DOI: https://doi.org/10.15276/hait.09.2026.26
UDC 681.51:004.8:621.31

Applied heuristic information technologies for automating power system management in mining and metallurgical complexes

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ABSTRACT

This paper addresses the problem of constructing a knowledge base for an expert system to ensure the quality of the post-contingency state of an electric power system based on the use of heuristic methods of dispatch control. **The aim** of the article is to study a potential approach to constructing the knowledge base of an expert system to support the decisions of dispatch personnel during the management of the post-contingency state of an electric power system. This study proposes developing the knowledge base using the sensitivity matrix of the controlled operating parameters. **The research methodology** relies on the principles of the theories of electrical networks and power systems, automatic control, experimental design, artificial intelligence systems, and mathematical statistics. As a result of experimental design, dependencies linking the parameters of the normal pre-contingency state and the network structure with the optimal magnitudes of control actions were obtained. **The scientific novelty** lies in the integration into a single knowledge base of dispatch operational guidelines during the elimination of emergency states, as well as the coefficients of the sensitivity matrix obtained from computational experiments, taking into account the configuration of the electrical network. **The results** of the work are structural models of the expert system knowledge base, a method of experimental design to construct the sensitivity matrix of regression polynomials of the efficiency of dispatch actions, and algorithms for the functioning of the expert automation system for heuristic control of the post-contingency state of the power system. The heuristic control system provides static stability support, power flow regulation, real-time state adjustment, display of current state parameters, and monitoring of the actions of operating personnel. **The practical significance** of the obtained results lies in the intelligent expert automation of post-contingency power system state management. The expert system can be integrated into the control subsystem of a general automated dispatch control system, thereby increasing management efficiency and the quality of the post-contingency state. Furthermore, the system can be used to train and verify the professional knowledge and skills of operational dispatch and technical personnel.

Keywords: Eexpert system; dispatch control; power system management; post-contingency state; semantic networks; regression models; productions; heuristics

For citation: **Kotov I. A., Shvets D. V., Hryhoriev Y. I., Karabut N. O., Kuttybayev Aidar "Applied heuristic information technologies for automating power system management in mining and metallurgical complexes".** ***Herald of Advanced Information Technology*****. 2026; Vol.9 No. 3: 400–416. DOI: https://doi.org/10.15276/hait.09.2026.26**

INTRODUCTION

Mining and metallurgical complexes (MMCs) are among the most energy-intensive enterprises in the industrial sector. According to [1], MMCs account for approximately 10.5 % of the total electricity consumption in Ukraine and 25 % of its consumption in industry. Furthermore, metallurgical plants and mining and processing plants collectively consume more than 13 billion kWh of electricity per year. In the mining segment, the main portion of these costs occurs at the ore preparation stage. The installed capacity of heavy equipment electric drives in just one grinding and classification section can reach up to 3-4 MW per system [2].

Due to this high concentration of power, the share of electricity costs in the cost structure of iron ore concentrate is 50-70 % [3], making the cost of concentrate highly sensitive to energy prices. A sudden power loss for such units not only halts the continuous technological cycle but also poses a threat of severe accidents (such as the clogging of mills and slurry pipelines), the elimination of which leads to prolonged downtime and major financial losses.

Under such circumstances, ensuring the reliability of power supply becomes a fundamental factor of technogenic safety and the strategic stability of MMC enterprises [4].

Given the highly dynazmic external business environment, identifying the dominant factors for adapting the mining complex is of particular importance, making it possible to maintain its functional integrity under changing conditions [5]. This determines the objective necessity for the development and implementation of automated heuristic control systems. Such systems are capable of adaptively mitigating fluctuations in power grid parameters, preventing emergency operating conditions, and ensuring stable quality indicators of the finished concentrate [6], [7].

This study addresses the problem of computer-based intelligent automation of power system management in mining and metallurgical complexes under emergency situations. To solve the automation problem, it is necessary to construct an expert system for dispatch control. For the operation of this expert system, a knowledge base is developed based on the values of the control actions of regulating stations. This work resolves the problem of implementing applied intelligent information technologies in managing the operating state of an electric power complex in an energy-intensive district of the Ukrainian power system. This industrial district includes large mining and metallurgical complexes.

Thus, the problem of heuristic search for control actions involves solving the following tasks: detecting and classifying an emergency situation, determining the application points and types of control actions depending on the situation, and determining the magnitudes of dispatch actions based on the use of an expert dispatch control system.

LITERATURE REVIEW AND PROBLEM STATEMENT

Based on the core problem of this study – constructing a knowledge base for an expert system to ensure the quality of the post-contingency state of an electric power system based on heuristic methods of situational dispatch control – an analysis of research results in the field of dispatch control was conducted. Particular attention must be paid to the power systems of mining regions due to their leading role in overall industrial energy consumption [8], [9].

Studies [10], [11] consider new dispatching concepts and modern approaches to increasing the management efficiency of an electric power system (EPS). The application of optimization methods to a virtual power plant model is described. Study [12] investigates real-time dispatching for secondary regulation of frequency fluctuations. The study in [13] addresses the economic aspects of dispatching under uncertainty. Works [14], [15], [16]. [17], [18] are dedicated to the analysis, modeling, and optimization of electric power systems, emphasizing environmental concerns and the integration of renewable energy sources. Papers [19], [20] examine emergency operating conditions of electrical networks, associated transient processes, and power system stability. Study [21] discusses the optimal allocation of distributed generation capacity to satisfy consumer demand. The study [22] analyzes the aspects of optimal power system state control and substantiates the necessity of making the dispatch control process intelligent.

The analysis indicates that for prompt and high-quality management of normal and, especially, post-contingency EPS states, it is necessary to implement heuristic methods of dispatch control. Currently, there is a large body of theoretical and practical material related to the application of decision support systems (DSS) for dispatchers, particularly in the field of ensuring parameter quality and optimizing the operating states of electric power systems. These dispatch decision support systems rely on the methodology of artificial intelligence systems in general, and expert systems in particular [23], [24], [25]. Studies [26], [27] consider aspects of using knowledge representation forms in artificial intelligence systems for industrial sectors and engineering disciplines. The authors analyzed existing main knowledge representation forms and their applicability in the professional field of power system dispatch control. The analysis revealed the need to integrate different forms of knowledge representation in a single system, primarily semantic networks and productions [28], [29]. The necessity of this approach is driven by the requirement for the comprehensive use of heuristics, which have a dual – static (qualitative-quantitative) and dynamic (causal) – meaning. In [30], a mathematical model for representing and processing knowledge in the form of semantic networks is considered. The developed theoretical basis allows for the synthesis of natural language knowledge base management systems. No fundamental limitations are imposed on the volume or form of information representation.

