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Intelligent computer-aided automation of operating state control for mining and metallurgical power complexes

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ABSTRACT

This paper addresses the synthesis of the informational framework for specialized expert systems designed to guarantee nominal power grid performance standards in post-contingency states through the application of heuristic situational dispatch control algorithms and automated decision support. **The aim** of this study is to substantiate a conceptual approach to the architecture of a knowledge base designed to support dispatch personnel decisions during power system parameter stabilization. The proposed paradigm involves generating a dataset utilizing a sensitivity matrix that correlates controlled state variables of the network with the magnitudes of dispatch control actions. **The methodological framework** of this research is based on the fundamental principles of power network theory, automatic control theory, artificial intelligence tools, mathematical statistics, and formal logic. Polynomial regression models were synthesized through multi-factor experimental design and the acquisition of a representative data sample. These mathematical relationships map the connection between the characteristics of the normal pre-contingency state, the network configuration, the nature of the disturbance, and the optimal magnitudes of control actions. **The scientific novelty** of this work lies in the development of a method for the comprehensive integration of heterogeneous information into a unified knowledge base. Specifically, formalized emergency restoration dispatch operational guidelines are integrated with calculated sensitivity matrix coefficients. The latter are determined via simulation modeling tied to the current network configuration and physical parameters of its equipment. Combining logico-semantic rules and numerical characteristics ensures high system performance sufficient for real-time operation. **Results:** the structural model of the knowledge base was optimized; the experimental design algorithm for calculating sensitivity matrix elements in regression models was adapted, along with the general algorithmic framework of the information and control system. The proposed heuristic control system facilitates solving a wide range of tasks: maintaining steady-state stability margins, optimizing active and reactive power flows, monitoring power grid parameters, and verifying the actions of operational and technological personnel. **The practical value** of this study lies in establishing a foundation for the deep intellectualization of automated dispatch control systems. Integrating the developed expert subsystem into active automated dispatch control system suites can significantly minimize decision-making time and enhance power supply reliability. An additional application of these models is their use as a baseline for training simulators intended for the professional development of dispatch and technological personnel.

Keywords: Production rule; semantics; regression, monitoring; control; network configuration; heuristics; factor; automation; mode; stability; dispatching; instruction; dosage

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INTRODUCTION

The mining and metallurgical complex (MMC) is one of the most energy-intensive industrial sectors. Approximately one-quarter of total industrial energy consumption is accounted for by metallurgical enterprises and mining and processing plants. In the mining segment, the highest energy expenditures occur during the ore preparation stage. The total installed capacity of heavy equipment electric drives within a single crushing and classification section can reach several megawatts.

This concentration of power accounts for a significant share of energy costs in the cost structure of iron ore concentrate. Consequently, the economic efficiency of production is highly dependent on energy tariffs. Power supply interruptions for such units disrupt the continuity of the technological process. Furthermore, they create risks of emergency situations that result in prolonged downtime and substantial financial losses.

Power supply reliability is a critical prerequisite for the technogenic safety and operational stability of MMC facilities [1]. Given the instability of external operating conditions of the power grid, there is an objective need to identify adaptation factors for mining production to preserve its integrity [2]. This substantiates the feasibility of developing and implementing automated heuristic control systems. These information and control systems can adaptively compensate for electrical network parameter fluctuations. Furthermore, they prevent transitions into emergency states and maintain nominal quality standards for iron ore concentrate [3], [4].

To ensure a stable post-contingency state of the electric power system (EPS), centralized emergency control subsystems must be established. The synthesis and parametric optimization of such computer complexes are complicated by the variability of normal and emergency states. These tasks are further challenged by the multiplicity of control actions and their integration points. The effectiveness of EPS control in the post-contingency state depends significantly on the representativeness of the training dataset, which contains characteristic quality indices of the pre-contingency state. Generating a complete dataset that covers the entire spectrum of possible states, network configurations, disturbances, and responses is essential. This comprehensive data maximizes the accuracy of the resulting decisions, specifically regarding control action type, application location, and magnitude.

This paper examines the design of intelligent computerized automation systems for dispatch control of power system nodes during emergency states. The specific nature of the research facility is determined by the presence of large consumers from the mining and metallurgical sector. The key element of the proposed solution is an expert system (ES). This system operates on a knowledge base (KB) that formalizes the parameters and algorithms of control actions for regulating stations. The presented results focus on integrating domain-specific information technologies into the coordination of power systems within energy-intensive districts of Ukraine. These regions are characterized by a high density of MMC enterprises.

This study addresses the implementation of intelligent information technologies in controlling a key element of the power complex. The Pivdennoukrainska NPP – Vinnytsia transmission interface and the regulating stations of central Ukraine are selected as this primary element. This section represents a regional part of the interconnected power system within a major industrial area, which specifically includes large MMCs.

Consequently, the task of synthesizing optimal control actions is decomposed into several key subtasks. These include recognizing and classifying the emergency state, selecting application points and the nature of control actions based on the current system state, and calculating the magnitudes of dispatch control actions.

