost maximum flow problem, where energy system can be represented as a graph with constraints on the throughput in arcs, and on the production, storage, and consumption volumes at the network nodes. The architecture of this software package is shown in Fig. 2.

The software, consisting of a user interface, a database, and business logic, builds a graphical image of the network, including the arcs, which represent network sections; the nodes, which stand for production, storage, and consumption facilities; and branch points where compressor stations are located in an initial ES. In addition, it makes it possible to visually display information about

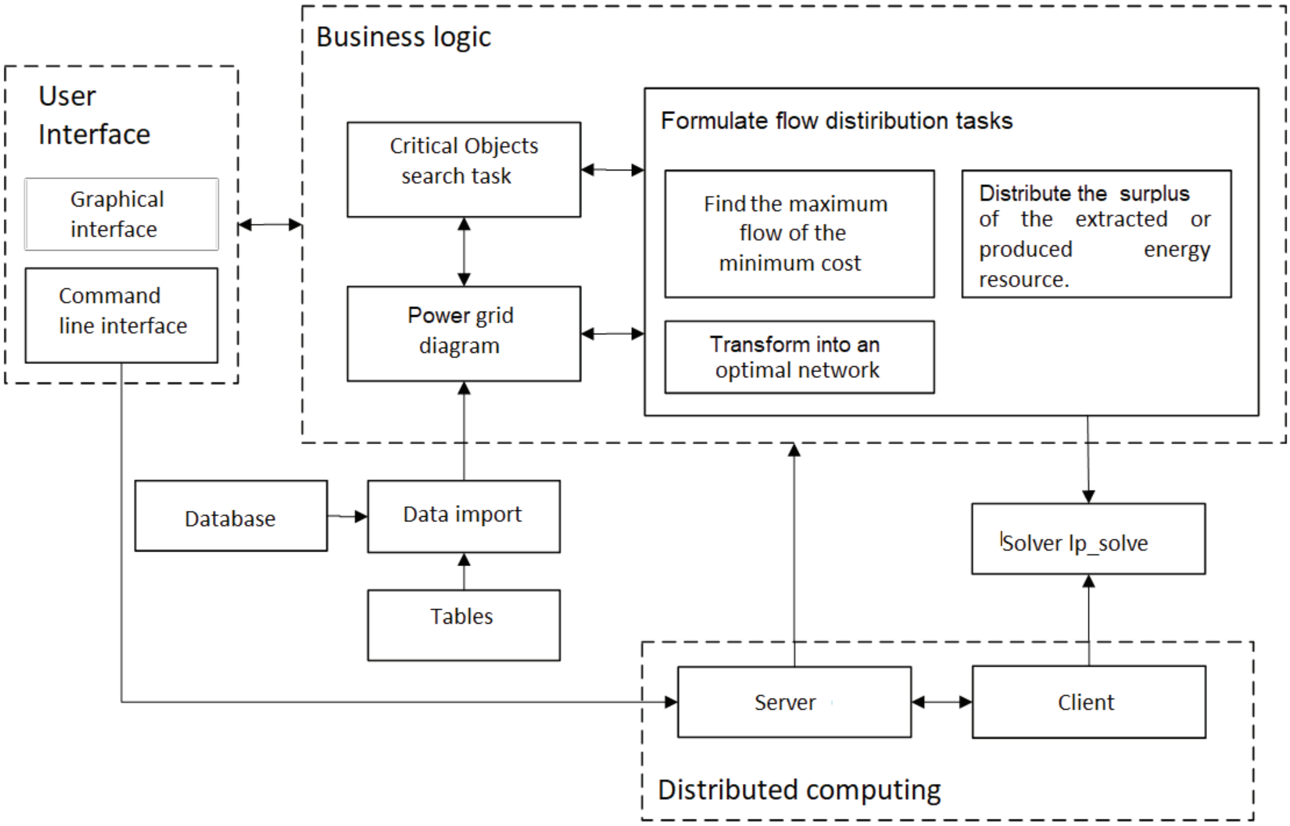

Fig. 2. Components of the "Oil and Gas of Russia" software.

each facility on the screen (volumes of production, storage, consumption at the respective nodes, and throughput in any network section belonging to the corresponding pipeline).

Before processing the database, the user needs to run the calculation program. The calculation program generates a file of results. Next, a settings file is created for the database. At the same time, the data is checked for completeness and compliance of the database files with each other and with the results file, and diagnosed errors are displayed in parallel on the screen. Only after such an analysis, the user can (or cannot) create graphic images on the screen. Diagnosed errors do not always negate the possibility of displaying graphic images. Thanks to this, it is possible to deal with each error and bring such a complex system as the UGS or OPS to the desired state (or develop another aggregation option). Several windows can be opened on one screen, i.e., for example, "Oil" and "Gas," a diagram before and after the flow distribution calculation can be shown simultaneously. The graph corresponding to the performed flow distribution differs from the original one in that the arcs and nodes involved in the calculation are shown in a different color on it. For example, the red color of the arc means that the limiting capabilities of the site have been used, the blue color means that there is no flow along the arc at all, the red color of the node indicates an undersupply of the energy resource to this node [23].

III. Analysis of the Software Package for Reengineering

The work with the software involves entering information into the database by using existing database management systems (DBMS), and importing data from excel tables or exporting model data from the database. Then, by running a separate script, the software can create a transitional configuration csv file; send the file to the calculation and computing module, using the data analysis interface; and obtain the information necessary for the study. If there is a need to change, add, or delete information, the researcher will have to re-enter the DBMS and repeat the whole cycle again. Legacy libraries are used to compile the program interface, to work with strings and display a visual interface, these methods are not supported by new versions of programming languages and do not allow switching to new development standards. Thus, reengineering encounters the following problems:

- The user wastes time due to the inability to change the system during the analysis from the interface;
- Direct interaction with the DBMS increases the risk of adding non-standardized information;
- Due to unnecessary information in the DBMS, software cannot create a transitional configuration file which the calculation and computing module depends on and without which will not be able to work correctly;
- The lack of support for methods implemented by legacy libraries makes it difficult to use software on new operating systems.

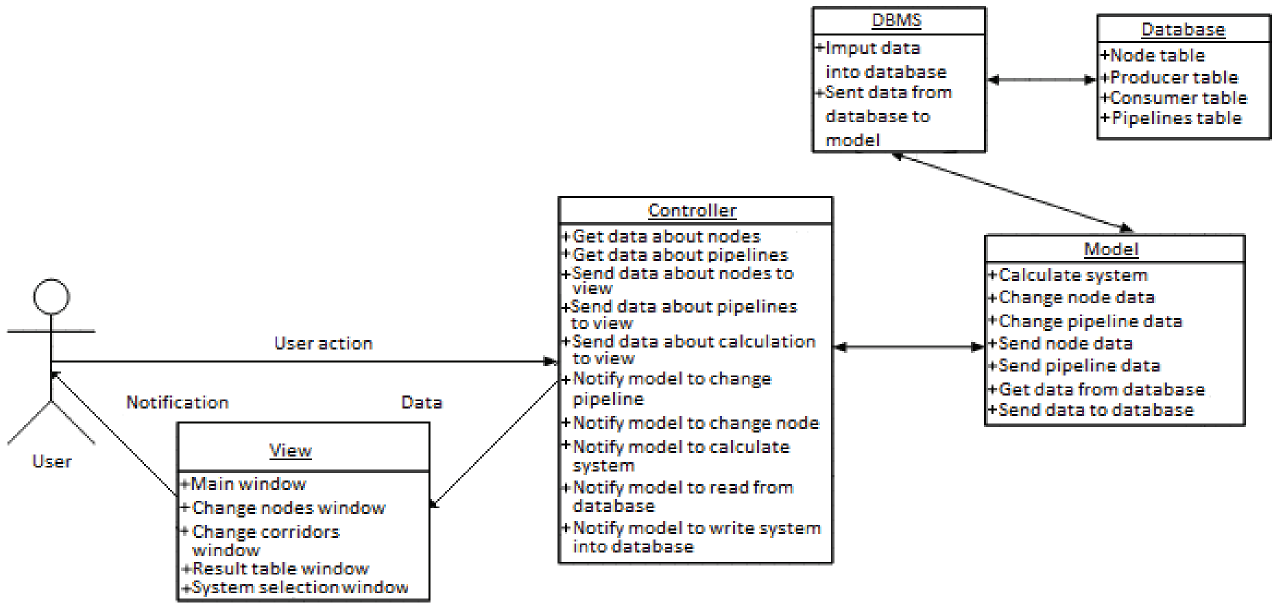

Fig. 3. New architecture of the "Oil and Gas of Russia" software.