The implementation of productions based on the mathematical apparatus of Petri net theory is described in [31], [32]. A crucial aspect of the developed mathematical models of productions is the absence of newly introduced restrictions on the standard definition of Petri nets. Practical tools for working with Petri nets are reviewed in [33], [34]. The work [35] is dedicated to tools for analyzing non-Markovian stochastic Petri nets. Study [36] investigates ordinary matrices for representing and processing Petri nets.

To solve the problem of heuristic dispatch control of the power system formulated in this paper, an approach to constructing a knowledge base based on experimental design to generate a sufficient sample of post-contingency state parameters is proposed.

General approaches to experimental design, processing, and interpretation of results are discussed in [37], [38]. In [39], approaches to designing and conducting experiments depending on professional fields and the specific tasks being solved are reviewed and systematized. Special issues of computer-aided experimental design methodology are presented in [40], [41]. The work [42] demonstrates the application of a full factorial experiment in the field of power engineering and, specifically, for modeling solar power generation.

RESEARCH AIM AND OBJECTIVES

The aim of this study is to develop the theoretical and practical foundations for constructing a dispatcher decision support system based on a knowledge base of regression models representing the impact of dispatch control actions. As noted above, this task can be broken down into subtasks. The subtask of detecting and classifying an emergency situation can be solved using pattern recognition and identification methods. The second subtask involves determining the most effective points of control action application (nodes of the EPS) and the structure of these actions to ensure the stable operation of the power system. The solution to this subtask can be achieved using experimental design or taxonomy methods, the results of which are implemented in informational expert decision support systems.

The main objective of the practical part of this study is to construct an expert system to support power system dispatchers by implementing “heuristic information technologies”. For this implementation, a knowledge base must be constructed. The knowledge comprises the degrees of influence of control actions (the power outputs of regulating stations) on the operating state of a critical section of the electrical network. To acquire this knowledge, multiple calculations of the electrical network states are required. Therefore, this work utilizes tools such as experimental design, screening experiments, regression model construction, statistical processing of results, and adequacy evaluation. Once the expert system is operational, these repetitive calculations are no longer performed.

The relative significance of individual actions is reflected in the corresponding coefficients of the regression model. The influence of coefficients on the response can be evaluated by setting them to zero. The application of taxonomy methods involves selecting a subset of regulating stations X that can be involved in control.

Research objectives:

- formulation, planning, and implementation of computational experiments to build regression models of the impact of magnitudes of dispatch control actions on the critical parameters of the electric power system;
- based on the obtained data, formation of knowledge base elements for the parameters of the operating state models of electrical network clusters with the largest post-contingency parameter deviations;
- integration of the obtained knowledge base with the dispatch operational guidelines based on power system state identification and the synthesis of logical consequents using the sensitivity matrix apparatus;
- development of structural models of the computer expert system and the dispatcher knowledge representation system;
- practical software implementation of the intelligent dispatch control automation system and development of a model for its integration into the hardware and software complex of the automated dispatch control system (ADCS) for real-time operation;
- identification of functional positions for implementing the expert decision support system into the ADCS structure.

The **aim** of the study is to construct a knowledge base and an expert decision-support system for dispatch personnel to manage the post-contingency state of an electric power system.

The **subject** of the research is the models, methods, and algorithms for knowledge representation and decision support in power system dispatching, focused on the synthesis and application of control actions in post-contingency state of electric power systems.

MATERIALS AND METHODS

Formally, the task of determining a subset of control nodes of the power system consists in finding the transformation $Y=F(X)$ (X is the initial n-dimensional factor space, Y is the new m-dimensional space, where $n > m$). In this case, the dimensionality in space Y must be minimal but sufficient to recognize the given taxon.

When selecting control actions, an additive operating state quality criterion is primarily used, which optimizes the parameters of the transient process (maximum rotor angle deviations of individual stations, their slip, voltage levels at required system points) as well as the magnitudes of control actions – the volumes of shed load and disconnected generating capacities.

After processing the results of all experiments, a dependency (typically polynomial) is obtained, linking the parameters characterizing the normal pre-contingency state, the network structure, and disturbances (independent factors) with the optimal control action magnitudes:

$$u_i = K_{i0} + \sum_{j=1}^{n} K_{ij} X_j + \sum_{j} \sum_{l} K_{ijl} X_j X_l + \ldots \qquad (1)$$

It follows from the above that the process of searching for dispatch control actions using statistical methods consists of three stages: recognizing the severity of the emergency situation; searching for application points and types of control actions; and determining the optimal control action magnitudes, as shown in Fig. 1.

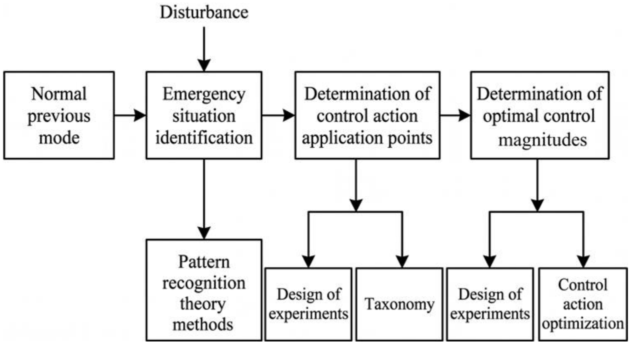

Fig. 1. **Block diagram of EPS control in emergency states**

***Source*: compiled by the authors**

Based on the discussed methodology, an expert system to support the decisions of an interconnected power system dispatcher has been constructed and tested.

Production networks were chosen as the primary form of knowledge representation in constructing the expert system. Productions implement structural-logical models of reasoning in the intelligent decision support system. To represent the semantic component of knowledge, semantic networks were selected. Semantic networks serve as concepts for productions. A graphical illustration of the proposed production model is shown in Fig. 2.

Fig. 2a shows the structures of “AND” and “OR” productions in the form of directed graphs. The elements of the productions $X_1, X_2, X_3, \ldots, X_n, Y$ represent clusters of semantic networks N_{S1}, N_{S2}, N_{S3}, … , $N_{Sn\text{-}1}$, N_{Sn} respectively.

Fig. 2b shows a generalized production graph as a model of the relationship between semantic network clusters.