LITERATURE REVIEW AND PROBLEM STATEMENT

To address the defined scientific problem – namely, the intelligent information-driven automation of state control in a power complex and the development of an expert system knowledge base to stabilize post-contingency states of electrical networks – this study systematizes research in the field of situational dispatch control based on heuristic modeling. Primary attention is focused on the operation of power systems in regions with a highly developed mining industrial complex. This focus is motivated by their high share in the total structure of industrial energy consumption [5], [6]. Studies [7], [8] present innovative dispatching concepts and modern approaches to intensifying EPS control processes. In particular, significant attention is paid to formalizing optimization algorithms for virtual power plant models, which increases control adaptability under dynamic load changes. The authors of [9] analyze real-time dispatch control mechanisms aimed at implementing secondary regulation of frequency fluctuations. Their study focuses on the dynamic stability of the system and algorithms for compensating active power imbalances. Furthermore, study [10] substantiates the economic aspects of dispatch control under high levels of stochastic uncertainty. Studies [11], [12] provide a comprehensive analysis of the modeling and optimization of electric power system operations. These studies emphasize resolving environmental challenges and developing strategies for integrating renewable energy sources into existing grids. Additionally, work [13] provides theoretical justifications and methods for ensuring the steady-state and transient stability of power systems under emergency operating conditions. This stability is critical to minimizing the consequences of large-scale technological disturbances. Study [14] highlights methodological aspects of optimally calculating the installed capacity of distributed generation facilities to fully satisfy consumer demand. Significant attention is paid to balancing local generating capacities and developing strategies to minimize power deficits. Moreover, study [15] performs a comprehensive analysis of power system operating state optimization and scientifically substantiates the

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paradigm of introducing intelligent dispatch control processes. This work emphasizes the increasing complexity of modern power grids, which necessitates the implementation of intelligent decision support systems. The literature analysis indicates that implementing heuristic tools for information-driven dispatch control automation is critical. These tools ensure prompt and high-quality correction of power system parameters in normal and, primarily, post-contingency states. To date, a substantial body of theoretical and applied results has been accumulated regarding the development and implementation of decision support systems (DSS) for stabilizing and optimizing EPS operating states. These intelligent complexes are based on artificial intelligence methodology. Specifically, they utilize expert systems (ES) [16], [17] to formalize the experience of highly qualified dispatch personnel. Study [18] details the application of various knowledge representation models in intelligent systems for the industrial sector and engineering disciplines. Within the context of these studies, the authors conduct a comparative analysis of fundamental knowledge representation forms and evaluate their deployment potential in professional power system dispatch control environments. Based on this analysis, integrating different knowledge representation models within a single intelligent system is highly expedient, primarily combining semantic networks and productions [19], [20], [21]. The necessity of this integrated approach is dictated by the requirement for comprehensive use of heuristic algorithms. These algorithms possess a dichotomous static (structural-parametric) and dynamic (causal) nature. Works [22], [23] present the methodological foundations of implementing production rules based on Petri net theory. A distinctive feature of the proposed mathematical models is their adherence to classical Petri net formalism without introducing additional limiting constraints. Furthermore, studies [24], [25] perform systematic reviews of modern software and hardware tools for Petri net modeling and analysis. Specifically, study [26] focuses on specialized tools for verifying non-Markovian stochastic Petri nets. The use of a matrix mechanism for the representation and algorithmic processing of Petri net structures is discussed in study [27]. To solve the scientific and practical problem of heuristic power system dispatch control, this study proposes an approach to constructing a knowledge base based on experimental design methodology. This approach aims to generate a representative dataset of post-contingency state parameters, which is necessary for training and verifying intelligent models. The fundamental aspects of experimental design, statistical processing methods, and the interpretation of the resulting data are thoroughly covered in sources [28], [29], [30]. Study [31] performs a comprehensive systematization of methodological approaches to experimental design and execution, taking into account the industry-specific nature of applied tasks. Particular attention is paid to adapting classical experimental design methods to specific professional domains. This adaptation optimizes empirical data acquisition for subsequent use in intelligent knowledge bases. Specific aspects of computer-aided experimental design methodology, based on modern software systems and algorithms, are detailed in works [32], [33], [34]. These studies reveal the features of synthesizing optimal designs under conditions of limited apriori information, which is critical for modeling complex processes in electric power systems. Finally, study [35] demonstrates the effectiveness of applying a full factorial experiment in the electric power sector. It defines a method for using mathematical apparatus to model power generation processes in photovoltaic systems at solar power plants.

RESEARCH AIM AND OBJECTIVES

The conducted analysis provides the foundation for formulating the research aim, which is to develop a methodology for the intelligent automation of state control processes in mining and metallurgical power complexes. This is achieved by constructing a DSS based on an intelligent KB. This knowledge base is developed using regression models that represent the impact of real-time dispatch control actions. Resolving this problem requires identifying the most effective locations for applying dispatch control actions. The methodological foundation of this study is experimental design theory. This framework optimizes the process of constructing a knowledge base under multi-factor conditions. When applying factorial experimental design methods, the variation ranges of dispatch control actions at EPS nodes are established. Concurrently, a quantitative assessment of their impact on system performance metrics is performed. Specifically, the target parameters include the maximum generator rotor angle swing or the integral transient performance criterion [13]. This approach formalizes the relationship between real-time interventions and transient stability. Based on the results of iterative transient simulation executed according to the selected factorial design, followed by statistical processing of the acquired data, a response function is synthesized. In the first approximation, this relationship between operating state quality metrics and the control action vector is approximated by a linear regression model. The relative significance of individual factors is reflected in the corresponding standardized regression coefficients. The significance of each control action on the target response function is evaluated by testing statistical hypotheses, specifically through the procedure of equating coefficients to zero. The subsequent application of taxonomic methods enables a scientifically substantiated selection of a subset of regulating stations X. Engaging this subset in the control process is highly expedient in terms of regulation efficiency and speed.

Given the urgency of the problem, the research aim is to develop the scientific-methodological principles and software-hardware tools for the intelligent automation of dispatch control in mining and metallurgical power complexes. This development is intended to ensure power system stability in post-contingency states.