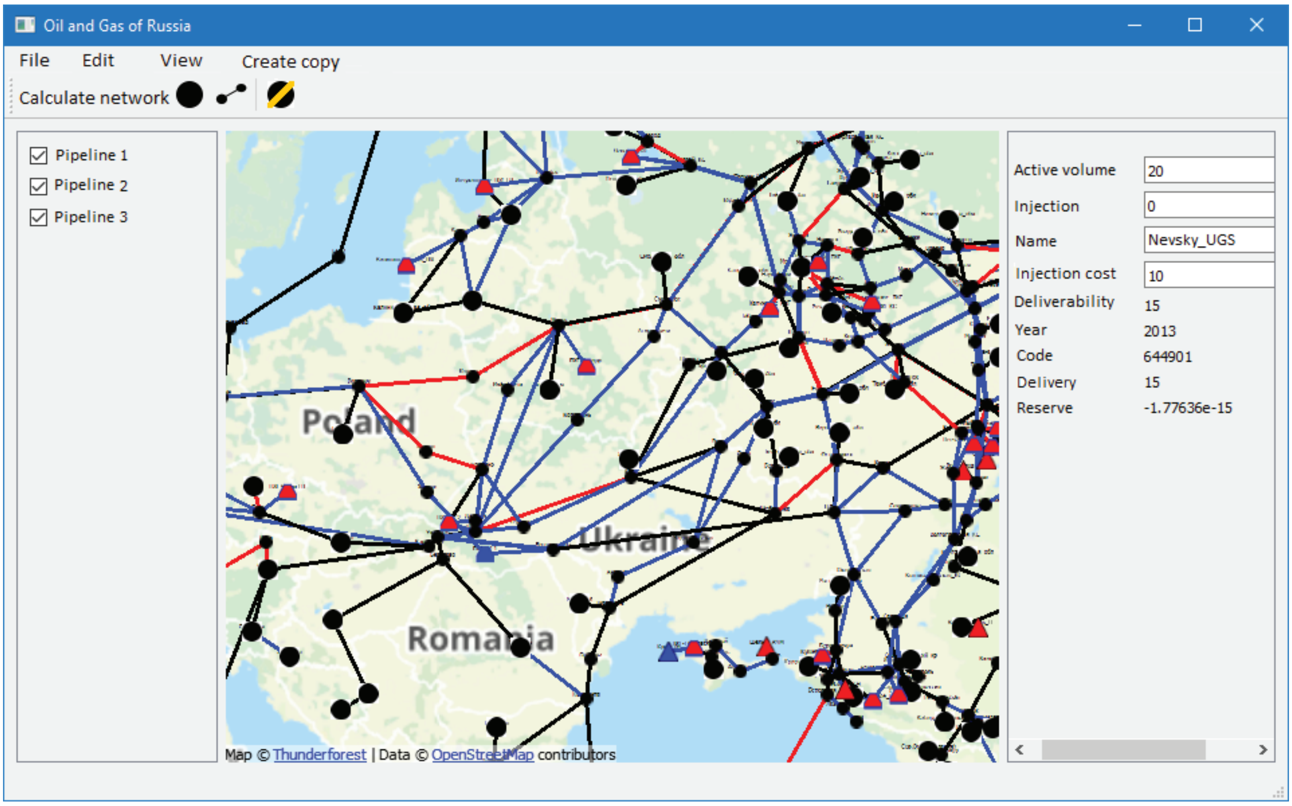

Fig. 4. View of the prototype dedicated geographic information system.

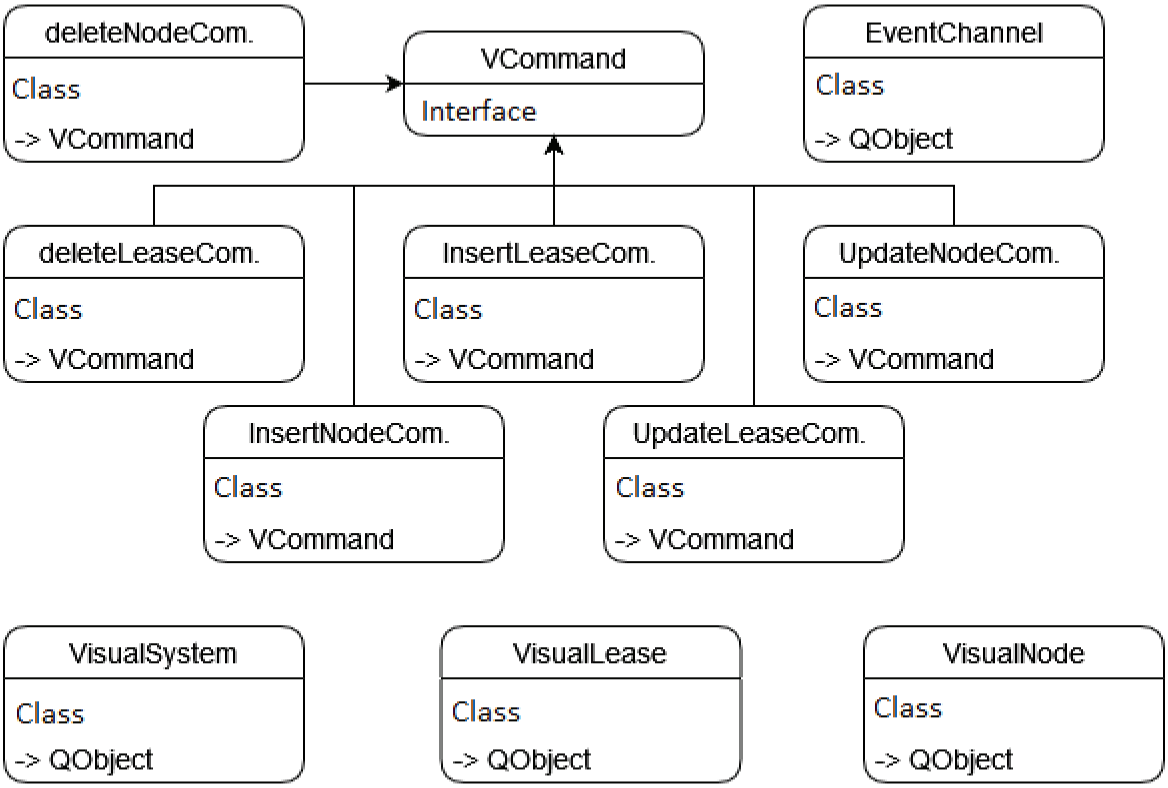

Fig. 5. A scheme of classes corresponding to the topological model of the metasystem.

IV. Software Package Reengineering

One of the architectural patterns for reengineering was the Model-View-Controller pattern, which divides data, user interface, and control logic into three separate components: model, view, and controller.

This architecture makes it possible to separate the business logic component associated with the creation of an energy system from user interface and visually represent the model (graph) on map by encapsulating it in as a graph model that sends information needed for representing ES on map, thereby removing the problem of business logic dependence on inherited components. The graph contains only information about the ES facilities necessary for construction, including the type of the facility, geographic data, its name and main characteristics. The controller is used to communicate with the business logic (model). It allows customizing the data flow and standardizing information for display in a topological model. Each model uses its controller, which sets up its data flow. This makes it possible to use different types of models without changing the graph representation for each model. An option of the new architecture is shown in Fig. 3.

To switch to this architecture and reengineer the application, the Qt framework was chosen. This environment supports the C++ programming language, which is necessary to simplify the refactoring of an application for a new architecture, and also has several distinctive features that simplify the development of this architecture:

- Meta-object system. This feature of the framework allows using signals and slots for software development. In this case, when developing a view, one can use the mechanism of slots and signals to develop behaviour, receive and send information from the application, and then use the controller to determine and interpret this information for business logic, which facilitates the development of MVC and MVVM applications [25].
- Libraries for working with geoinformation data and displaying it by using geocoding. This library allows using the meta-object system to display objects on the map and to perform actions with them, for example, find out the distance between two nodes.
- Libraries for working with the SQLite database.

The Model-View-Controller architecture allows components to be modified independently of one another. This will subsequently simplify refactoring one of the components under the new software development standards (Fig. 5).

To work with business logic, the EventChannel controller class is used, which receives requests from the environment to receive information from the model or enter it into the model, thereby not binding the interface to a specific model, which allows using this class diagram (Fig. 6) to develop software applicable to other ES models in the future.

The classes deleteNodeCommand, DeleteLeaseCommand, InsertNodeCommand, InsertLeaseCommand, UpdateNodeCommand,

