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MULTI-AGENT BASED FORMALIZATION OF ELECTRIC POWER DISTRIBUTION SYSTEM DESIGN PROCESS

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Abstract: This paper is concerned with the conceptual basis of multi-agent based formalization of the process of electric power distribution system design. A choice of a multi-agent software architecture is made, the interface protocols and approaches to the coordination of intellectual agents are described. Based on the ontological approach, a multi-aspect information model of electric power distribution systems has been formed. The program implementation of iCAD software for electric power distribution systems has been performed.

Key words: electric power distribution system (EPDS), multi-agent system (MAS), intellectual CAD (iCAD).

1. Introduction

Currently, intellectual CADs (iCAD) are the most forward-looking means to improve the effectiveness of design engineers' work. They are rapidly developed and widely used in different spheres of industry. Among the basic principles of creating a new generation of CAD software, such principles as integration and intellectualization of the design process at information and methodological levels play an important role [1].

The principle of the iCAD intellectualization usually presumes algorithmization and automation of separate design procedures based on the methods and technologies of artificial intellect. Thus, the most popular ones are the technologies of formalization, storage and usage of knowledge in iCAD (Knowledge Based Engineering [2]), as well as the euristic search methods for solving the problems of optimization (genetic algorithms, neural networks, etc.). The principle of the iCAD integration aims at formalizing and automating the design process in general: starting from the statement of a design task to the preparation of detailed engineering design documentation. Proper strategy implementation of the iCAD integration principles should include:

1. Integration of program agents (PA) of the project subsystems in a single information space of iCAD in the way of creating unified program protocols and interfaces of their interaction, as well as forming data bases and knowledge bases using the common principles.
2. Integration of a designer and PA of the project subsystems based on an interactive intelligent interface of the user that interacts with the designer in acceptable forms and terminology of the subject area.
3. Integration of the project stages at the methodological level when even the least formalized stages are automatated, particularly the stages of data acquisition and conceptual design.

The ultimate goal of the principle of iCAD integration is implementing the end-to-end design technology, which should completely ensure a changeover to electronic form of the document flow and significantly reduce the duration of the design process. There are no effective iCAD solutions for Electric Power Distribution Systems (EPDS) that meet the previously mentioned requirements yet. The development of iCAD software for EPDS is connected with significant difficulties, primarily with the lack of effective theoretical formalization principles of the iCAD design process.

The most promising approach to the solution of this problem is using the multi-agent approach to iCAD software development [3, 4]. According to this approach, iCAD can be considered as an open distributed information system formed from a set of intellectual agents (IA) jointly solving the challenging design tasks.

2. Problem statement

The goal of this research is formalization of the EPDS design using the multi-agent approach to the implementation of effective iCAD for electric power systems. For this purpose, it is necessary:

a) to formulate the conceptual principles (fundamentals) of the multi-agent iCAD software, which includes the formation of a multi-agent software architecture, protocols of interaction, and coordination of intellectual agents;

b) to conduct the software implementation of iCAD for EPDS based on the multiagent approach and evaluate the potentials of its usage.

3. Conceptual principles of the multi-agent iCAD system

3.1. An intellectual agent in the iCAD system*:* an interior structure, goals and actions in the exterior environment

An intellectual agent is an autonomous computer-based system included into the exterior environment and able to operate independently according to its own needs [5]. In common CAD software, the essence of intellectual agents' activity (Fig. 1) lies in performing the design procedures, with the information model of the design object being the exterior environment for the intellectual agent. The information model of the design object (IMDO) includes the following aspects: restrictions and a functional model, physical design, construction technology, and operational maintenance plan.

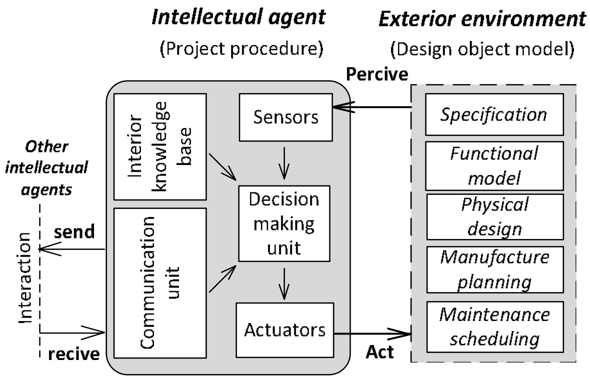

Fig. 1. Intellectual agent in the iCAD system.

The activity of an intellectual agent can be described mathematically as a transform of IMDO from one state into another using the following form:

$$F : M^{(i)} \rightarrow M^{(i+1)}. \qquad (1)$$

Let us assume that the initial state of IMDO ($M^{(0)}$) corresponds to the input design information. The final goal of the intellectual agent is forming a comprehensive pattern of the object being designed ($M^{(k)}$). The design process can be represented in the form of the history of interaction between IA and the environment as an ordered set of "state-action" pairs:

$$M^{(0)} \xrightarrow{F1} M^{(1)} ... \xrightarrow{Fi} M^{(i)} .... \xrightarrow{Fk} M^{(k)}, \qquad (2)$$

where $M^{(i)}$ is the state of IMDO that corresponds to an intermediate description of the design object resulting from the action F_i .