To achieve this aim, the following objectives were defined and addressed:

– methodological design and execution of computational experiments to synthesize regression models that quantitatively describe the impact of adjusted dispatch measures on the critical parameters of EPS transient stability;

– development of structural elements for the knowledge base by analyzing empirical data obtained for power grid clusters characterized by the most significant post-contingency parameter deviations;

– conceptual integration of the knowledge base with the operational guidelines of automated dispatch control systems (ADCS). This integration involves developing algorithms for real-time operating state identification and synthesizing logical consequents using the mathematical apparatus of sensitivity matrices;

– design of structural models for the expert system and knowledge representation architectures tailored to the cognitive characteristics of decision-making by dispatch personnel in high-stress situations;

– practical software implementation of the intelligent system and its hardware-software integration into the active automated dispatch control system (ADCS) loop for real-time operation;

– scientific justification and determination of functional positions for implementing the developed DSS within the overall hierarchical structure of power complex dispatch control.

MATERIALS AND METHODS

As shown in [14], the problem of determining the optimal subset of control nodes in a power system is formalized as finding a transformation operator

$$Y = f(X),$$

where X represents the initial n-dimensional factor space of all possible control points, while Y denotes the new m-dimensional space of relevant factors ($n>m$).

The key requirement for this transformation is to minimize the dimensionality of the space Y. At the same time, it must preserve sufficient descriptive capacity to identify and recognize a specific taxon, which represents a power system state class.

When selecting a control strategy, priority is given to an additive operating state quality criterion that ensures comprehensive optimization of transient parameters.

This criterion accounts for the following:

– transient stability indicators: the amplitude of maximum generator rotor angle swings and their slip;

– voltage quality: voltage levels at critical load nodes;

– economic efficiency and technical cost of the control action: the total volume of forced load shedding and generator curtailment.

Based on the comprehensive processing of experimental data, an analytical relationship is formulated, typically as a second-order polynomial. This relationship establishes a functional connection between the independent factor vector and the optimal control parameters.

The independent factor space comprises:

– parameters characterizing the initial normal pre-contingency state;

– the topological structure of the electrical network;

– the type and location of the emergency disturbance.

The study establishes that the real-time search for dispatch control actions using statistical identification methods is implemented in three sequential stages:

– emergency identification and severity assessment: classification of the power system state and risk analysis of stability violation;

– selection of control action locations and types: determination of optimal nodes for applying control inputs and selection of specific measures (such as load shedding or excitation boosting) based on pre-defined clusters;

– determination of optimal magnitudes: calculation of precise control parameter values using the obtained regression models to minimize operating state deviations.

Based on the presented scientific and methodological concept, an expert decision support system (EDSS) for interconnected power system

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dispatchers was developed, software-implemented, and successfully tested. The validation results confirmed the operability of the proposed models and algorithms under actual power complex operating conditions. Furthermore, they demonstrated high accuracy in identifying operating states and high efficiency in the generated recommendations for control action magnitudes. This work was conducted using actual operational guidelines from the National Dispatch Center (NDC) of the Ukrainian power grid. As an example of a dispatch control facility, a critical transmission interface of the main electrical network of the Integrated Power System (IPS) of Ukraine – specifically, the "Pivdennoukrainska NPP – Vinnytsia" interface – was analyzed.

The knowledge base is constructed by integrating dispatcher instructions for active power flow regulation at a specific node with new knowledge derived from experimental operating state research data.

During the design and execution of computational experiments, a preliminary selection of factors that exert the greatest influence on power system parameters should be conducted. In the first approximation, the active factors were considered independent. This assumption enabled screening experiments to be conducted at three points in the factor space.

The resulting relationships can be approximated using the Lagrange interpolation formula (1).

$$Y(X)=\sum_{k=0}^{n}\frac{(X-X_0)(X-X_1)\dots(X-X_{k-1})(X-X_{k+1})\dots(X-X_n)}{(X_k-X_0)(X_k-X_1)\dots(X_k-X_{k-1})(X_k-X_{k+1})\dots(X_k-X_n)}Y(X_k) \quad .(1)$$

The calculated coefficient values enabled a preliminary evaluation of factor influence intensity on the operating parameters of power facilities and their components. Subsequently, ranking and selection of the most influential factors were performed. This reduction minimized the number of variables required for the design of computational experiments and the synthesis of target regression models.

To conduct computational experiments and synthesize target regression models, the steady-state electrical network equations were utilized. These equations were represented in a general matrix form (2), as well as in power balance (3) or current balance (4) forms.

$$\mathbf{W}(\mathbf{X}=\mathbf{X}(\mathbf{Y}),\mathbf{Y})=0, \quad (2)$$

$$\dot{W}_{Si}=\dot{S}_i+\dot{U}_i\widehat{U}_i\sum_{\substack{j=1\\ j\neq i}}^{n+1}\widehat{Y}_{ij}-\dot{U}_i\sum_{\substack{j=1\\ j\neq i}}^{n+1}\widehat{U}_j\widehat{Y}_{ij}=0, \quad (3)$$

$$\dot{W}_{Ii}=\frac{\hat{S}_i}{\widehat{U}_i}+\dot{U}_i\sum_{\substack{j=1\\ j\neq i}}^{n+1}\dot{Y}_{ij}-\sum_{\substack{j=1\\ j\neq i}}^{n+1}\dot{U}_j\dot{Y}_{ij}=0, \quad (4)$$

where W is a vector of functions of size $N \le 2n$; n is the number of network nodes excluding the slack node; X is the vector of dependent operating state parameters; and Y is the vector of independent operating state parameters specified during equation solving. The terms $\dot{S}_i = P_i + jQ_i$ and $\hat{S}_i = P_i - jQ_i$ represent the direct and conjugate complex power at node i. $\dot{U}_j, \widehat{U}_j$ represent the direct and conjugate complex voltages at node j. $\dot{Y}_{ij} = g_{ij} - jb_{ij}$ and $\widehat{Y}_{ij} = g_{ij} + jb_{ij}$ represent the direct and conjugate complex branch admittances between nodes i and j. Finally, n denotes the number of independent nodes in the electrical network configuration.