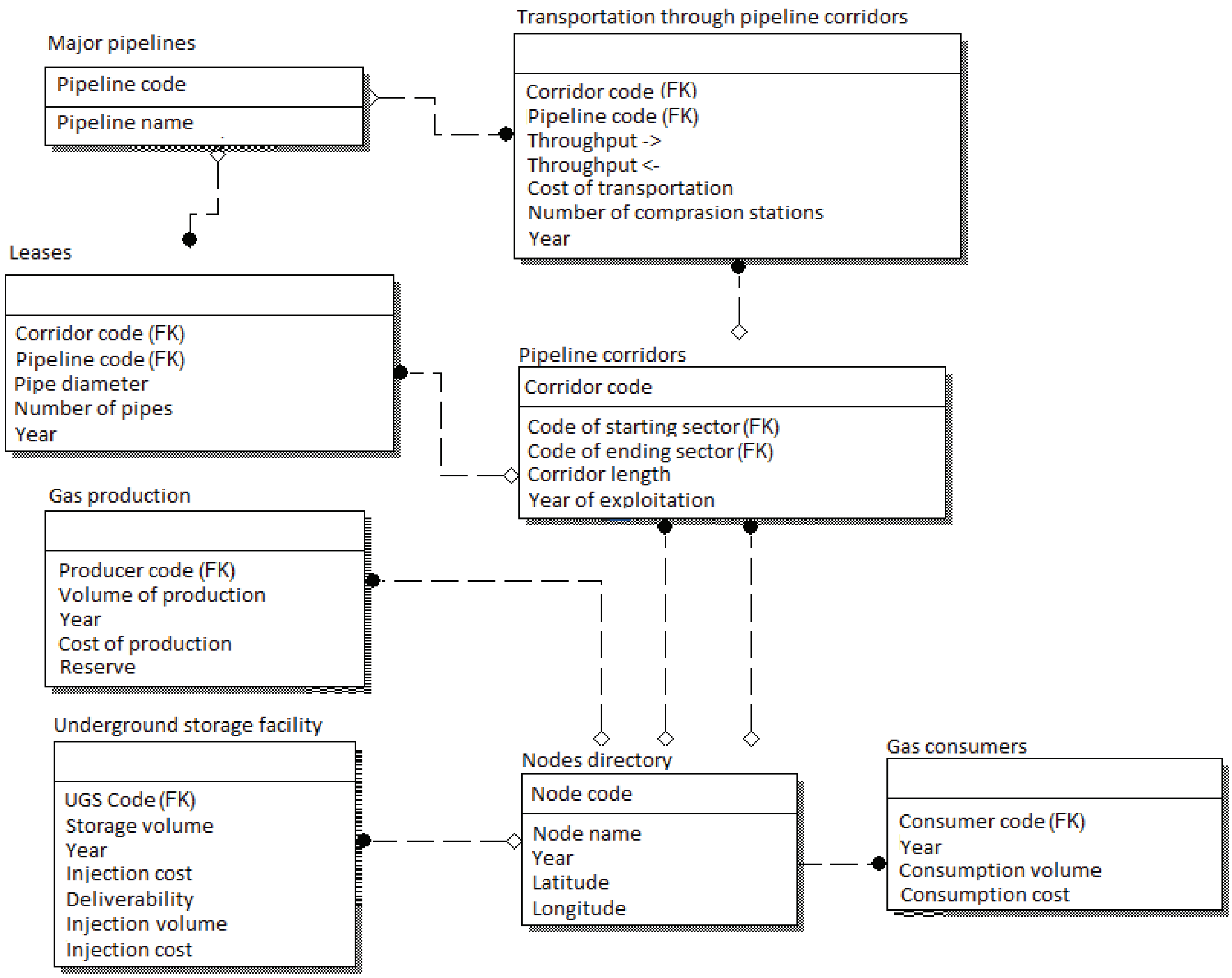

Fig. 6. Database structure.

UpdateLeaseCommand are used to create requests to add, change, or delete information from the model. These classes are developed using the "Command" programming pattern and inherit the VCommand interface, which specifies the basic functions for canceling and returning information.

The VisualSystem, VisualLease, VisualNode classes are designed to display geographic information about objects (Fig. 5), abstracting from the calculation module and storing only important information for display, position, object type.

Also, in addition to the chosen architecture, it was decided to switch from the Paradox DBMS to the embedded SQL Lite DBMS to simplify the interaction of the software with the database where the model is stored.

The proposed structure of the relational database shown in Fig. 7 reflects the explicit separation of the ES simulation into topological and functional components.

The list of database directories required to create a topological model includes:

- the directory of all nodes containing their unique codes, names, geographic coordinates;
- the directory of pipeline sections with information about the start and end nodes, a unique code, and date of commissioning.

Construction of a functional model requires the following directories:

- A directory of pipelines;
- Directories of consumers, producers and underground gas storages with their functional characteristics;
- A directory of capacity of pipeline sections.

V. Conclusion

The reengineering of the "Oil and Gas of Russia" software aims to update the legacy software of the ES resilience analysis.

The reengineering of the "Oil and Gas of Russia" software involves mainly the transition to a new architectural type Model-View-Controller. This architecture divides the program into three rare components and allows their modification independently of each other.

In addition to the transition to a new architecture, one of the modern compact relational database management systems is also employed.

Thus, the main problems of the inherited software are:

- lack of support for new versions of operating systems;
- use of legacy libraries by the program;
- lack of application portability due to client-server architecture.
- These problems have been solved and the new version provides the following features the legacy version did not have:
- capability to deploy a portable version of the application due to the embedded DBMS;
- capability to add and change the model from the program due to the transition to a new architecture;
- support by new operating systems due to refactoring of methods relying on legacy libraries.

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Enhancing Security of the Belarusian Power System in the Context of Nuclear Power Expansion

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Abstract — **The security of the Belarusian power system has been historically affected by both internal and external factors. The commissioning of a nuclear power plant (Belarusian NPP) in the Republic of Belarus in 2021 caused radical transformations in the power system due to the need to ensure reliable power output from the plant. Along with changes currently observed in the topology of internal 330 kV grids, there are also changes in the structure of external intersystem 330 kV tie lines. The Belarusian power system is connected to the UES of Russia via one 750 kV transmission line, which brings about the issue of regulating active power flows between the grids of 330 kV and 750 kV voltage classes. Due to the specific structure of the backbone grid of the Belarusian power system and its external connections, we propose solving the above problem by using the phase-shifting transformer (PST) as a type of a phase-shifter to be installed at the backbone 750/330 kV substation Belorusskaya. The paper presents the results of computational experiments, which confirm the efficiency of this type of the PST in the repair and post-emergency states of the Belarusian power system, and an analysis of technical and economic performance indicators.**

Index Terms: **power system, nuclear power, phase-shifting transformer, active power losses, active power flows, voltage.**

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I. Introduction

The commissioning of a nuclear power plant in the Republic of Belarus in 2021 caused a radical transformation in the power system, as the installed capacity of the Belarusian nuclear power plant is about 40% of the annual maximum load.

The voltage of backbone grid of the Belarusian power system and tie lines with adjacent power systems is 330–750 kV. At present, along with changes in the internal 330 kV lines, there are also changes in the structure of external 330 kV tie lines. In this regard, maintaining the standard backup capacity in the Belarusian power system poses a question of how to regulate the active power flow between the grids of 330 kV and 750 kV voltage classes.

In connection with the changes in the topology of the 330–750 kV backbone grid as was outlined above, given the limited redundancy capabilities of intersystem tie lines, the Belarusian power grid comes close to the need to build an active-adaptive 330–750 kV grid, allowing real-time grid control using phase shifters (PS).

The paper considers the possibility of regulating active power flows along the 750 kV transmission line Smolensk NPP – Belorusskaya, which connects the Belarusian power system and the UES of Russia.

As is known, the active power flow in an AC power line is determined by expression (1):

$$P = \frac{U_1 \cdot U_2}{X_l} \cdot \sin \delta_{21}, \tag{1}$$

where U_1 and U_2 are the voltage magnitudes of the power source at the beginning of the line and the voltage of the electric load at the end of the line;
X_l is line reactance;
δ_{21} is the phase angle between the voltage vector of the power source and the load.

The voltage magnitudes at the power source and load buses (including those at different points of power systems) are obtained based on specified parameters of power flows, equipment reliability, reactive power balances, and other basic conditions, and they do not have a significant regulation range to address the issue of active power flow control. Thus, it follows that the amount of active power transmitted through the transmission line can be controlled in two ways:

- by changing the line reactance,
- by changing the phase angle between the source and load voltage vectors.

The AC line resistance is predominantly inductive in nature. Therefore, one of the engineering solutions to regulate the active power flow along a transmission line is series compensators, which are capacitor batteries connected in series in the transmission line to compensate for part of its inductance. However, in the repair and emergency states of the Belarusian power system, as will be shown below, it is necessary to limit the active power flow along the 750 kV transmission line Smolensk NPP - Belorusskaya.

Therefore, regulating the power flow in the 750/330 kV grid by changing the phase angle between the vectors of voltages at the transmission line beginning and end proves relevant for the Belarusian power system

To regulate the active power flows in three-phase AC grids, one uses the phase shifter, a specialized modification of the power transformer. The phase shifter consists of two transformers: a regulated transformer, which is connected in parallel with the line, and a series transformer, the secondary winding of which is connected in series with the line. In this case, due to the winding connection scheme, the voltage vector on the series winding is directed at an angle of 90 electrical degrees to the phase voltage of the grid.

By changing the voltage on the series winding with a regulated transformer, it is possible to rotate the vector of total voltage at the beginning of the grid and control the shift angle between the voltage vectors at the beginning and at the end of the transmission line by changing the active power flow transmitted through it relative to the natural load flow [1].

There are two types of phase shifters:

- phase-shifting transformers (PST): they can continuously regulate quadrature voltage;
- quadrature booster: they regulate step voltages.

The quadrature booster (QB) is a single-tank three-phase transformer with no tap changers. QB is a simple, cheap, and reliable phase shifter used in power flow control in a 220–500 kV grids of elaborate topologies.

At 750 kV substations (SS), the functions of the PST can be performed by a quadrature booster installed at the neutral point of a 750/330 kV autotransformer (AT).

It is worth noting that at present, the output voltage phase shift is changed mainly by means of traditional mechanical on-load tap changers (OLTC). OLTCs have a relatively low response time (a few seconds) and a relatively low reliability. However, if it is necessary to increase the speed of the phase shifter, thyristor switches can be used, which perform a similar function of switching transformer windings using thyristors or triacs [1].

Phase shifters have been widely used globally since the second half of the 20th century. Phase shifters have been used in the British power grid since 1969 [2]. In the IPS of the North-West at the Leningrad NPP, 750/330 kV AT1 is equipped with a phase shifter. In 2019, a 500/220 kV phase shifter with a capacity of 195 MVA was commissioned at the Volzhskaya HPP [3]. Since 2009, the 500 kV Ulken substation in Kazakhstan has been using a 500/220 kV phase shifter with a capacity of 400 MWA [4].

II. Special Considerations Relating to the Application of Phase Shifters in the Belarusian Power System

The Belarusian power system is connected to adjacent power systems through the 750 kV power line Smolensk NPP – Belorusskaya and some 330 kV transmission lines, whose load is formed on the basis of power flows of all power systems involved. The lack of control of the distribution of active power between transmission lines of 330 kV and 750 kV voltage classes limits the utilization of the design capacity of grid elements. These limits do not allow going through all maintenance and emergency states without changing the structure of generating and consuming facilities in the Belarusian power system, which compromises the security of the power system.