The algorithm of traditional design methodology for any technical system includes a cyclic performance of four basic types of tasks: a) statement of the problem; b) structural synthesis; c) parametric synthesis; g) analysis. According to this design process diagram, we shall develop a conceptual IMDO in the form of a connected ontological graph as a set of concepts *(E)* and relations *(R)* between them:

$$M =< E, R >. \qquad (3)$$

At the first stage, the conceptual IMDO will include just a set of objects of the *Requirement* class incapsulating the requirements and restrictions to the system of *Entity* class. At the second stage, the structural synthesis of EPDS using the examples of *Entity* and *Relation* classes and establishing the associated connections between them should be carried out. At the third stage, the parametric synthesis of EPDS is carried out by changing the parameter values (*Param*) of the objects created.

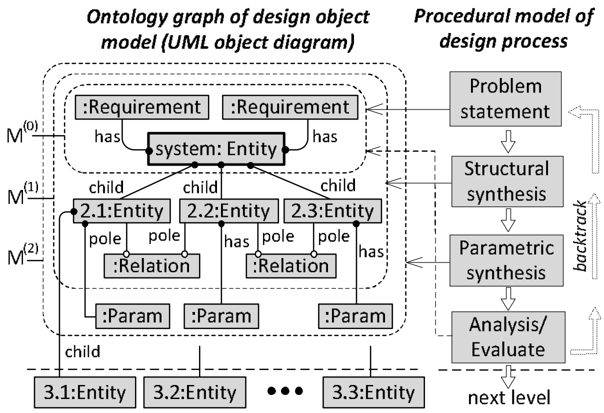

Fig. 2. Structure and deployment of the ontology graph of the design object during the design process.

At the final stage, the procedure of analysis by traversing the synthesized ontological graph is performed. This is followed by doing calculations to check the correspondence of the graph structure and the element parameters to the formed system of restrictions and requirements of EPDS. If the requirements and restrictions are not satisfied, IMDO returns to the state of the first stage, and the problem formulation becomes slightly changed. If the requirements and restrictions are satisfied, the next IMDO level starts to expand. The associative (associated) relations of the *child* type ensure the "system-subsystem" navigation between the elements belonging to the neigbouring hierarchical levels. Such an IMDO structure corresponds to the block-hierarchical approach to structuring knowledge of the design object, and the above-mentioned approach to its expansion corresponds to the basic (lowest) design style. Therefore, performance of the basic types of the tasks dealing with applied programming of intelligent agents consists in step-by-step addition of some amount of information (ΔM) to IMDO:

$$M^{(i+1)} = M^{(i)} \mathbf{U} \Delta M. \qquad (4)$$

In the simplest case, for such types of operation to be performed, it is reasonable to use a reflexive agent. The structure of the reflexive agent is given in Fig. 1, and its internal realization can be presented in the form of a pseudocode:

```
Perceive (M) {
    state ← senseEnvironment (M);
    action ← choiseAction (rules, state);
    M ← applyAction (action)   }
```

According to this code, the agent evaluates the state of the external environment (IMDO), extracts relevant information (state) associated with the area of its interests, and on the basis of the internal productional knowledge database (*rules*), of *if-then* type, chooses an operation (*action*) to change a state of the external environment. Note that depending on the IA features (the class of the task to be solved), it would be more appropriate to use a specific form of knowledge representation. For example, for a structural synthesis, the relevant form of knowledge representation is morphological sets, for a parametric synthesis, it is a production system, and for an analysis – algorithms.

3.2. Multi-agent interaction in the iCAD system: communication and coordination mechanisms

The choice of communication protocol and coordination method of IA is the main problem of the multi-agent system formation. In iCAD,, the interaction of a set of IAs with shared task roles will take a cooperative form. Given the cycling of design processes connected with interchanging the procedures of synthesis and analysis (Fig. 2), it is necessary to enable the fulfilment of design tasks by one IA to be controlled by the others. Therefore, a vertical double-pass architecture of the multi-agent system is rational for the creation of iCAD software [6]. Its structure is shown in Fig. 3, *a*, and the interaction protocol of IA in the form of a UML (Unified Modeling Language) sequence diagram is presented in Fig. 3, *b*.

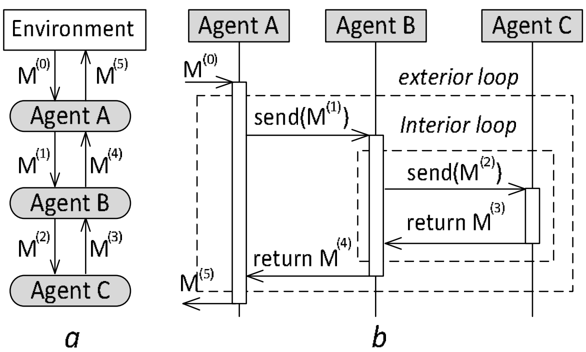

Fig. 3. Multi-agent interaction: a – vertical layered architecture of MAS; b – interaction protocol.