The calculated intensities of the dispatch control actions were obtained using the following experimental design and data processing workflow. The factors were selected considering the computational experiment objectives and the structural characteristics of the Ukrainian power grid configuration. Ongoing changes in network configuration, node capacities, and other regulating node parameters do not fundamentally alter the methods and approaches proposed in this study, nor do they diminish the scientific value of the results.

The factors were designated as follows: Dnipro HPP-1 – F1, Dnipro HPP-2 – F2, Kakhovka HPP – F3, Kremenchuk HPP – F4, Seredniodniprovska HPP – F5, Kaniv HPP – F6, Kyiv PSPP – F7 and Dniester HPP – F8. The selected dispatch control nodes and their factor variation ranges are presented in Table 1.

The factor variation intervals shown in Table 1 are expressed in units of active power (MW) because the initial research phase focused on locating the central point of the experimental design. Consequently, moderate accuracy requirements were placed on the screening trials.

Furthermore, preliminary dispatch calculations for the transmission interface under study revealed that the active power component of the stations exerted a dominant influence on the power flow magnitude. To reduce the dimensionality of the problem, the first stage assumed fixed active capacities at the nodes. However, the subsequent

Table 1. **Variation ranges for regulating station capacities**

No.	Station	Installed Capacity, MW	Parameter values at levels, MW			Intervals, MW	
			-1	0	+1	-Δ*P*	+Δ*P*
1	F1	665	161	325	485	164	160
2	F2	910	225	452	678	227	226
3	F3	335	85	170	257	85	87
4	F4	700	170	341	512	171	171
5	F5	352	88	175	264	87	89
6	F6	500	110	221	332	111	111
7	F7	440	93	186	278	93	92
8	F8	702	176	352	527	176	175

Source: **compiled by the authors**

main experiment, aimed at obtaining an adequate model for power flow distribution and voltage profiles, incorporated the full complex capacities of the regulating nodes.

Steady-state power flow calculations based on the preliminary central point parameters (Table 1) enabled selecting the final central point and parameters for the screening experiments. To filter the factors, computational screening experiments were conducted. Their central points were determined using actual steady-state operating parameters that maximize the sensitivity of the calculation models. The results of these screening experiments are summarized in Table 2.

Based on the results of the screening computational experiments, the factors exerting the greatest influence on the target function – namely, the power flow across the monitored transmission interface – were selected. The newly scheduled computational experiment around the chosen central point is detailed in Table 3.

Table 2. **Results of calculations in screening experiments**

No.	Station	Intervals	P_{node}, MW	Q_{node}, MVAr	Node complex power amplitude, MVA	Power flow of transmission interface, MW
1	F1	-1	-449.90	-96.42	460.12	1405.18
		0	-287.90	-61.70	294.44	1407.43
		+1	-125.90	-26.98	128.76	1409.67
2	F2	-1	-569.20	154.08	589.68	1404.80
		0	-343.20	92.90	355.55	1407.43
		+1	-117.20	31.72	121.42	1409.94
3	F3	-1	-331.00	-44.57	333.41	1403.22
		0	-325.50	-35.3	327.41	1407.43
		+1	-240.00	-26.03	241.40	1411.62
4	F4	-1	47.90	3.04	48.00	1409.74
		0	218.90	13.90	219.34	1407.43
		+1	389.90	24.76	390.69	1405.70
5	F5	-1	-350.00	-102.10	372.27	1407.10
		0	-270.00	-77.00	280.77	1407.43
		+1	-182.00	-51.90	189.26	1407.76
6	F6	-1	-202.00	-88.35	220.48	1489.26
		0	-91.00	-39.80	99.32	1407.43
		+1	20.00	8.75	21.83	1326.00
7	F7	-1	-46.40	-50.53	68.60	1457.39
		0	46.10	50.20	68.16	1407.43
		+1	138.60	150.93	204.91	1358.03
8	F8	-1	58.5	12.93	59.91	1551.57
		0	234.00	51.70	239.64	1407.43
		+1	409.50	90.48	419.38	1265.68

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Table 3. **Experimental design parameters for the selected regulating stations**

No.	Station	Factors	Factor levels			Interval	Unit
			-1	0	+1		
1	F3	$\tilde{x}_1$	-413.41	-327.41	-241.41	36.00	MVA
2	F6	$\tilde{x}_2$	-220.48	-99.32	21.83	121.15	MVA
3	F7	$\tilde{x}_3$	-68.60	68.16	204.91	136.76	MVA
4	F8	$\tilde{x}_4$	59.91	239.64	419.38	179.73	MVA

Source: **compiled by the authors**

Using the data obtained from the experiments, the regression coefficients were estimated and their statistical significance was verified.

To simplify the general variance model, several assumptions were made, and certain statistical errors were neglected. This simplification was justified by the purely computational nature of the experiment and the absence of variance in parallel trials. Furthermore, the objective was to demonstrate a methodology for extracting new knowledge regarding the electrical network operating state and integrating this knowledge as sensitivity matrix components alongside dispatcher guidelines in the knowledge base. The adequacy of the model in a linear approximation – under relatively small variations in regulating node capacities – permits ranking the regulating stations based on their influence on the interface power flow.

The reproducibility variance is generally defined as follows:

$$\sigma^2(Y) = \sigma^2(b_0) + \sum_{i=1}^{N}[b_i^2 + \sigma^2(b_i)]\sigma^2\left(X_i^H\right)^2 + \sum_{i=1}^{N}\sum_{j=1}^{N}\left[b_{ij}^2 + \sigma^2\left(b_{ij}\right)\right]\sigma^2\left(X_i^H\right)\sigma^2\left(X_j^H\right), \quad (5)$$

where $\sigma^2(b_0)$ is the variance of the mean value of the target parameter; $\sigma^2(b_i)$ and $\sigma^2(b_{ij})$ are the variances of the regression equation coefficients; and $\sigma^2\left(X_i^H\right) = \frac{\sigma^2(X_i)}{\Delta X_i^2}$ is the variance of the *i*-th normalized variable.