The substation that serves as a junction connecting 750 kV and 330 kV grids is the 750 kV Belorusskaya substation. A unique feature of the 750 kV Belorusskaya substation circuit is that the 750 kV and 330 kV grids are connected through a single component being the 750/330 kV AT.

The analysis of the experience of operating PSTs in CIS countries indicates that the most appropriate way to regulate the power flows through the 750/330 kV AT of the 750 kV Belorusskaya substation is to use a standard single-phase regulating transformer of the ODTsNP 92000/150 type, designed specifically to work with the 750/330 kV AT and already proven in use.

Our study attests to the fact that the use of this engineering solution, both in normal and in emergency states, offers the opportunity to control the loading of the 750/330 kV autotransformer, and, consequently, that of the only 750 kV transmission line Smolensk NPP – Belorusskaya.

Currently, the Belarusian power system is connected to the adjacent power systems of Russia, Lithuania, and Ukraine through eight 330 kV transmission lines and one 750 kV transmission line. The 330 kV power transmission lines previously connected to the Ukrainian power system were disconnected due to Ukraine's joining ENTSO. In the case of the withdrawal of the Lithuanian power system from parallel operation with the Belarusian power system, only four power lines, including three 330 kV transmission

Fig. 1. 330 kV and 750 kV transmission lines connecting the Belarusian power system with the UES of Russia.

lines and one 750 kV tie line with the UES of Russia, will remain in operation (Fig. 1):

1. 750 kV overhead line Smolenskaya NPP – Belorusskaya;
2. 330 kV overhead line Krychaw – Roslavl;
3. 330 kV overhead line Viciebsk – Talashkino;
4. 330 kV overhead line Polatsk – Novosokolniki.

III. Calculations of Power Flows and Voltages

The expansion of power grids is accompanied by an increase in additional power and electricity losses caused by the growth of equalizing power due to their heterogeneity. In this case, grids of different voltage classes are loaded according to their impedances and topology, and the transfer capability of the entire closed network is often limited by its single component. Managing the power flow of such a network can optimize active power and electricity losses and ensure the required level of transfer capability of such a closed network by redistributing power flows between grids of different nominal voltages.

As noted above, the standard solution for regulating the flows between the 330 kV and 750 kV grids is to install a phase-shifting transformer (PST) with a regulation range of ± 68 kV (± 20 × 5%) in the primary winding of the existing 750/330 kV AT, which performs **quadrature control** of the AT voltage.

To perform **in-phase voltage control**, an on-load tap changer (OLTC) with a ± 64 kV (± 20 × 5%) additional EMF regulation range is currently installed at the neutral point of the AT of the 750 kV substation Belorusskaya.

The additional EMF of the phase-shifting transformer is directed at a 90º angle to the main phase voltage. The in-phase and quadrature voltage control is carried out at the neutral point of the 750/330 kV autotransformer. Therefore, the total transformation ratio of the autotransformer is a complex number and is defined by the expression:

$$K_{T} = \frac{\dfrac{U_{nom.MV} \pm \Delta U_{OLTC}}{\sqrt{3}} + j\Delta U_{PST}}{\dfrac{U_{nom.HV} \pm \Delta U_{OLTC}}{\sqrt{3}} + j\Delta U_{PST}} = K_{TR} + jK_{TI}\,, \quad (2)$$

where

$U_{nom.MV}$ – nominal voltage of the MV winding of the autotransformer, equal to 330 kV;

$U_{nom.HV}$ – nominal voltage of the HV winding of the autotransformer, equal to 750 kV;

ΔU_{OLTC} – the value of additional in-phase EMF generated

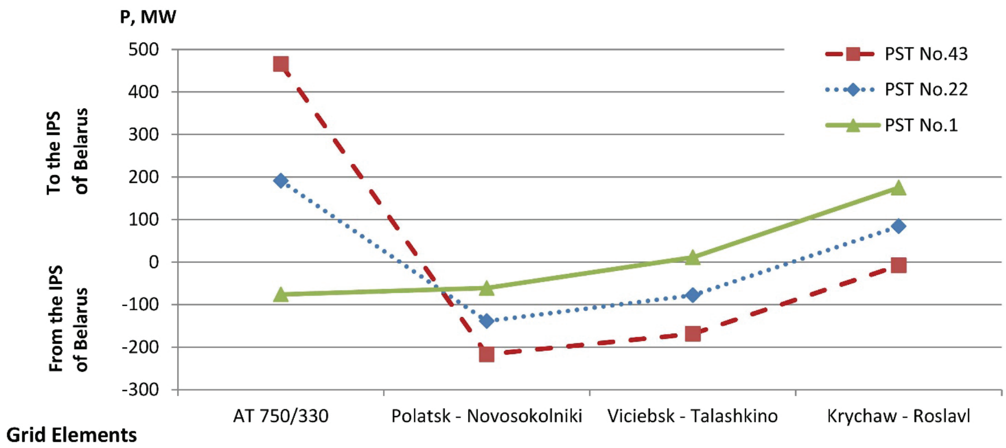

Fig. 2. Profile of active power flows on 330 kV transmission lines and the 750/330 kV AT of the IPS of Belarus with different PST taps selected in the normal operating state.

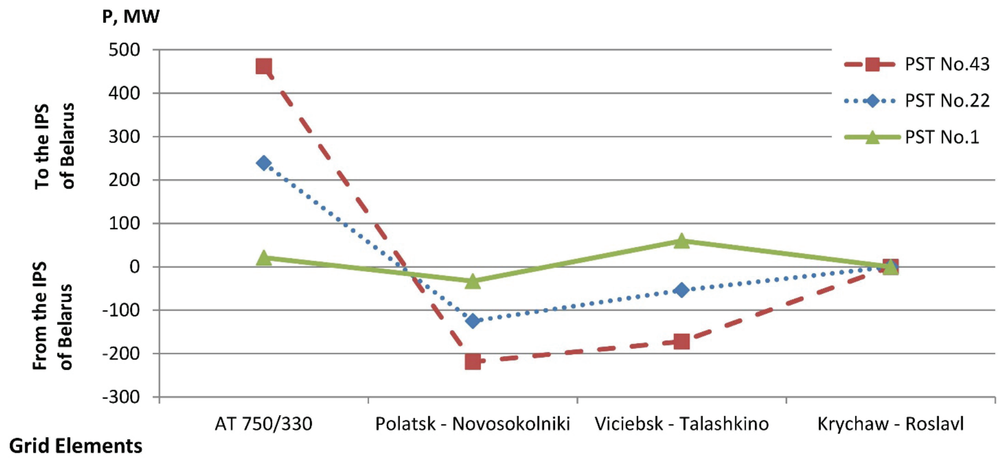

Fig. 3. Active power flow profiles along the 330 kV transmission line and the 750/330 kV AT of the IPS of Belarus with different PST taps selected in the maintenance state (disconnection of the 330 kV Krychaw – Roslavl overhead line).

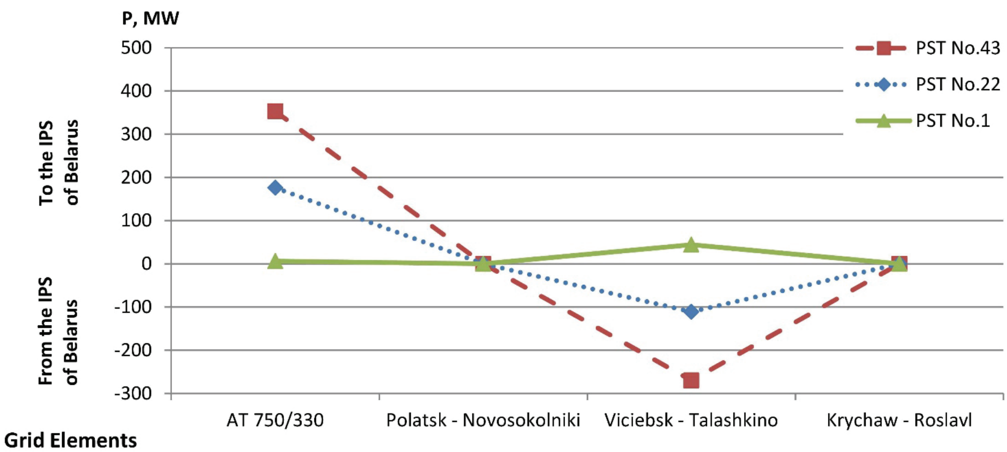

Fig. 4. Active power flow profiles along the 330 kV transmission line and the 750/330 kV AT of the IPS of Belarus with different PST taps selected in the maintenance and emergency state (disconnection of 330 kV overhead lines Krychaw – Roslavl and Polatsk – Novosokolniki).