Fig. 2c illustrates a detailed production scheme showing the presence of semantic networks in its nodes.

Fig. 2d illustrates further detailing of the node's semantic network into a network of facts and, subsequently, into statement triplets.

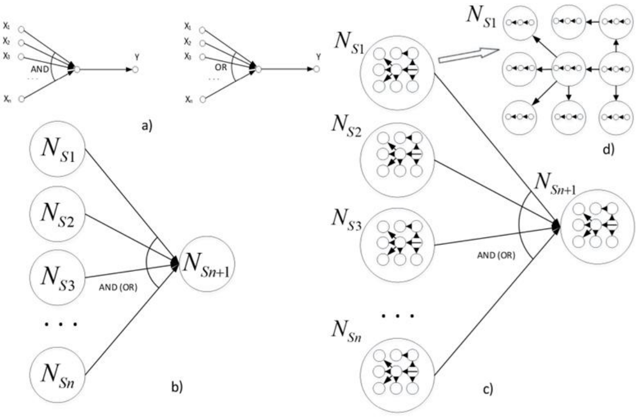

Fig. 2. **Production model based on semantic network clusters**

***Source*: compiled by the authors**

In this study, the following formal production model was adopted [24], [25]:

$$R = \langle S, L, A \rightarrow B, Q \rangle, \qquad (2)$$

where S is the class of situations for which production R is adequate; L is the condition for activating the production; $A \rightarrow B$ is the core (structure) of the production; and Q is the informal justification of the production.

The main part of the production – its core – is formalized based on the proposed concept of constructing productions using clusters of a semantic network.

The main final terminal alphabet of the production is a set of semantic network clusters:

$$\Sigma = A_t = \{\varepsilon\} \cup N_S^{Clust},\quad N_{Si}^{cj} \in N_S^{cj},\quad N_S^{cj} \subseteq N_S. \tag{3}$$

The interpretation of the semantic network of production N_s as a network of clusters, based on the formalism of semantic networks and taking into account the evolution of ontologies in the hierarchical knowledge representation system is introduced:

$$N_s =< N_S^{Clust}, I^{Clust}, G^{Clust} >, \tag{4}$$

where $N_S^{Clust} = \{N_{Si}^{Clust}, i = 1, n^{Clust}\}$ is the set of clusters (concepts) forming the semantic network of the production; $I^{Clust} = \{i_l, l = 1, n_l\}$ is the set of links between clusters N_{Si}^{Clust} (concepts); $G^{Clust} = \{g_q, q = 1, n_q\}$ is the set of incidence mappings of the set of links to the set of clusters (concepts).

In Eq. (4), the model components have the following original meanings. The links between clusters of semantic subnetworks $I^{Clust} = \{i_l, l = 1, n_l\}$ represent the connection of completely identical statements from facts relating to different clusters.

That is, i^{Clust} can be defined as:

$$\forall\left(s_i, s_k \middle| s_i \in f_i \in N_{Si}^{Clust}, s_k \in f_k \in N_{Sk}^{Clust}\right),\quad (s_i = s_k) i^{Clust}: (s_i, s_k) \to s, \tag{5}$$

where the incidence mapping has the form:

$$g_q: c_l = (s), s \in f_i \wedge s \in f_k. \tag{6}$$

Consequently, production synthesis within the developed set-theoretic interpretation is described as a concatenation procedure of sets of clusters of semantic KB (knowledge base) subnetworks that satisfy the following condition:

$$\exists(N_{S1}^{Clust}, \ldots, N_{Sn-1}^{Clust}, N_{Sn}^{Clust})(\overset{k=1}{\overset{n-1}{\cap}} N_{Sk}^{Clust} = s_{sn}) \vee (\overset{k=1}{\overset{n-1}{\cap}} N_{Sk}^{Clust} = s_{an}) \rightarrow. \quad (N_{S1}^{Clust}, \ldots, N_{Sn-1}^{Clust}, N_{Sn}^{Clust} \in R) \tag{7}$$

The obtained files of operating data used as knowledge base components allow for a rapid evaluation of the emergency state severity as well as its dispatch correction. Along with the calculated magnitudes of control actions, the knowledge base also consists of linguistic concepts, facts, and rules of dispatch instruction materials. To construct the KB, a sample was taken from dispatch instructions, which are considered a source of reliable knowledge for the operational control of emergency states.

Based on the instructional linguistic corpus, the productions of the knowledge base are represented. A fragment of the professional domain production knowledge base file is presented in Fig.3.

Summarizing the obtained results of knowledge acquisition from the professional domain and using the developed theoretical foundations, the knowledge base of the intelligent system was constructed to provide decision support for dispatch control of power system states in normal and emergency situations.

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    </fact>
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    </fact>
   </antecedent>
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sections</acceptor_content>
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_content>
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kV</acceptor_content>
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  </rule>
 </rule_base>

</data-set>
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Fig. 3. **Fragment of the professional domain production knowledge base file**

***Source*: compiled by the authors**

RESEARCH RESULTS

In this work, the technical efficiency of the created knowledge base of instructional dispatch materials was evaluated. Indicators of the relative efficiency of professional domain thesauri are informative, and they adequately reflect the semantic and quantitative characteristics of the fact base of the linguistic corpus of instructions for eliminating emergencies in the electric power system. However, these indicators change as the KB accumulates and when several specific professional areas overlap. Therefore, a need arose for a constant integral indicator of the technical efficiency of thesauri. To this end, an integral efficiency indicator of professional thesauri was proposed. The calculation of the indicator is based on the approximation of absolute efficiency data of professional thesauri. The obtained values of the approximation results are presented in Table 1.

Table 1. **Values of approximation parameter estimates**

a_1	b_1	a_2	b_2	a_3	b_3
1	2	3	4	5	6
1.00	0.00	0.2821	72.9233	0.1591	88.0872

***Source*: compiled by the authors**

The graphical results of the approximation are shown in Fig. 3. The physical meaning of the integral thesaurus efficiency coefficient lies in the ratio of the slope of the approximating line of the thesaurus growth rate to the slope of the approximating line of the initial database growth rate. Since the sample sizes along the axes are given in the same units and scales, the slope angles of the approximating lines will stabilize. In Fig. 4, the following notations are used: VTF is the volume of the thesaurus and professional jargon, VFL is the volume of the fact base by growth, VTFL is the volume of the fact thesaurus by growth, and VTFA is the volume of the jargon and abbreviation thesaurus by growth.