Since the experiment is purely computational, it can be assumed that the reproducibility variances of parallel trials are zero. Furthermore, the variances of the regression coefficients can be considered negligible.

Consequently, assuming that the model parameters are normally distributed, the following relation holds:

$$X_i = M(X_i) \pm 3\sigma(X_i)\ , \quad (6)$$

where $M(X_i)$ is the mathematical expectation of the variable X_i.

For the normalized values $X_i^H = \pm 1$ and $X_j^H = \pm 1$, we obtain:

$$M\left(X_{i0}^H\right) = 0, \quad (7)$$

$$\sigma(X_i) = \frac{1}{3}, \qquad \sigma^2(X_i) = \frac{1}{9} = 0.11. \quad (8)$$

Given these relationships, equation (5) simplifies to (9):

$$\sigma^2(Y) = 0.11\sum_{i=1}^{N} b_i^2 + 0.0121\sum_{i=1}^{N}\sum_{j=1}^{N} b_{ij}^2. \quad (9)$$

The second term can be neglected due to its insignificance. This simplifies the relation to (10) and (11):

$$\sigma^2(Y) = 0.11\sum_{i=1}^{N} b_i^2, \quad (10)$$

$$\sigma(Y) = \sqrt{0.11\sum_{i=1}^{N} b_i^2} = 0.3317\sqrt{\sum_{i=1}^{N} b_i^2}. \quad (11)$$

Based on the experimental results, we obtain:

$$\sigma(Y) = 0.3317\sqrt{29\ 553{,}9322} = 57.0234. \quad (12)$$

Ultimately, for *f=16-1=15* degrees of freedom, a significance level of *α=0.05*, and a Student's *t*-value of *t*=2.131, the confidence interval is:

$$\Delta b = 2.131\frac{57.0234}{\sqrt{16}} = 30.3792. \quad (13)$$

For the calculated confidence interval, the coefficients b_2, b_3 and b_4 are statistically significant.

Consequently, the regression equation is represented as:

$$Y = b_0 + b_2X_2 + b_3X_3 + b_4X_4. \quad (14)$$

Or, expressed in physical variables for the transmission interface active power flow (MW):

$$P = 1409.32 - 0.67S_2 - 0.36S_3 - 0.80S_4.$$

Next, the adequacy of the model is verified. Assuming $n = 8$ and $N = 3$, the adequacy variance is:

$$\sigma_{ad}^2(Y) = \frac{0.708}{8-(3+1)} = 0.177. \quad (15)$$

The reproducibility variance is:

$$\sigma_{rep}^2(Y) = 3\ 251{,}668.$$

The calculated Fisher's criterion value is:

$$F = \frac{\sigma_{ad}^2(Y)}{\sigma_{rep}^2(Y)} = \frac{0.177}{3251.668} = 0.000054. \quad (16)$$

Since the critical value is F_{crit} = 6.94 (at the corresponding significance level), the hypothesis regarding model adequacy is accepted.

The maximum relative error of the model under the condition $X_1 = X_2 = X_3 = X_4 = 0$ is:

$$\Delta\varepsilon = \frac{1409.32 - 1407.43}{1407.43} 100\% = 0.13\ \%. \quad (17)$$

Thus, it can be concluded that the obtained linear regression model adequately describes the influence of the regulating stations on the power flow magnitude across the monitored transmission interface. Consequently, this model can be utilized to construct knowledge base elements for the power system dispatch decision support system.

RESEARCH RESULTS

As a result of the calculations and analytical experiments, sets of response functions for dispatch control actions at specified network nodes were obtained. The resulting regression models are highly relevant for describing how the capacities of the selected controlled substations affect the active power flow magnitude at the monitored network node. Furthermore, these models can be applied to formulate dispatch control actions. After setting individual regression parameters to zero, metrics representing the influence of the power plants on the node power flow were obtained. The experimentally identified dispatch control actions and emergency management guidelines constitute the foundation for creating the knowledge base. The knowledge base is constructed by integrating dispatcher instructions for active power flow regulation at a specific node with new knowledge derived from experimental operating state research data. The development of the knowledge base was carried out by combining new knowledge obtained from experimental operating state research with the dispatch operational guidelines for active power flow control in the specified transmission interface.

Obviously, the set of relationship models between the subsets of influencing and monitored operating state parameters can be represented as a sensitivity matrix.

$$\begin{vmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1k} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2k} \\ \cdots & \cdots & \cdots & \cdots \\ \beta_{m1} & \beta_{m2} & \cdots & \beta_{mk} \end{vmatrix}$$

where $\beta_{ij}=(n_i p_j)$ is the influence ratio; n_i and p_j are the primary (controlled) and monitored operating state parameters of the dispatch control facility, respectively. The relationship β_{ij} is implemented in the form of standard regression models.

Following the statistical evaluation of the obtained models for adequacy, they can be utilized as new knowledge regarding the state management of a specific dispatch control facility. Using such knowledge as sensitivity matrix elements eliminates the need for full steady-state power flow calculations when assessing the quality of system operating characteristics and formulating dispatch decisions. This advantage significantly facilitates the real-time implementation of the decision support system.

The general operational sequence of the expert system complex can be described as follows.

1. The decision support system creates an information file containing the current date and time of the required telemetry measurements. This file includes the names of the files containing the necessary code numbers for the telemetry measurements.