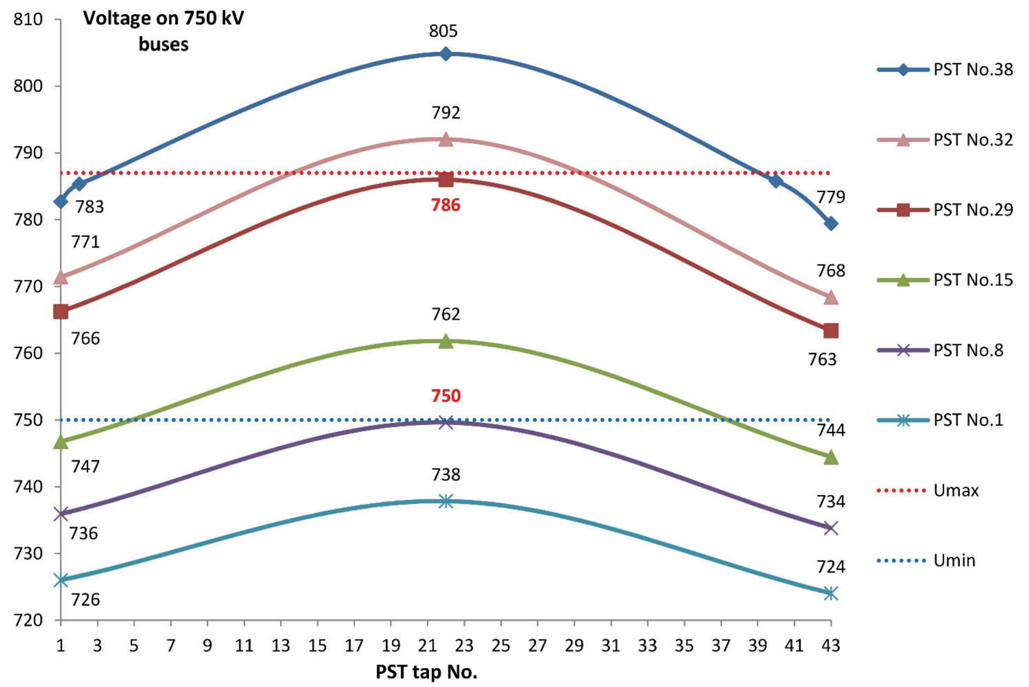

Fig. 5. Alignment chart of voltage on 750 kV buses of the 750 kV substation Belorusskaya for different positions of taps of the OLTC and PST.

by the OLTC (± 64 kV);
ΔU_{PST} – the value of the additional quadrature EMF generated by the PST (± 68 kV).
K_{TR} – the real part of the complex transformation ratio;
K_{TI} – the imaginary part of the complex transformation ratio.

The technical performance of the PST at the 750 kV substation Belorusskaya was evaluated through a series of electrical analysis calculations of the backbone grid of the IPS of Belarus in its normal and maintenance states under different PST taps (there is no quadrature control in the case when PST tap No. 22 is selected) for winter maximum and summer minimum power flows. In the calculations of power flows, we assumed that the condition of the self-balancing of the Belarusian power system holds in terms of active power.

Analysis of the calculation results shows that the regulation ranges of active power flows between the 330 kV and 750 kV grids are determined by the grid configuration and do not depend on the level of loads. The configuration of the grid of the Belarusian power system does not depend on the season of the year, therefore, below are the results of calculations for winter maximum power flows.

The profiles of active power flows over the 750/330 kV AT and 330 kV transmission lines (Krychaw – Roslavl, Viciebsk – Talashkino, and Polatsk – Novosokolniki) with different PST taps selected in the normal, maintenance (n – 1), and maintenance-emergency (n – 2) states are shown in Fig. 2–4.

The analysis of Figures 2–4 shows that the possible range of change in the active power flow through the 750/330 kV AT of the 750 kV substation Belorusskaya is as follows:

- in the normal operating state, it is 540 MW,
- in the repair state – 440 MW;
- in the maintenance and emergency state – 350 MW.

Consequently, with the in-phase and quadrature voltage control at the 750 kV substation Belorusskaya, the flow of active power can be transmitted from the 330 kV grid of the cross-border section of the IPS of Belarus – IPS of the Center to the 750 kV overhead line Smolenskaya NPP – Belorusskaya and back, in the range of 540-350 MW.

The security of the power system is understood as the ability to withstand sudden power flow changes, preventing cascading accidents with mass disruption of power supply to consumers. The deterministic criterion n – 1 is widely used to assess the security of a power grid. The criterion means that in case of emergency involving the loss of any independent component of the grid, the grid continues to perform its functions in full [5].

One of the objectives of this study was to ensure the security of the power system by providing the required transfer capability of 750 kV and 330 kV tie lines in the event of an emergency shutdown of the Belarusian NPP.

The power flow analysis performed for a shortage of active power in the Belarusian power system (in case of an emergency shutdown of the Belarusian NPP) shows that the limiting element for receiving backup power is the 750/330 kV AT at the 750 kV substation Belorusskaya, whereas the transfer capability of the 330 kV transmission lines proved adequate. In these states, the PST allows eliminating the overloading of the 750/330 kV AT by increasing the load of 330 kV transmission lines by about 200–250 MW. Thus, when receiving backup power from the UES of Russia, there is no overloading of grid elements and no need to disconnect consumers.

Managing the loading of 750 kV and 330 kV grid elements using the PST also makes it possible to go through maintenance states in the backbone grid of the Belarusian power system without compromising the required parameters.

IV. Additional Considerations Related to the Use of the PST

As mentioned above, during an emergency shutdown of the Belarusian NPP, the PST allows increasing the transfer capability of tie lines of the Belarusian power system by up to 250 MW, and, consequently, the power system does not incur losses for electricity not served. The economic effect from the installation of the PST, according to aggregate estimates, will be 110% of the cost of its installation.

In addition, a similar effect of eliminating the imbalance of active power in the power system can be achieved by constructing a new 330 kV overhead tie line or a shunting generating unit of similar capacity. The cost of PST installation is 10–20 times less than the cost of either of the above options.

It should be noted that the possibility of regulating active power flows between the 750 kV and 330 kV grid is determined by the permissible voltages for these grids (787 kV and 363 kV, respectively). Voltages at the nodes of the 330–750 kV power system are determined by reactive power balances, which largely depend on the active power load of consumers and, consequently, the load with respect to the active power of grid elements.

Figure 5 shows an example of an alignment chart of the voltage on the buses of 750 kV substation Belorusskaya for different positions of taps of the on-load tap changer and PST.

Since the change in the power system load is a dynamic process with not infrequently sharp fluctuations in active power (in case of emergencies), in the future, the real-time determination of the tap of the PST and OLTC appropriate for the current state (with the aid of an alignment chart similar to Fig. 5) will require the creation of a digital twin of the in-phase and quadrature control device [2] and its integration into the model of the digital twin of the power system.

V. Conclusion

1. With the PST, the control ranges of active power flows between the 330 kV and 750 kV grid are determined by the grid configuration and do not depend on the magnitude of loads.
2. The use of PST to control loading of 750 kV and 330 kV grid elements makes it possible to go through all maintenance, maintenance-and-emergency, and emergency states without constructing new transmission lines.
3. When adopting the PST, it is advisable to create its digital twin and integrate it into the model of power system digital twin.

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Country-Specific Aspects of Operations of Wholesale Power and Capacity Markets

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***Abstract* — The modern energy sector, in both the Russian Federation and other countries, features the so-called "finer points," the challenging issues addressed in many analytical documents as well as in published research. The paper discusses key electric power market developments in different countries, the dynamics of indicators measuring their performance, the results of actions taken to date, as well as the approaches to their regulation and influencing the quality of power supplied. We consider the main features of the adopted regulatory models and the basic principles adhered to by electric utilities as means of successful expansion planning and operation under given conditions.**

The purpose of this research is to study individual elements of operations of energy markets and the features of regulation as applied to the models originating from abroad and from domestic wholesale electricity and capacity markets. The study also takes into account the technology-related aspects such as the level of reliability of the power system. The study outlines the development vector for the effective operation of generating companies in a given context. The focus is on the areas with the highest potential in terms of contributing to growth.

The scope of the paper also covers an overview of key trends of electricity market operations, both as practiced abroad and in this country. We present market models and discuss different approaches to determining the level of quality and reliability of electric power supply.

***Index Terms*: electricity market, market models, power and capacity market.**

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I. Introduction

The modern energy sector, in both the Russian Federation and other countries, features the so-called "finer points," the challenging issues addressed in many analytical documents as well as in published research. The challenges posed by the energy industry are amongst the most demanding but also rewarding from the standpoint of research. In the case of the energy industry, of particular interest is the interplay between domestic wholesale power and capacity markets, as well as the understanding of how the same mechanism is rendered in other countries.

This paper reviews the principles governing energy industry operations in different countries in the context of interaction and regulation of activities in the models of power and capacity market.

Each country has its regulatory framework, target parameters as well as specifics of market relations and development of industries. They are both a driving force for the development and modernization of interactions in the energy industry, but also a criterion to be considered when streamlining logistics and developing the regulatory principles. In what follows, we consider the domestic and international examples related to specifics of operation and analyze technical parameters and features.

The presentation of the aspects of development and regulation models of interaction from different perspectives benefits from consideration of several contrasting examples: hence, the paper covers case studies of the UK, Germany, and Russia.

II. Foreign Experience in the Construction of Electricity Market and Its Operation

The UK is an island country with its structure, historically established principles, and its industrial and energy sector.

The existing market model was adopted in 2000 by the Utilities Act. This has allowed the Pool to be replaced in March 2001 by the New Electricity Trading Arrangements (NETA), which evolved into the British Electricity Trading and Transmission Arrangements (BETTA) in 2005, when they were extended to cover Scotland. The Act is still in effect today.