The expressions for calculating the integral efficiency coefficients of the thesaurus corresponding to the general and professional vocabulary of abbreviations and jargon are presented in the following formulas:

$$K_{ET} = \left(1 - \frac{\alpha_T}{\alpha_B}\right) * 100\% = \left(1 - \frac{arctg(\alpha_T)}{arctg(\alpha_B)}\right) * 100\%, \quad (8)$$

$$K_{ETA} = \left(1 - \frac{\alpha_{TA}}{\alpha_B}\right) * 100\% = \left(1 - \frac{arctg(\alpha_{TA})}{arctg(\alpha_B)}\right) * 100\ \%. \quad (9)$$

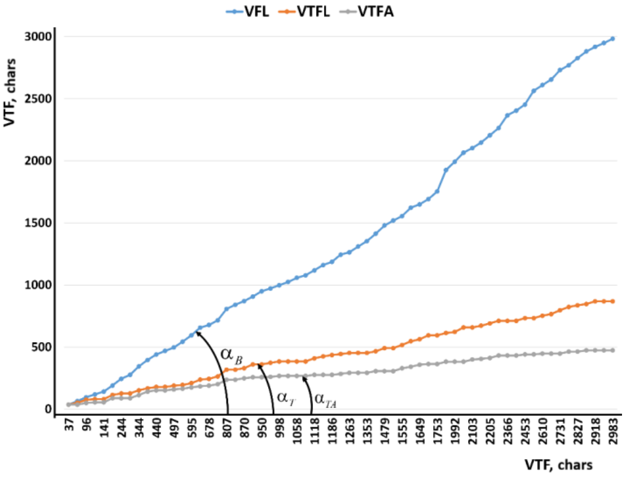

Fig. 4. **Calculation of integral thesaurus efficiency coefficients (where α_B corresponds to the slope of the VFL curve, α_T corresponds to the VTFL curve, and α_{TA} corresponds to the VTFA curve)**

***Source*: compiled by the authors**

where K_{ET} is the efficiency coefficient of the general thesaurus; K_{ETA} is the efficiency coefficient of the abbreviations and jargon thesaurus; α_T is the slope of the approximating function for the general thesaurus; α_{TA} is the slope of the approximating function for the abbreviations and jargon thesaurus; α_B is the slope of the approximating function for the fact base; α_T is the coefficient of V_{KB} in the line equation for the general thesaurus; α_{TA} is the coefficient of V_{KB} in the line equation for the abbreviations and jargon thesaurus; and α_B is the coefficient of V_{KB} in the line equation for the fact base.

Substituting the calculated values yields the following results:

$$K_{ET} = \left(1 - \frac{arctg(0,2751)}{arctg(1)}\right) * 100\ \% = 65,82\ \%,$$

$$K_{ETA} = \left(1 - \frac{arctg(0,1439)}{arctg(1)}\right) * 100\ \% = 81,81\ \%.$$

As follows from the formulas, the efficiency of the general thesaurus is 65.82 %, and the efficiency of the abbreviations and jargon thesaurus is 81.81 %. Therefore, it can be concluded that the efficiency of using a knowledge base based on the incorporation of professional dispatch ontologies will be higher the more specialized the professional linguistic corpus of the professional DSS knowledge base is. The professional domain of post-contingency power system state control is highly specialized, making the construction of specialized thesauri highly appropriate.

Following the evaluation of the efficiency of using the knowledge base built on the concepts of the professional thesaurus of dispatch instructions for eliminating emergencies in the power system, the task of formalizing the knowledge base management and logical inference procedures was solved.

As a formal basis for constructing unified KB management procedures the use of mivar (Multidimensional Informational Variable Adaptive Reality) models and the mivar information space is proposed.

The use of the proposed model for representing the knowledge base architecture is justified. This work utilizes an ontological approach to constructing the knowledge base structure as the most general one, allowing for the application of a hierarchy of various knowledge representation forms. This is an approach of universalism, as opposed to specialized approaches for different problem areas. The basis of a formal ontology is a set of concepts, a set of relations between concepts, and a set of interpretation functions. The basis of a mivar is a set of objects, a set of object relations, and a set of object properties. As can be seen, a one-to-one correspondence between an elementary ontology and an elementary mivar can be established. Thus, ontology can be viewed as a concept in the mivar space: objects – relations – properties. This makes it possible to link the ontology (and its components, such as productions) with these parameters. In conventional knowledge base models, for every input parameter, all rules are scanned to select the one that can be activated. As the number of rules grows, the system's operating speed decreases drastically. In the mivar model, a specific concept (rule) in the space of these parameters is assigned to each combination of input parameters. An increase in the number of rules does not affect the system's speed because there is no search procedure across the knowledge base. For this reason, the mivar model was chosen to represent the knowledge base.

A mivar is an element of a discrete information space and is expressed as a triplet:

$$M =< V, S, O >, \tag{10}$$

where $V = \{v_i | i = 1, m_v\}$ is the set of objects (or their identifiers); $S = \{s_i | i = 1, m_s\}$ is the set of properties of the objects; and $O = \{o_i | i = 1, m_o\}$ is the set of relations (or operations) linking the objects.

The graphical interpretation of the used approach is shown in Fig. 5.

Now, the formal model of the mivar ontological space is expressed as follows:

$$M_O = \{m_{O_i} | i = 1, n_m\}, \tag{11}$$

where $\forall m_{Oi}, m_{Oi} \in M_O : m_{Oi} =< c_{ai}, r_{ai}, f_{ai} >$.

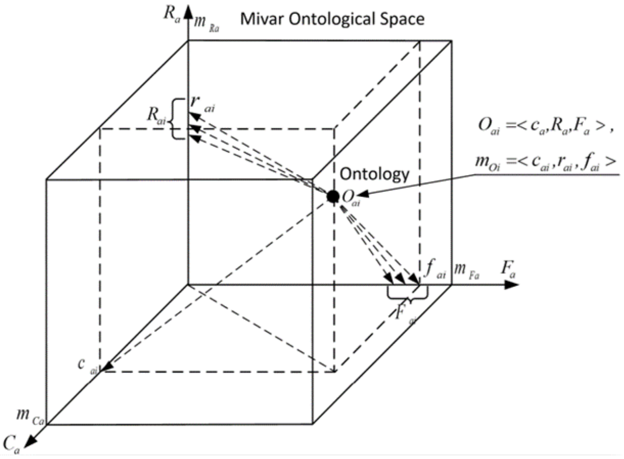

Fig. 5. **Model of the atomic ontology structure in the mivar information space**