2. Following a specified timer countdown, control is transferred to a utility program that displays the physical values of the telemetry data. A string specifying the path to the previously created information file is passed to this utility as a parameter.

3. Upon reading the initial information and launching the utility program from the expert system, the utility accesses the database of the real-time information and control system's central computer network. It then determines the physical values associated with the specified telemetry measurement numbers.

4. The physical values of the required electrical network operating parameters are written to the output information file.

5. Control is returned to the decision support system.

6. The internal system procedures for reading and pre-processing the telemetry data are initiated.

7. Based on the acquired information, the logical inference engine is activated, and control is transferred to the user dialogue block.

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8. Upon concluding the dialogue, depending on the results, control either returns to the main system menu or is scheduled for the next timer cycle.

The described operational sequence of the expert system complex is implemented programmatically in the form of the algorithm shown in Fig. 1.

DISCUSSION OF RESULTS

The developed real-time intelligent decision support system for interconnected power system dispatchers was validated in conjunction with the active power grid ADCS and confirmed the operability of the constructed theoretical models for representing and logically processing dispatch knowledge.

The general view of the developed expert system software suite for the power complex dispatcher is shown in Fig. 2.

The software suite test results are adequate, and they form the basis for conclusions regarding the primary directions of decision support system implementation. When implementing the expert system, it is necessary to consider the specific characteristics of the automated dispatch control system's hardware-software environment as well as the tasks to be resolved:

– normal operating state assurance tasks: ensuring steady-state stability; regulating power flows; real-time operating state correction; displaying current operating state parameters; monitoring operational staff actions;

– emergency forecasting and mitigation tasks: eliminating parallel operation violations; forecasting emergency scenarios; general management of emergency mitigation;

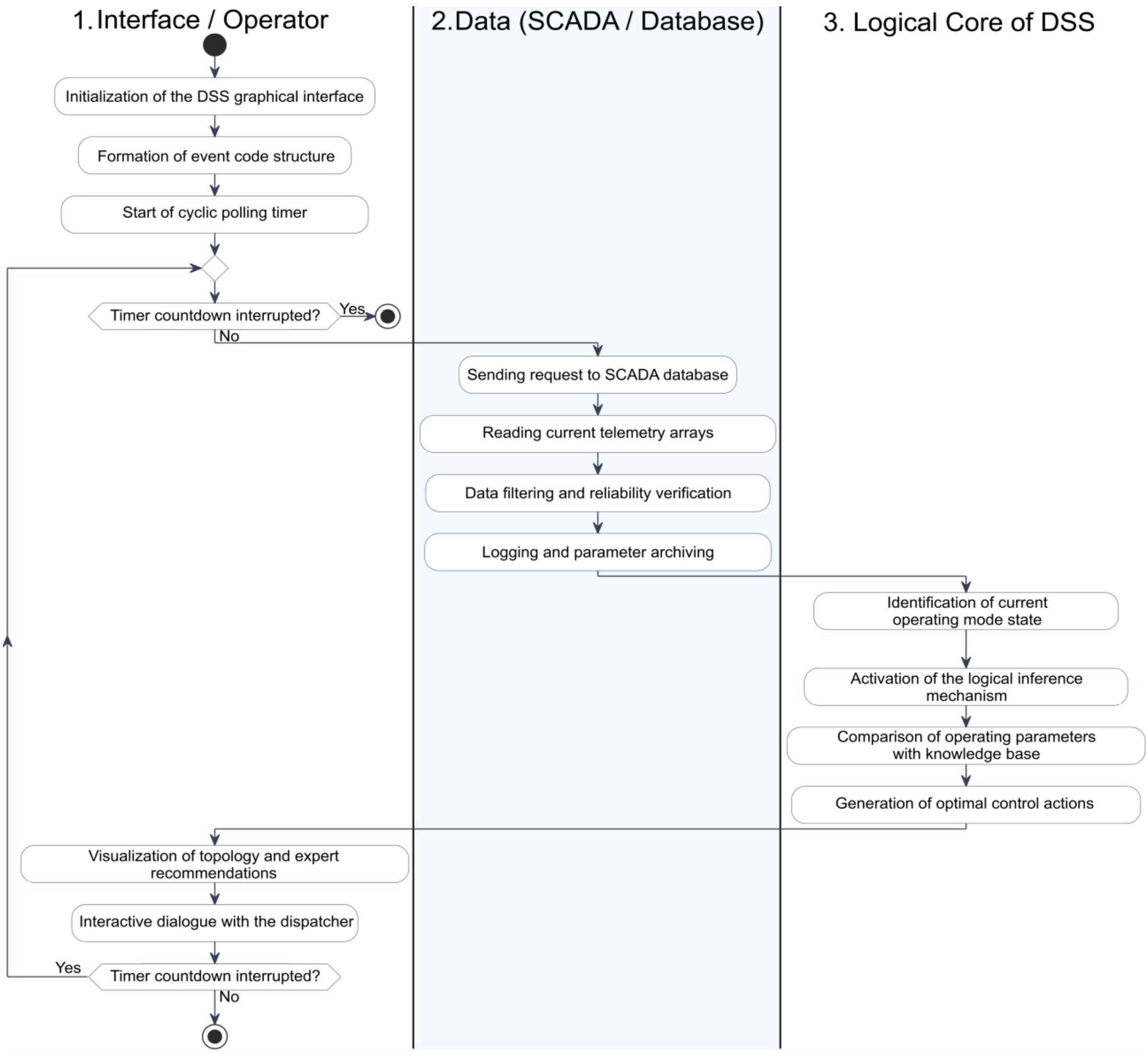

Fig. 1. **Generalized algorythm of expert system complex functioning**
Source: compiled by the authors

– personnel operation support tasks: providing recommendations on safe operating states for transmission interfaces; ensuring rapid access to real-time operational data; providing an interface with the real-time data transmission and processing system;

– education and training tasks: instruction and professional knowledge/skill verification of the dispatch, operational, and technical staff.