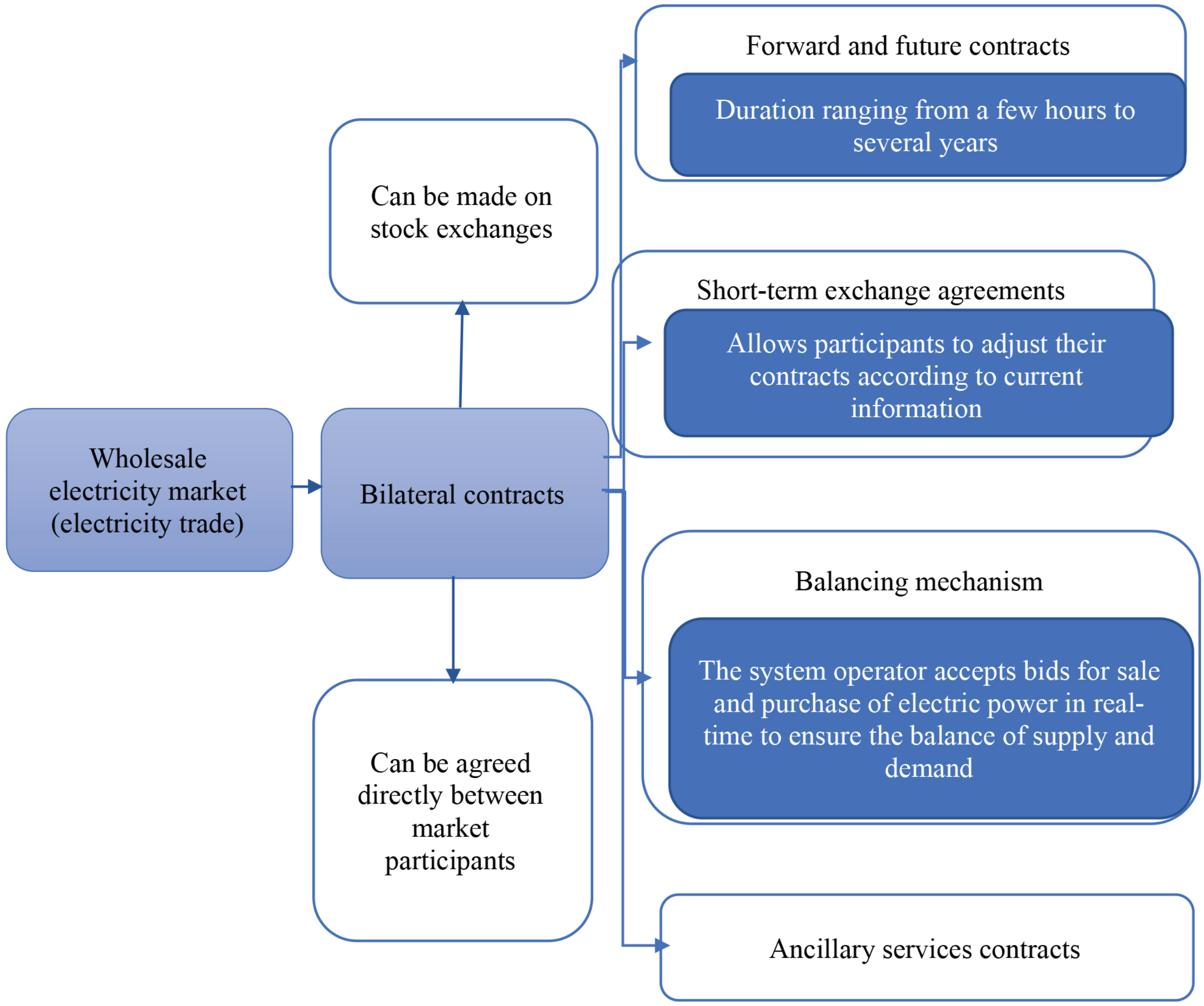

Fig. 1. Model of the UK wholesale electricity market (England and Wales).

The introduction of the rules was intended to increase competition in the wholesale electricity market while preserving the reliability of the power system, thus ensuring the transition from a centralized organization to decentralized market relations [1].

Energy is traded forward through bilateral over the counter trades between sellers and buyers or through direct exchanges between market participants, their duration varying from several hours to several years. Thus, the trades are treated as "forward" and "future" contracts.

The inclusion of short-term exchange agreements in the NETA allows sellers and buyers of electricity to cover their short-term demand in addition to having direct trades. The presence of a balancing mechanism (adjustment of power output and demand in real-time to match them) should also be noted. All generating companies with a capacity above 50 MW and supplying companies with a consumption capacity above 50 MW are required to notify the system operator of their production and consumption activities when using it.

The factors that ensure the success of this system are the following:

- excess capacity in the UK electric power industry;
- state-of-the-art and flexible generating equipment;
- sufficient throughput capacity of the backbone grid;
- experience gained in a competitive environment;
- mature regulatory framework [1].

Based on the factors identified, the Government proposed a reform of the electricity market and passed the Electricity Act in December 2013 (Energy Act 2013), one of the main goals of which was the creation of a capacity market, which was approved by the European Commission in 2014.

The auction arrangements are as follows:

- The auction takes place over four days with four bidding rounds each day.
- In the first round, generating companies are offered a fee of 75 pounds per 1 kW of capacity. However, companies are expected to offer more than the required amount of capacity at such a high price.
- In the next round, the price is lowered by £5 and generators who are not ready to supply capacity at that price remove their bids.

- The price reduction continues in each subsequent round until the total capacity in all remaining bids equals capacity demand - the sum of the system's maximum load and the required capacity reserve [1].

It merits taking a closer look at each tool that enables negotiating and performing transactions for the supply of electric power:

1. The UK Power Exchange (UKPX) was established in June 2000 by a Swedish company (Finnish-Swedish stock exchange operator) and was the first independent British energy exchange. The system initially traded only forward contracts for the sale of electricity with a maturity of no more than 18 months, and all transactions were concluded online (online trading system). A year later, when NETA was launched, the UKPX started trading spot contracts for the next 24 hours. Meanwhile, the Dutch Amsterdam Power Exchange (APX), continental Europe's first energy exchange, established its UK branch in 2001 under the name of APX-UK, which began its operations in May 1999 [1,3]. This company is now called APX-ENDEX after several more mergers.

The exchange offers its participants daily electricity future contracts for 2 and 3 months, 4 quarters, and 4 seasons (winter, spring, summer, autumn), and demand-period supplies for 3 months, 4 quarters, and 4 seasons (8.3 to 17.3 CET).

2. NETA balancing mechanism is used as a way to reconcile the load levels of generators and demand in real-time, which matches the actual total consumption level. It may differ significantly from the forecast value, as well as in terms of the need to factor in the grid capacity limitations, since these limitations were not taken into account when entering into contractual relations between market participants [1]. Therefore, in addition to the calculation of imbalances, NETA also provides for the creation of a "Balancing mechanism". According to this mechanism, the system operator determines which actions to take to maintain the balance between consumption and generation. The rules governing the calculation of imbalances and actions to balance the system are established in the Balancing and Settlement Code. It is monitored by Elexon, a dedicated not-for-profit entity whose shares are owned entirely by National Grid Energy System Operator, that also provides market participants with technical opportunities to participate in this process.

The trading of electric power supplied in a particular half-hour period takes place before the so-called "Gate Closure", which occurs one hour before the start of that period. For example, in the case of the supply of electric power from 12:00 to 12:30 all market participants are required to notify the System Operator (National Grid Company) of their final positions. These data are called the Final Physical Notifications (FPN) and they determine the actual demand for electric power during a particular half-hour.

No further changes to these positions are allowed. If it turns out that the generating company has produced more electricity than declared for the given half-hour, or the supplier has overestimated their demand for electricity, the excess electricity is purchased from them at the System Selling Price (SSP). Similarly, additional, unanticipated demand for power is paid for by the buyer or by the generator who unexpectedly reduces their output at the System Purchase Price (SBP) [2]. In the early years of the adoption of this mechanism, the SSP was significantly lower than the market price and the SBP was significantly higher, but the prices eventually leveled off by 2005.

Today, the British grid has a more flexible mechanism for regulating deviations from the FPN. Each market participant can submit a request for additional capacity or offer possible "excess" power in advance, specifying the desired price, and the System Operator, according to the actual state of the power system, sets its price, which all companies that have applied with bids and offers are automatically forced to accept. It is assumed that the larger the deviation from the FPN is, the less favorable the conditions for the market participant who allowed this deviation are. This mechanism provides the system with extra flexibility and allows, in particular, creating a capacity reserve in case of unforeseen changes in demand. Moreover, the System Operator has contracts for balancing services with some producers and consumers of electric power, which can promptly adjust capacity. In particular, hydropower plants (HPP) play this role in Great Britain, although their share in the total power balance is only 3.5% [4].

The amounts of electricity that are traded through exchanges and on the basis of bilateral contracts must be communicated to the clearing house, which carries out the calculation of imbalances, so that the amount of imbalance for each participant can be determined.

The goal of implementing a balancing market is to ensure the physical balance of power and other critical parameters of the system operation. To achieve this goal, the system operator performs the following functions: maintains frequency in the power grid, adjusts power flows to ensure reliability, and provides ancillary system services by balancing market participants.

As soon as generators and sales companies determine their generation and consumption volumes, they are required to notify the system operator. This requirement applies only to generators whose installed capacity exceeds 50 MW and to consumption points that receive more than 50 MW from the grid. Along with communicating this information to the system operator, generators and sales companies may also communicate their willingness to deviate from the planned level of production or consumption in one direction or another for an appropriate fee. For this purpose, they can apply for an increase or decrease in generation and consumption (applications for participation in the Balancing Mechanism). The system operator can accept such applications and use them to manage the balance between generation and consumption in real-time.

The adequacy analysis below takes into account the amount of capacity reserves exceeding the projected maximum consumption load (on the "de-rated" basis) and standard outages of power grid and generating equipment. In general, according to the analysis conducted by the system operator, the amount of available generating capacity for the winter period of 2021–2022 will amount to 103.2 GW; imported capacity during the peak consumption period – 4.2 GW; maximum consumption including ACS** (including 1.5 GW of required reserve capacity) – 59.5 GW; duration of possible capacity shortage – 0.3 hour per year [5].