***Source*: compiled by the authors**

Then:

$$M_O = C_a \times R_a \times F_a,$$
$$|M_O| = n_C \cdot n_R \cdot n_F. \tag{12}$$

and the mappings are realized:

$$f_{mc} : m_{Oi} \to c_i | R_a = \emptyset, F_a = \emptyset,$$
$$f_{mf} : m_{Oi} \to f_i | C_a = \emptyset, R_a = \emptyset, \tag{13}$$
$$f_{mr} : m_{Oi} \to r_i | C_a = \emptyset, F_a = \emptyset.$$

When taking into account the set of semantic contexts in the model:

$$T = \{t_k | k = 1, N_t\},$$

such that:

$$\forall c_i \in C, \exists t_k \in T : c_i \Leftrightarrow t_k,$$

the general mivar ontological space takes the form of the following model:

$$\forall m^t_{Oi}, m^t_{Oi} \in M^t_O : m^t_{Oi} =< c^t_{ai}, r^t_{ai}, f^t_{ai} >,$$
$$m^t_{Oi} = (< c_{ai}, r_{ai}, f_{ai} >, t), \tag{14}$$

or:

$$\forall M^t_O : M^t_O \in M_O \wedge t \in T,$$
$$M^t_O = \{ m^t_{Oi} | i = 1, n_m \},$$
$$\forall m_{Oi}, m_{Oi} \in M_O : M_O = \{(< c_{ai}, r_{ai}, f_{ai} >, t_1), \ldots \tag{15}$$
$$, \ldots, (< c_{ai}, r_{ai}, f_{ai} >, t_k), \ldots, (< c_{ai}, r_{ai}, f_{ai} >, t_{N_t})\}.$$

Thus, the ontology model is generalized by the mivar model, which provides advantages in unifying the operations of processing knowledge representation forms, taking into account their variability and linear computational complexity. On this basis, the operations for managing the concepts of ontologies of production knowledge networks of the professional domain in the mivar space have been unified.

The operation of adding a production to the KB:

$$\begin{aligned}&\lambda id_R, id^t, N^{ant+}, N^{con+}, \mu_R . ADDR(\\ &\qquad < id_R / con_{IDR} >, \\ &\qquad < id^t / con^t >, \\ &\qquad < N^{ant+} / con^{ant}_{CL} >, \\ &< N^{con+} / con^{con}_{CL} >, < \mu_R / con_{\mu} >),\end{aligned} \tag{16}$$

where the parameters of the operation are:
id_R is the identifier of the production being added to the KB; id^t is the context identifier; N^{ant+} is the antecedent cluster of the production; N^{con+} is the consequent cluster of the production; and μ_R is the starting marking of the production.

The operation of deleting a production from the KB:

$$\lambda id^-_R . DELR\left(< \frac{id^-_R}{con^-_{IDR}} >\right), \tag{17}$$

where the parameter of the operation is: id^-_R is the identifier of the production to be deleted.

Other operations were formalized in a similar manner.

The developed formal models allow for the algorithmization of the functional model of the production ontology concept management module. A graphical illustration of the functional block diagram of the algorithm for managing production concepts based on the ontology knowledge base of production networks is shown in Fig. 5.

When implementing knowledge processing algorithms, particular attention must be paid to evaluating the algorithmic complexity, as a significant increase in the knowledge base size and, accordingly, the volume of computations is expected.

Modern automated information processing systems (AIPS) demonstrate high efficiency when manipulating large volumes of heterogeneous data. At the same time, the growing volumes of information arrays necessitate the modification of the architecture or a complete rewrite of the software code of AIPS components. Further intensification of data accumulation and the complication of their internal logical structure create additional obstacles for designing intelligent systems. Therefore, the design of adaptive hierarchical systems is considered a promising direction for the development of knowledge bases. In this case, there is an objective need to develop a dynamic configuration of knowledge bases with their subsequent adaptation to the specifics of the subject area.

In this work, a formal mivar model to represent the hierarchical structure of knowledge base concepts is used. This structure combines a virtually free network model with a relational indexed direct access model. This ensures a linear growth in computational complexity against the background of an exponential growth in the volume and relationships within the knowledge base.

Mivars are interconnected by corresponding relations in space M, which allows for the interpretation of this space as a mivar network. When the connections between mivars are determined by productions, it becomes possible to perform logical inference based on such networks.

The fundamental difference between logical mivar networks and traditional production models lies in the rule activation mechanism. While production networks implement an iterative search for rules that match the conditions of the antecedent, the mivar-based approach strictly associates each object with its current processing algorithm by index. The latter can be positioned as a coordinate in the N- dimensional space M. Thanks to this determinism, logical inference using the mivar paradigm is characterized by linear computational complexity relative to standard production sets.

Therefore, it can be stated that the time efficiency of the algorithm for processing production knowledge interpreted through ontological models in the mivar space is directly proportional to the volume of input data. This means that the computational complexity of the algorithm corresponds to the class $O(n)$. Thus, the time spent on performing computational operations increases linearly with a sharp increase in the dimensionality of the input data array.

To practically form the knowledge base of the intelligent system, experimental computational studies of power flows from the regulating stations of the power system were conducted. The work was carried out using the actual instructional material of dispatch control from the National Dispatch Center (NDC) of Power Engineering of Ukraine. A critical transmission interface of the main electrical network configuration of the Integrated Power System (IPS) of Ukraine (South Ukraine NPP – Vinnytsia) was considered as the object of dispatch control.