The detailed functional diagram for implementing the decision support system into the hardware and software suite of the automated dispatch control system is shown in Fig. 3.

CONCLUSIONS

As a result of the research, scientific, and practical developments, the following objectives have been resolved:

– methodological design of the computational experiment has been executed to synthesize regression models that quantitatively describe the impact of adjusted dispatch control actions on the stability of EPS electrical components;

– structural elements of the knowledge base have been developed by analyzing the acquired empirical data for power grid clusters characterized by the most significant post-contingency operating state parameter deviations;

– an approach has been developed for the conceptual integration of the knowledge base with the operational guidelines of automated dispatch control systems (ADCS), involving the design of algorithms for real-time operating state identification and the synthesis of logical consequents using the mathematical apparatus of sensitivity matrices;

– structural modeling of the expert system and knowledge representation architectures has been performed, tailored to the cognitive characteristics of decision-making by dispatch personnel in high-stress situations;

– the software suite of the intelligent system has been developed and its hardware-software integration into the active ADCS loop for real-time operation has been executed;

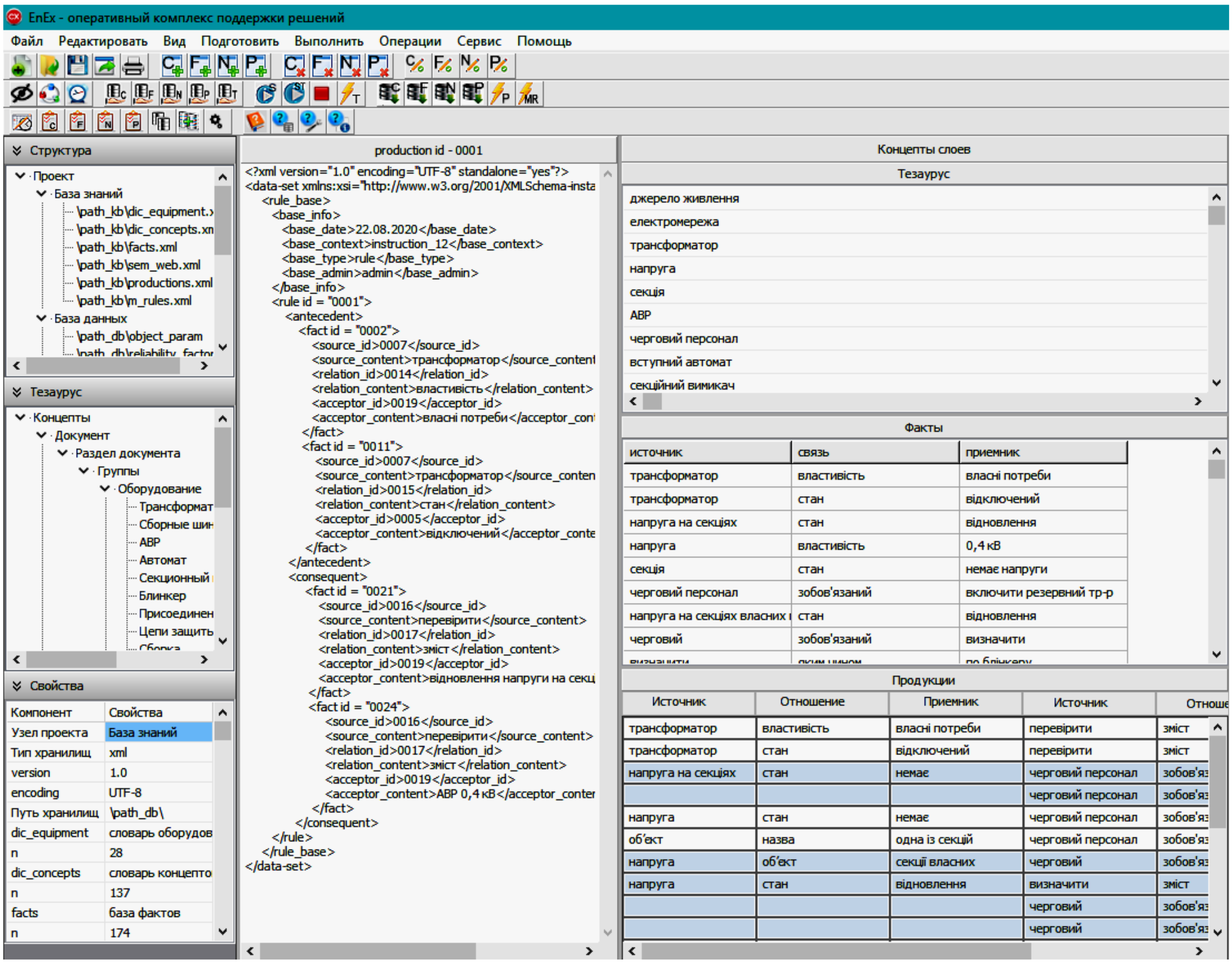

Fig 2. **Software suite of the intelligent computer-aided decision support system for state control in the mining and metallurgical power complex**
Source: compiled by the authors

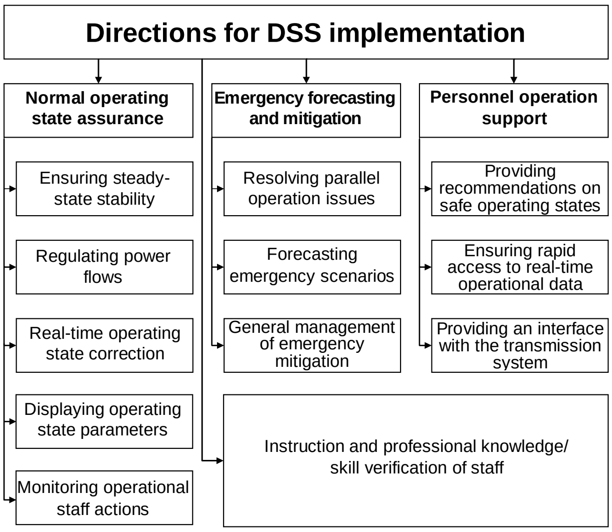

Fig. 3. **Primary functional directions for decision support system implementation**
Source: compiled by the authors

– scientific justification and determination of functional positions have been conducted for implementing the developed DSS within the overall hierarchical structure of power complex dispatch control.