In order to mitigate these risks, the National Grid Electricity Transmission (NGET) company, which is the operator of the main grid in England and Wales, has developed the Grid Code. The document regulates the operational processes and principles of managing the relationships between the operators of high voltage networks and all users of the high voltage system. The document covers the following:

- Planning Code (PC);
- Balancing Code (BC);
- Operation Codes (OC);
- Code of technical conditions for technological connection (Connection conditions – CC);
- Data Registration Code (DC), the Code of Rules for Provision of Information by Power Industry Entities and Consumers (Data Registration Code – DC).

Loss-adjusted bids accepted by the system operator are paid at the prices specified in those bids. Upward deviation bids are paid to the participant who submitted that bid at the price in the bid multiplied by the deviation volume, adjusted for losses. In the case of downward deviation bids, the bidder is paid by the Balancing Mechanism the price in the bid multiplied by the deviation amount, adjusted for losses.

As follows from the above, NETA lacks the centralized mechanism for selecting the mix of equipment, developing and maintaining the power flows of the power system that were characteristic of the Pool of England and Wales. Instead, the actions of both sellers and buyers are determined largely by the contracts they have been able to enter into. The possibility of functioning of such a system of trade relations, as well as ensuring the reliability of power supply, is based on the following features of the UK power sector:

- availability of excess capacity, much of which is state-of-the-art and flexible equipment;
- availability of a strong backbone network with sufficient capacity;
- accumulated experience during the recent years of operating in a competitive environment;
- a thoroughly developed legal and regulatory framework;
- perfect structure of financial relations;
- well-developed metering system and availability of ASEMM (automated systems for electricity monitoring and metering),
- almost completely liberalized fuel markets.

In particular, such a system as applied to electricity trading includes physical trading under bilateral contracts without taking into account network capacity limitations; self-dispatching. There is no dispatch schedule for the day ahead and centralized selection of generation equipment. The participation of the System Operator in eliminating power imbalances just one hour ahead is virtually impossible in Russia due to the much weaker power grids.

Thus, the success of the reform of the UK energy market is due to the following rather favorable factors: availability of significant capacity reserves with a moderate growth of electricity consumption; extensive use of (then) cheap natural gas as the main fuel for power plants (replacement of coal-fired power plants by co-generation plants); presence of sufficiently developed (in terms of capacity and reserve capacity) power grids, etc. As a result, the introduction of a competitive electricity market has helped to improve the efficiency of power generation and reduce electricity prices.

At the same time, it is worth noting that at first, almost the entire effect of deregulation was aimed at significantly increasing the profitability of generation, and sales prices significantly exceeded production costs.

In Great Britain, the energy exchange plays the role of a "fine-tuning" mechanism that allows electricity suppliers and buyers to adjust their current needs in addition to having direct contracts. In practice, traders can buy more or less electricity than they have sold, generators can physically produce more or less than they have sold, and end users can consume more or less electricity than their sales companies have purchased. NETA centralized systems are designed to measure these surpluses and shortages (imbalances) and determine the prices at which they are traded and send out bills for them. The processes by which imbalances are calculated and billed are called Imbalance Settlement. The purpose of Imbalance Settlement is not to set wholesale electricity prices, as it was previously, but to price and settle for deviations between planned and actual values with relatively small discrepancies between the contractual and physical positions of market participants.

At present, the British power system has a more flexible mechanism for regulating deviations from the FPN. Each market participant can apply for additional capacity or offer possible "excess" power in advance, specifying the desired price, and the System Operator, according to the actual state of the power system, sets its price, which all companies that have applied with bids and offers are automatically forced to accept. As a rule, the larger the deviation from the FPN is, the less favorable the conditions for the market participant who has allowed this deviation.

In what follows, we review the arrangement of market operations in Germany.

Germany's national grid is largely integrated into the European grid. In terms of technical requirements for the security of energy supply, at the national level, the following codes have been effective since 2007: Transmission Code 2007 and Distribution Code developed by the Association of Network Operators (VDN – beim VDEW – Der Verband der Netzbetreiber e. V.) which now are no longer effective, and the association itself has been liquidated. The main statutory regulation in Germany for the safe and reliable supply of electricity is the Energy Act, which aims to ensure the efficient supply of electricity and gas based on the principles of competition as well as the safe, long-term efficiency, and reliability of the energy supply network. This goal is achieved by implementing and enforcing EU legislation in the field of energy supply [5].

The Energy Act establishes requirements for the compliance of power generation, transmission, and distribution equipment with the national technical regulations of the Association for Electrical and Information Technology [6].

Foundations of modern regulation of the wholesale power and capacity market were laid in 2009 and they built upon the use of existing experience and accumulated knowledge from previous periods, as well as analytical documents on the state of affairs in other countries. The main idea behind the transformation is that the physical volume of renewable energy transmission to sales companies should be in the range between the established minimum and maximum values. Consequently, there was a need for system operators to purchase additional amounts of electricity from power plants running on conventional fuels, which led to high costs and was not an effective regulatory lever. Due to this, a new mechanism of market operations was developed, which led to a change in the system operator's functionality. In the new model, the system operator trades electricity on the power exchange instead of the previously designated power supply to sales companies.

Sales on the spot market do not always reach the level that corresponds to the established remuneration for operator services. Distribution companies compensate System Operators for the difference between the established and actual cost of service (the so-called Renewable Energy Act payments). Sales companies include payments under the Renewable Energy Act in the cost of electricity, thereby transferring them to the consumer. For energy-intensive industries, the mechanism provides for a partial exemption from compensation payments [8].

In 2014, another reform of the Renewable Energy Act was carried out and changes were introduced into the vision of how to proceed with further development of renewable energy. Being only one part of the set of legislative acts on the "Energiewende" program, its amendments are treated accordingly.

The legal framework for the Energiewende consists of a series of laws regulating emerging relationships in the four main areas of the energy industry.

The reform of the energy market made it possible, according to one option available within this model, for electricity sellers to pay a higher price to the generation company because they were partially exempt from payments under the Renewable Energy Act if the structure of their energy portfolio met certain legal requirements. The System Operator could choose a different option – an individual markup model, under which it is entitled to claim compensation for the difference between the current market price and the amount of state payments, as well as the additional costs of direct sales through the state-imposed markup.

In this case, the main activity in the German electricity market is structured around the European Energy Exchange (EEX) AG – the central European power exchange located in Leipzig, Germany. It develops, operates, and ensures secure connections, liquid and transparent markets for energy and related products, including contracts for derivative capacity, emission allowances, agricultural and freight products.

EEX emerged from a merger between and Frankfurt-based EEX in 2002. The derivatives division of Deutsche Börse Group Eurex acquired a majority stake in EEX in 2002. The structure of the exchange and the contractual relationship models are given in Fig. 2.

1. The electricity spot market is operated by EPEX SPOT, a joint venture owned by Germany's EEX AG and France's Powernext SAS (its 100% subsidiary). EPEX SPOT conducts daily day-ahead auctions for three markets: Germany/Austria, France, and Switzerland. The physical delivery of electricity takes place the next day. EPEX SPOT also provides an intraday market for Germany, France, Belgium, the Netherlands, Luxembourg, Switzerland, Austria, and the United Kingdom. This market can be used to cover short positions, for urgent power needs or for short-term overcapacity sales. Market participants can buy electricity 45 minutes in advance of each hour at a certain hour. This market is open 24 hours a day, seven days a week. Electricity for the next day can be sold from 3 p.m. onward.

EEX also offers a spot market for EU quotas. Since 2005, EEX has operated both a spot market and a derivatives market for emission allowances. All bidders admitted to auction emission allowances at EEX can participate in the auction without any additional licensing conditions. From the outset, this has also included all bidders who participated in the existing Eurex collaboration on the futures market.

The day-ahead markets are organized through an auction, which compares supply and demand curves once a day and thus fixes prices in an anonymous but transparent and secure manner. Exchange participants enter their hourly electricity bids into the order book, which closes at 11:00 a.m. for Switzerland and at 12:00 p.m. for all other markets. EPEX SPOT calculates the supply and demand

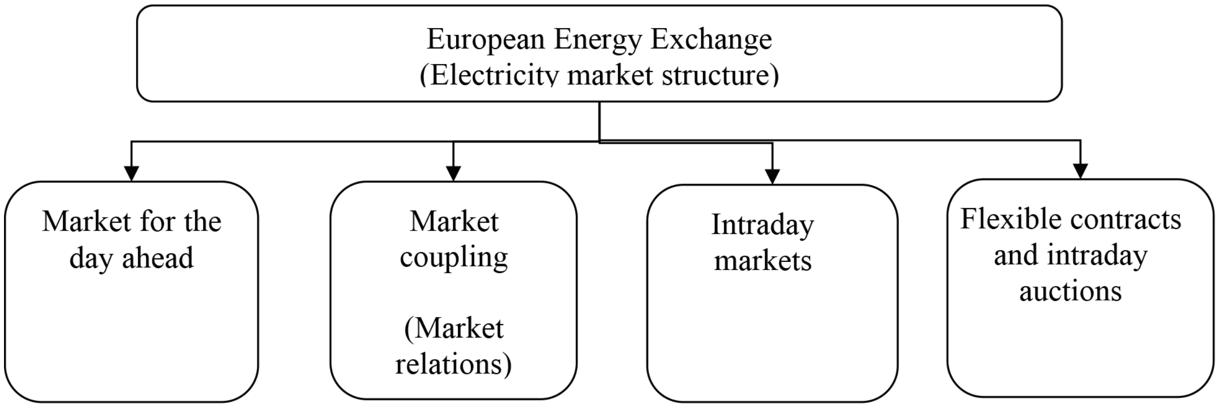

Fig. 2. Structure of the European Energy Exchange.

curves and their intersection for each hour of the next day. The results are published from 11.10 (Switzerland) and 12.55 (all other markets) [8].