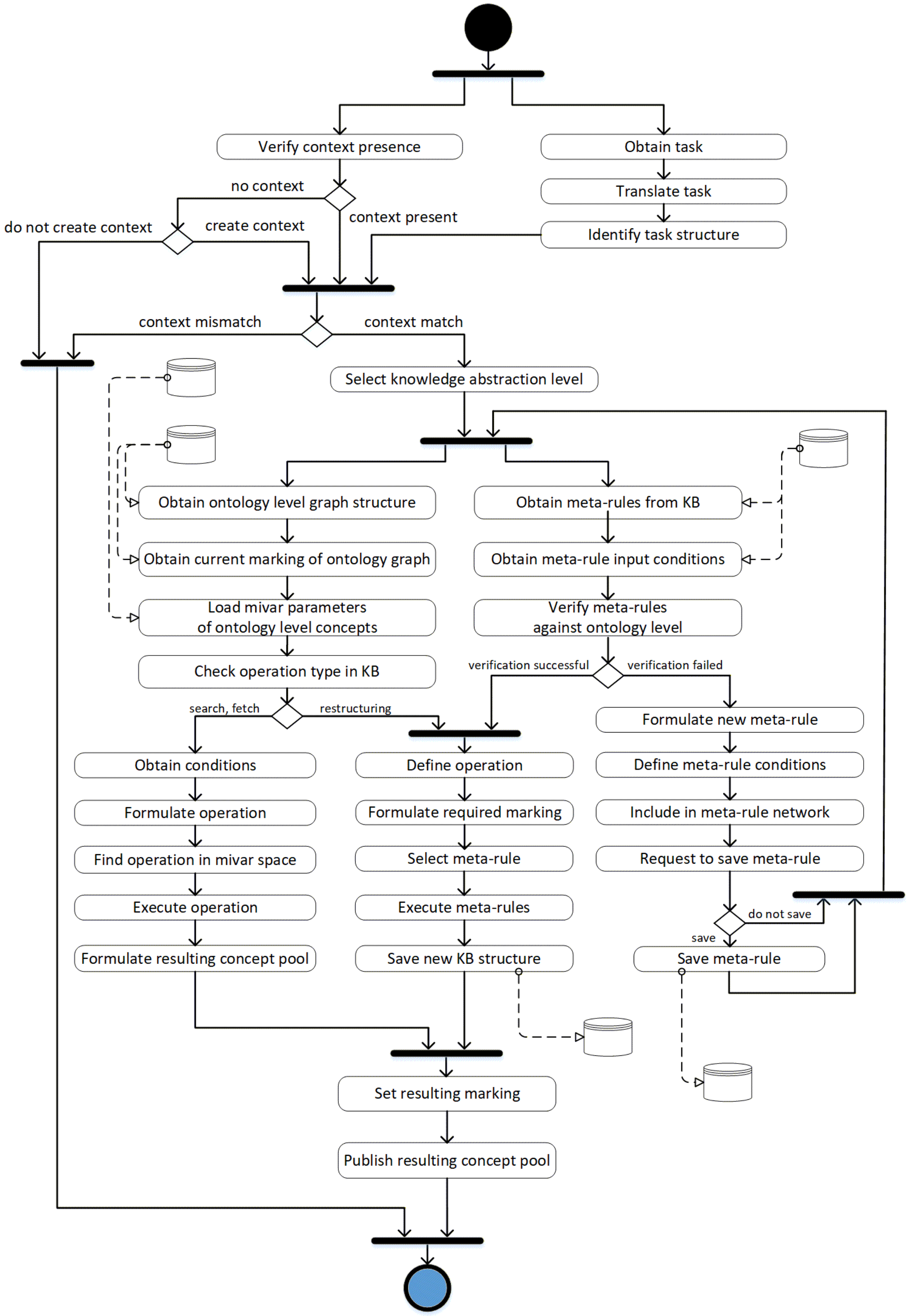

Fig. 6. **Generalized functional block diagram of the algorithm for managing production concepts based on the ontology knowledge base of production networks**

***Source*: compiled by the authors**

The knowledge base was formed by combining dispatcher instructions on regulating the active power flow in a specific transmission interface with new knowledge obtained from experimental studies of the operating state.

The calculation of the magnitudes of the dispatch control actions was carried out according to the following scheme of experimental design and results processing. Factors were selected taking into account the goals of the computational experiments and the features of the Ukrainian power system network scheme. Current changes in the configuration of the network scheme, capacities, and other parameters of regulating nodes do not fundamentally affect the methods and approaches proposed to solve the problem formulated in this work, nor do they diminish the scientific value of the results obtained.

The following notations for factors were adopted: Dnipro HPP-1 – F1; Dnipro HPP-2 – *F*2; Kakhovka HPP – *F*3; Kremenchuk HPP – *F*4; Serednodniprovska HPP – *F*5; Kaniv HPP – *F*6; Kyiv PSPP – *F*7; Dniester HPP – *F*8. The selected dispatch control action points and factor variation levels are presented in Table 2.

Steady-state calculations performed based on the initial parameters of the center point of the experiment according to Table 2 allowed for a decision to be made regarding the selection of the center point and parameters of the screening experiments.

In Table 2, the variation intervals of the factors are specified in terms of active power (MW), based on the fact that the first stage of the research addressed the selection of the initial (center) point of the experiment. Therefore, no special requirements were imposed on the precision of the screening experiment. In addition, dispatch calculations for the studied interface showed the predominant influence of the active components of the stations' capacities on the power flow in the interface. Thus, to reduce the dimensionality of the first-stage problem, it was decided to consider only the active power components of the nodes. In the main experiment, to obtain an accurate picture of the distribution of power flows and voltage levels, the full capacities of the regulating nodes were taken into account.

Based on the results of the screening computational experiments, factors having the greatest impact on changes in the target function – the power flow in the monitored transmission interface – were selected. The new planned computational experiment at the selected center point is shown in Table 3.

Based on the data obtained from the experiments, estimates of the regression coefficients were determined, and their statistical significance was verified.

Then, the regression equation in terms of the variables will have the form:

$$Y=b_0+b_2X_2+b_3X_3+b_4X_4,$$

or (considering that the variables X_1, X_2, X_3, X_4 in the experiment are the capacities S_1, S_2, S_3, S_4) in natural values for the power flow in the interface (MW):

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

The results of processing the outcomes of the main experiment showed a minor influence of factor S_1 on the value of the target function (its statistical insignificance) compared to other factors. Therefore, it is not included in the final equation.

Table 2. **Variation levels of regulating station capacities**

No.	Station Factor	Installed Capacity (MW)	Actual Parameter Values at Levels (MW)			Intervals (ΔP, MW)	
			-1	0	+1	-ΔP	+ΔP
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**

Table 3. **Experimental design parameters for the selected stations of influence**

No.	Station	Factor		Levels of Factors			Interval	Unit
				-1	0	+1		
1	F3	S_1	$\tilde{x}_1$	-413.41	-327.41	-241.41	36.00	MVA
2	F6	S_2	$\tilde{x}_2$	-220.48	-99.32	21.83	121.15	MVA
3	F7	S_3	$\tilde{x}_3$	-68.60	68.16	204.91	136.76	MVA
4	F8	S_4	$\tilde{x}_4$	59.91	239.64	419.38	179.73	MVA

***Source*: compiled by the authors**

The significance of the factors was determined using Student's t-test. The adequacy of the model was calculated using Fisher's criterion at a 5% significance level as follows. The criterion was used in the form of the ratio of the adequacy variance (0.177) to the reproducibility variance (3251.668). The specificity of the numbers is due to the purely computational nature of the experiment. Then, the calculated Fisher criterion is: $F=0.177/3251.668\approx0.000054$. The tabular value of Fisher's criterion is 6.9. Since the calculated value does not exceed the tabular one, the model can be considered adequate.