The developed software tools for dispatch knowledge representation and the constructed dispatch control knowledge base enabled the direct synthesis of the expert system. In this case, it is possible to interrupt the timer countdown and return from the real-time state monitoring of the observed facility to the main system menu to modify the task conditions.

To verify and evaluate the effectiveness of the obtained results, it is expedient to perform their comparative analysis with existing counterparts. As a baseline for comparison, we consider modern intelligent complexes implemented in the operational dispatch and emergency control of electric power system operating states:

– LDIS software (AI Center of the Information Processing Research Center, Japan). Primary functions: comprehensive technical monitoring and operational reliability assessment of boiling water reactor (BWR) systems;

– CEALMON software (Electric Power Research Institute, USA). Primary functions: hierarchical structure of emergency operating states based on a formalized set of rules and decision-making support algorithms for nuclear power plant dispatchers;

– GIS-DSS software (O.M. Beketov National University of Urban Economy in Kharkiv, Kharkiv National University of Radio Electronics, Ukraine). Primary functions: automated monitoring and logging of normal and emergency network operating events, with subsequent graphical visualization of the spatial-hierarchical structure of power facilities in the user interface.

A comparative analysis of decision support systems (DSS) in the power facility management environment enabled the formulation of conclusions regarding their architecture and knowledge base organization principles. It is the topology and logical structure of knowledge that determine the resulting effectiveness of intelligent platforms when solving domain-specific tasks. Given the diversity of modern models for representing declarative and procedural information, this problem becomes fundamental for the development of intelligent technologies in general. The generalization of the research results proves that scaling DSS development and intensifying intelligent functions are achievable exclusively within a unified, integrated approach based on the incorporation of domain-specific ontologies.

The direction of further research involves studying the capabilities, characteristics, and methods of obtaining new, mathematically adequate functional relationships between dispatcher control actions and the monitored operating state parameters of the power system electrical network.

Furthermore, future implementation of the expert system must account for the specific technical characteristics of the ADCS software suite itself as well as the professional workflows of the operational engineering staff.

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Інтелектуальна комп’ютерна автоматизація регулювання режимів гірничо-металургійного енергокомплексу

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АНОТАЦІЯ

Роботу присвячено вирішенню **актуального завдання** синтезу інформаційної основи спеціалізованих експертних систем для гарантування нормативних показників електроенергетичної мережі в післяаварійних станах шляхом застосування евристичних алгоритмів ситуаційного диспетчерського керування та автоматизованої підтримки прийняття рішень. **Мета дослідження** полягає в обґрунтуванні концептуального підходу до архітектури бази знань, орієнтованої на підтримку рішень диспетчерського персоналу в процесі стабілізації параметрів енергосистеми. Запропонована парадигма передбачає формування масиву даних із залученням матриці чутливості, яка пов'язує керовані змінні стану мережі з інтенсивністю диспетчерських впливів. **Методологічний апарат** дослідження базується на закономірностях теорії електричних мереж, принципах автоматичного регулювання, інструментарії штучного інтелекту, а також методах математичної статистики та апараті формальної логіки. В результаті планування багатофакторного експерименту та отримання репрезентативної вибірки даних синтезовано поліноміальні регресійні моделі. Ці математичні залежності встановлюють зв'язок між характеристиками нормального передаварійного стану, топологією мережі, характером збурення та оптимальною величиною керуючих впливів. **Наукова новизна** роботи полягає у розробленні методу комплексної інтеграції різнорідної інформації в єдину базу знань. Зокрема, об'єднано формалізовані інструктивні регламенти з ліквідації аварій та розрахункові коефіцієнти матриці чутливості. Останні визначені шляхом імітаційного моделювання з прив'язкою до поточної топології електричної мережі та фізичних параметрів її обладнання. Поєднання логіко-семантичних правил і числових характеристик гарантує високу швидкодію системи, достатню для функціонування в режимі реального часу. **Результати:** оптимізовано структурну модель бази знань, адаптовано алгоритм планування експерименту для обчислення елементів матриці чутливості в регресійних моделях, а також загальну алгоритмічну базу функціонування інформаційно-керуючого комплексу. Запропонована система евристичного керування дозволяє вирішувати спектр завдань: підтримувати запаси статичної стійкості, оптимізувати перетоки активної та реактивної потужностей, здійснювати моніторинг параметрів електромережі та верифікувати дії оперативно-технологічного персоналу. **Практична цінність** дослідження полягає у створенні підґрунтя для глибокої інтелектуалізації автоматизованих систем диспетчерського керування. Впровадження розробленої експертної підсистеми в існуючі комплекси автоматизованих систем диспетчерського керування здатне суттєво мінімізувати час прийняття рішень та підвищити надійність енергопостачання. Додатковим напрямком застосування моделей є їх використання як основи для тренажерних комплексів, призначених для підвищення кваліфікації диспетчерського та технологічного персоналу.

Ключові слова: продукція; семантика; регресія; контроль; керування; схема; евристика; фактор; автоматизація; режим; стійкість; диспетчеризація; інструкція; дозування.

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