2. Market coupling. The countries of Central and Western Europe, with the exception of Switzerland and the markets of the Nordic countries, are linked through a mechanism called Market Coupling. It links the member countries' electricity markets through a price-coupling solution in order to optimize cross-border capacity utilization between these countries, increasing public welfare gains in all markets.

3. Intraday markets. EPEX SPOT also manages the daily electricity markets for Austria, Belgium, Denmark, Finland, France, Germany-Luxembourg, Great Britain, the Netherlands, Norway, Sweden, and Switzerland. The intraday markets are organized according to the principle of continuous trading – participants' orders are continuously entered in the order book. As soon as two orders match, the trade transaction is completed. Hourly, half-hourly, and quarterly contracts can be sold 5 minutes before delivery [8]. M7, the intraday trading system used by EPEX SPOT, allows for simultaneous cross-border transactions on the exchange and through the OTC market. EPEX SPOT's permanent intraday markets, with the exception of the UK and Switzerland, are linked through the pan-European overnight link [8].

4. Flexible Contracts and Intraday Auctions. In December 2011, EPEX SPOT introduced 15-minute contracts in the German continuous intraday market. These contracts facilitate trading with intermittent energy sources and help cope with intra-hour fluctuations in generation and consumption [8]. With the launch of the intraday market in Switzerland, 15-minute contracts were extended to that market.

- In December 2014, EPEX SPOT launched an auction of 15-minute contracts on the German domestic market to provide a reliable price signal on a quarter-hour basis. This auction, which took place at 3:00 p.m. CET, provided balancers with an opportunity to adjust their portfolios on a 15-minute basis during times of increasing generation and deviations from forecasts. By doing so, the price signal of 15-minute contracts promoted additional flexibility while at the same time provided incentives to stabilize the system [8, 10]. In 2017, EPEX SPOT introduced 30-minute contracts in the continuous intraday market of France, Germany, and Switzerland, allowing for local and implicit cross-border transactions at their respective borders. These contracts were designed to better manage emerging flexibility issues in energy markets and helped market participants meet their balancing requirements via the French transmission system operator. EPEX SPOT has been offering additional intraday auctions in Austria, Belgium, and France since 2020, in the UK since 2018, and in Switzerland since 2019.

To sum up, the UK and Germany have fully competitive retail markets.

III. The Model of Electricity and Capacity Market in the Russian Federation

As for the domestic model, the creation of the wholesale power and capacity market depends on providing incentives to attract investment in the development of the industry as well as to increase the efficient use of available electric power by consumers.

According to the Federal Law "On Power Industry," the wholesale power and capacity market is defined as the scope of circulation of special commodities (electric power and capacity) within the Unified Energy System of Russia and the boundaries of the single economic space of the Russian Federation.

Wholesale market entities are entities that were legally authorized to participate in the wholesale market circulation of electric power and/or capacity under the Wholesale Market Rules [13]. Its main participants are power supply companies, generating companies, and large power consumers [9].

There are two commodities traded on the wholesale market – electric power and capacity. The electricity and capacity produced are then sold on the wholesale electricity and capacity market, which in turn represents a structure consisting of several sectors differing in terms of

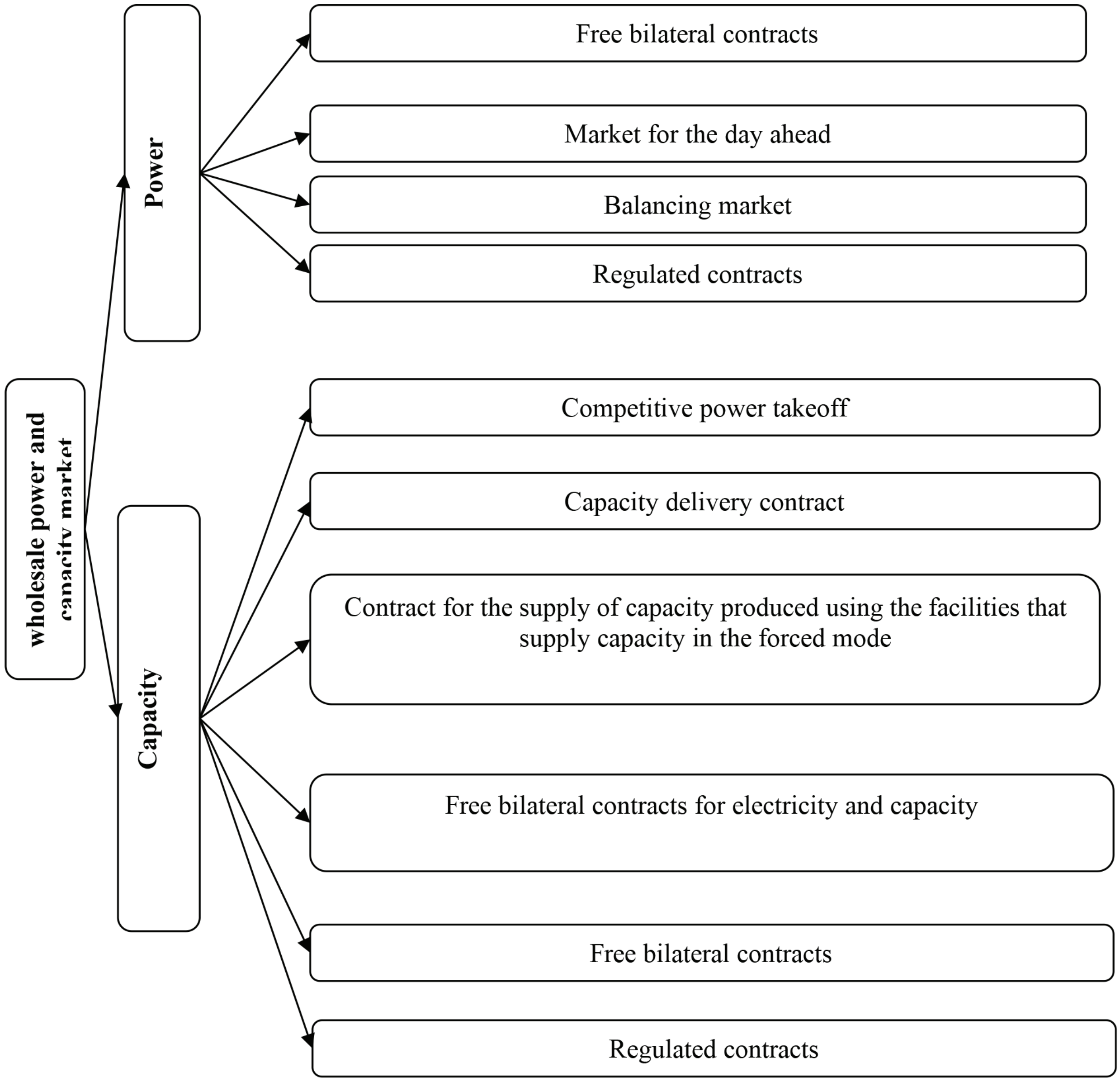

Fig. 3. Structure of the wholesale power and capacity market depending on the pricing mechanism in the electricity and capacity market.

transactions and delivery terms: regulated contracts sector, free contracts sector, day-ahead market, balancing market, and others (Fig. 3).

Since January 1, 2011, the market of electric power and capacity in Russia has been completely liberalized [14], except for the supply of electric power and capacity to the population and consumer groups deemed equivalent to them under regulated contracts.

The DAM (day-ahead market) accounts for the largest amount of electric power supplied. To participate in the DAM, it is necessary to submit price bids (in what follows, referred to as PB). The PB is a 24-hour sub-application that contains up to three monotonically increasing "price – electricity amount" steps. If zero price is indicated in the step, such a step is considered to be "price-accepting," and after the competitive selection the corresponding amount is paid at the price established at the market at the given node [10, 11, 12].

The bilateral contract is, first of all, a tool of hedging the spot price risk, because it allows one to fix for a long period of time the price of the commodities sold (electric power and/or capacity) [15].

Balancing market (BM) reflects deviations from the planned schedule of consumption/production of electric power, allowing to provide balance between production and consumption in real-time. The price is formed by means of competitive selection of suppliers' bids. Participation in the balancing market is mandatory for everyone, but the financial obligations/claims within this market arise only for the participants who have actual deviations from the planned schedule, as formed in the DAM [11].

IV. Conclusion

The wholesale power and capacity market in the Russian Federation is a rather young, complex, and poorly researched market in contrast to the electricity market of the UK and Germany. The market has a multi-stage organization based on certain rules, regulations and principles. The wholesale power and capacity market acts as an intermediary between producers and consumers, while maintaining the balance of the entire power system.

In preparing materials on this topic, the author has consulted various sources – published research, data from official websites. A detailed study proved that the models of power markets shared similar parameters, which allowed markets to operate successfully, while taking into account geographical features. It is necessary to stress the differences, which are something also related to geographical features and in spite of which the level of quality of services delivered along with the reliability and efficiency of operation ensure successful development. While recognizing the benefits of the models, one should also consider their downsides, namely the role of the "fine-tuner," whose decision-making may be opaque with subjective factors involved.

Future research could investigate the regulation from the standpoint of technology, including artificial intelligence and computer modelling.

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