6. DISCUSSION OF RESULTS

Thus, statistical evaluations showed that the obtained regression model in the first linear approximation adequately describes the influence of regulating stations on the power flow in the monitored transmission interface. The model can be used to generate the magnitudes of dispatch control actions as elements of the knowledge base of the expert decision support system for power system dispatchers.

Based on the developed formal knowledge base model and the obtained experimental corpus of the control action matrix, a new design structure for the DSS core is proposed. A distinctive feature of the developed DSS is the presence of a block of hardware and software triggers, a block of meta-rule transactions, an interpreter block for meta-rule transactions, an ontology block, as well as a new structural configuration for the KB and the logical inference block. The new structure of the DSS core is based on combining the logical inference mechanism in the form of meta-knowledge and the ontology knowledge base, the simultaneous incorporation and evolutionary compatibility of various knowledge representation forms in a single ontology KB, and the linking of logical inference meta-knowledge to triggers associated with events of EPS control objects. Given the configuration of the DSS core, possible implementation points for the DSS in the data transmission paths of the ADCS complex were identified. For this purpose, various ADCS architectural solutions were taken into account [43]. In the resulting ADCS+DSS coupling, the task of automating decision-making and EPS state management is achieved by including a data acquisition and telecontrol block connected with the information subsystems block of the real-time information and control system (RTICS) in the complex. It interacts with the technological data exchange network block and the telecontrol systems software block through the information collection and display block. The resulting generalized model of the integrated ADCS+DSS complex is illustrated in Fig. 7.

The DSS core contains a meta-rule transaction block connected to a hardware and software trigger block, which is linked via data transmission channels to the telemetry and remote signaling sensor block, and telecontrol devices that receive state parameters from sensory elements of the electrical network, as well as to the automated workstations block and the technological data exchange network block. The DSS core contains a logical inference block that includes a meta-rule transaction interpreter, a knowledge base block, and professional ontology blocks.

The testing results of the software complex alongside the active automated dispatch control system of the power system are adequate, and based on them, conclusions were drawn regarding the main directions for system implementation. When implementing the expert system, the specifics of the hardware and software environment of the automated dispatch control system and the tasks solved by the ADCS must be considered.

The specifics of the ADCS hardware and software environment require solving a set of issues regarding the organization of information interactions between the RTICS and the DSS software. Information channels are organized based on the IEC family of data exchange protocols IEC data exchange protocols are international standards for the interaction of automation and remote control devices in the field of electric power engineering.

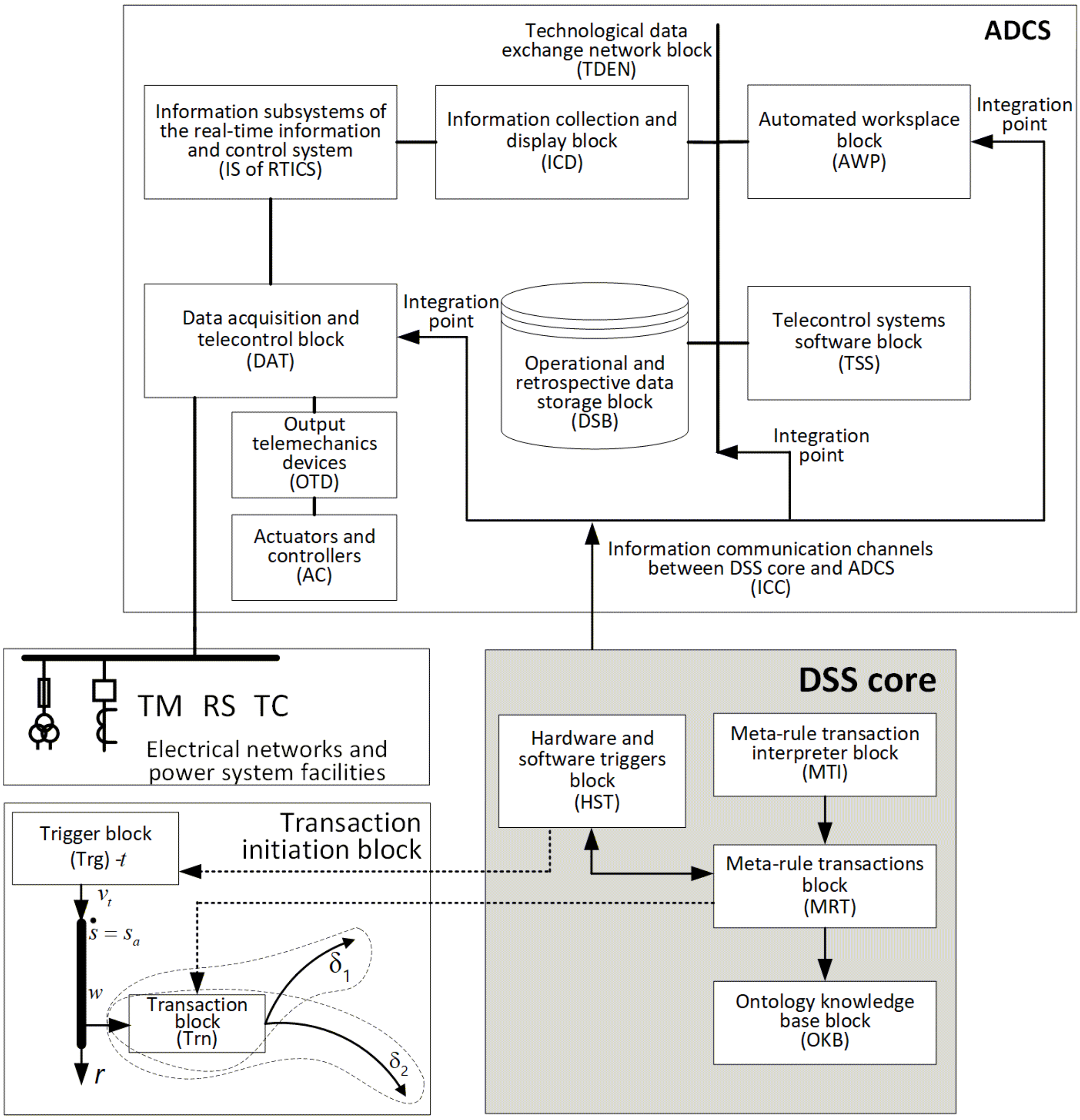

Fig. 7. **Integration diagram of the DSS core into the ADCS hardware and software complex**

***Source*: compiled by the authors**

The main components of the IEC protocols are IEC-61850 for digital substations and IEC-60870-5-101/104 for telemetry channels and effective communication with SCADA (Supervisory Control and Data Acquisition) systems.

This protocol regulates the formats of transmitted data, norms for describing power facility components, and a set of directives for organizing interactive data transmission.

The main advantages of the IEC-61850 protocol include: the possibility of establishing communication between equipment components from independent manufacturers; simple alignment of message formats for third-party application access to information; significant simplification of software developers' work; an object-oriented structure of data organization; detailed and flexible configuration; improved visibility of substation operation evaluation; and economic viability.

Network communication between computing centers and SCADA components is carried out based on the standard TCP/IP protocol. Control networks use the MMS protocol as a component of IEC and a reduced stack of the OSI network model with the TCP/IP protocol at the transport-network layer. Ethernet or RS-232 is used as the medium for transmitting information and control signals. This setup ensures interaction management that is invariant to the type of network or configuration of connected devices.

CONCLUSIONS

As a result of research, scientific, and practical developments, the following tasks have been solved:

- experimental design and computational studies were planned and conducted to build regression models of the impact of magnitudes of dispatch control actions on the critical parameters of the electric power system;
- based on the obtained computational data, knowledge base rules were formed for decision-making regarding the parameters of the operating state models of electrical network clusters with the largest post-contingency parameter deviations;
- a structural model of the computer expert system and the dispatcher knowledge representation system was developed;
- the knowledge base was integrated with the dispatch operational guidelines based on the sensitivity matrix apparatus;
- software for the expert system of dispatch control automation and models of its integration into the ADCS hardware and software complex for real-time operation were implemented.

The developed software tool for representing dispatch knowledge and the constructed dispatch control knowledge base allowed for the direct synthesis of the expert system. Furthermore, it is possible to interrupt the timer countdown and return from the monitoring mode of the current state of the observed object to the main menu of the system to change the task conditions.

The results obtained in this study can be evaluated in comparison with existing analogues of similar systems. Examples of DSS developed for the professional field of power system management and, in particular, dispatch post-contingency control of EPS states include:

- the GIS-DSS system (developed by Kharkiv National University of Municipal Economy and Kharkiv National University of Radio Electronics, Ukraine). Functions: registration of normal and emergency events in the system with the capability to visualize the hierarchical structure of the power system for users;
- the LDIS system (developed by the AI Center of the Information Processing Research Center, Japan). Functions: diagnostics of a boiling water reactor;
- the CEALMON system (developed by the Electric Power Research Institute, USA). Functions: classification of emergency action levels based on rules defined for nuclear power plant operators.

An analysis of both general-purpose and specialized DSS for power system management allowed for generalizing conclusions, which primarily relate to their structure and the representation of information in knowledge bases. Specifically, the organization of the knowledge base structure ultimately affects the effectiveness of the DSS in a specific task domain. Modern AI systems utilize a vast array of knowledge representation forms. The problem of knowledge representation in DSS is fundamental both for specific DSS and for AI systems as a whole during their construction. The analysis of the obtained results convincingly demonstrates that the mass production of DSS, reduction of their cost, and increase in their efficiency are possible only based on a unified, integrated approach based on the incorporation of professional ontologies.

The direction of further research is to study the capabilities, features, and methods of obtaining new adequate functional dependencies between the control actions of dispatch personnel and the monitored parameters of the electrical network state of the power system.

Furthermore, in future work, when implementing the expert system, the specifics of both the ADCS software complex itself and the professional sphere of activity of the specific specialist should be taken into account.

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Conflicts of Interest: The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other, which could influence the research and its results presented in this article

Received 10.04.2026
Received after revision 12.06.2026
Accepted 18.06.2026

DOI: https://doi.org/10.15276/hait.09.2026.26
УДК: 681.51:004.8:621.31

Прикладні евристичні інформаційні технології для автоматизації управління енергосистемою гірничо-металургійного комплексу

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АНОТАЦІЯ

В статті розглянуто проблему побудови бази знань експертної системи для забезпечення якості післяаварійного режиму електроенергетичної системи на основі використання евристичних методів диспетчерського управління. **Метою статті** є вивчення можливого підходу до побудови бази знань експертної системи для підтримки рішень диспетчерського персоналу під час управління післяаварійним режимом електроенергетичної системи. У роботі пропонується формувати базу знань на основі матриці чутливості керованих параметрів режиму. **Методи** дослідження ґрунтуються на використанні положень теорій електричних мереж та енергетичних систем, автоматичного керування, планування експерименту, систем штучного інтелекту та математичної статистики. У результаті планування експерименту отримано залежності, що пов'язують параметри нормального передаварійного режиму, структуру мережі з оптимальними дозуваннями керуючих впливів. **Наукова новизна** полягає в інтеграції в єдину базу знань інструктивних матеріалів з диспетчерського управління під час ліквідації аварійних станів, а також коефіцієнтів матриці чутливості, отриманих у результаті розрахункових експериментів з урахуванням конфігурації електричної мережі. **Результатами** роботи є моделі структури бази знань експертної системи, метод планування експерименту для побудови матриці чутливості регресійних поліномів ефективності диспетчерських впливів, алгоритми функціонування системи експертної автоматизації евристичного управління післяаварійним режимом енергосистеми. Система евристичного керування забезпечує підтримку статичної стійкості, регулювання перетоків потужності, оперативне коригування режиму, відображення поточних параметрів режиму, контроль дій оперативного персоналу. **Практична значимість** отриманих результатів полягає в інтелектуальній експертній автоматизації управління післяаварійним режимом енергосистеми. Експертна система може впроваджуватися в середовище керуючої підсистеми загальної автоматизованої системи диспетчерського керування і, тим самим, підвищувати ефективність управління та якість післяаварійного режиму. Крім того, система може використовуватися з метою тренування та перевірки професійних знань і навичок оперативно-диспетчерського та технологічного персоналу.

Ключові слова: експертна система; диспетчерське управління; управління енергосистемою; післяаварійний режим; семантичні мережі; регресійні моделі; продукції; евристика

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