The presented UML sequence diagram allows step-by-step modelling of IA interaction. The agent ***A*** assigns a task to the agent ***B*** by sending a message $M^{(1)}$. The agent ***B***, depending on the type of the task, solves it using its own resources or assignes it to the agent ***C***. The agent ***B*** returns the result to the agent ***A*** using the message $M^{(4)}$. In case the result of the task fulfilment does not satisfy the agent ***A***, it can somewhat change the formulation of the task and assign it to the agent ***B*** again. Thus, based on such an architecture, it is possible to provide a feedback between individual project procedures in the iCAD software.

In order to implement a high-level logic of the design process control (alternative design scenarios), coordination of IA group operations in the multi-agent environment can be performed by introducing coordinating agents into the vertical double-pass architecture as illustrated in Fig. 4, ***a***. In such a case, it is convenient to represent a general architecture of the multi-agent environment as a tree (Fig. 4, *b*). The coordinating agents are placed on the upper levels of the tree, and the IAs performing specific design tasks are placed in it branches.

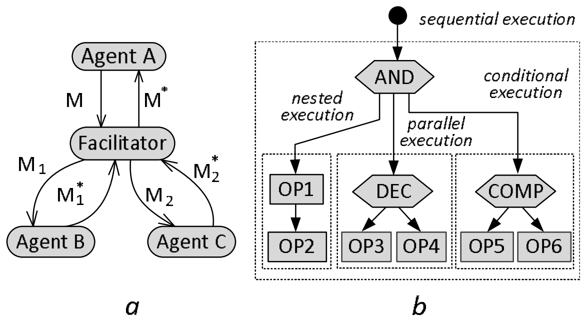

Fig. 4. Multi-agent coordination: a – facilitator agent b – example of MAS architecture with coordinating agents.

In the first place, the coordinating agents can implement the logic of sequential fulfilment of design procedures (AND), parallel fulfilment of design procedures (DEC), and multi-variant design (COMP).

The activity of coordinating agents can be described in terms of input and output information flows, child and parent agents. For example, the agent of parallel execution (DEC) based on the assigned decomposition function ***dec***, decomposes the IMDO graph into several parts, which are assigned to the child agents, and returns the combined result of their actions to the parent agent:

$$dec(M) \to M = M_1 \cup M_2, M_1 \cap M_2 = \varnothing; \quad (5)$$
$$M^* = M_1^* \cap M_2^*.$$

4. Agent-environment model: multi-aspect information model of electric power distribution system

An information model of the design object (in our case it is EPDS) is the focus of the iCAD software. From the perspective of SmartGrid technologies, to describe the EPDS elements and interrelations between them, the most widely used standard is that of IEC 61970-301: The Common information model [7]. This standard is suitable for describing a functional aspect of EPDS, but does not describe secondary aspects of electric power systems that are significant in the traditional computerized design methodology. The multi-aspect information model of EPDS is proposed to be used as the first step to create iCAD software based on the ontology approach. Its program implementation includes meta-ontology and domain ontology (Fig. 5, *a*).

Meta-ontology describes the most general concepts, which do not depend on a specific subject area. The structure of current meta-ontology is given in the form of a class diagram using the UML. Its structure includes the classes that describe the following aspects of a technical system: functional, structural, technological and organizational.

The functional aspect represents a set of items, the way of their connectins, and a list of parameters and limitations. The structural aspect describes a structural performance of the elements in a physical space (geometry and location). The technological aspect describes types, sequence of the required operations and a list of resources required for this purpose. The organizational aspect describes the amount of resources required during the EPDS operation cycle.

Domain ontology is implemented by creating corresponding examples of meta-ontology classes. The structure of domain ontology is presented in Fig. 5, *b*. It includes six levels and describes technical and information infrastructures of an electric power system.

The first level of such domain ontology consists of an EPDS block-diagram that describes its energy infrastructure in the most general way. The second and third levels contain a one-line diagram and an electrical connections diagram, which provide the block-diagram of the first level with further details. The fourth level includes functional diagrams of the systems of electric substations' (CP&MS protection, monitoring and control. The fifth level provides a description of centralized supervisory control and data acquisition (SCADA).

A combination of the EPDS information model aspects and levels forms blocks. Each block has a defined way of visualizing in a convenient for a designer form (block-diagrams, drawings, tables, etc.). Considering that the EPDS information model is seamless (its ontological graph is connected), it is possible to create a multi-aspect visualization subsystem.

Its principle is in the fragmented representation of the design object image in various blocks with the ability of fast navigation between different blocks within the EPS information model in the directions of levels and aspects. For the design process to be formalized and automated, a multi-agent system for the conceptual design of EPDS has been developed.

5. Multi-agent architecture of iCAD for electric power distribution system

The structure and content of the proposed multi-agent system are depicted as a tree in Fig. 6. The roles and responsibilities concerning some design procedures of the existing computerized methodology are distributed among IAs in the multi-agent system.

The agents are organized in three groups. This corresponds to the following design stages: forming input data, conceptual design, and preparing design documentation.

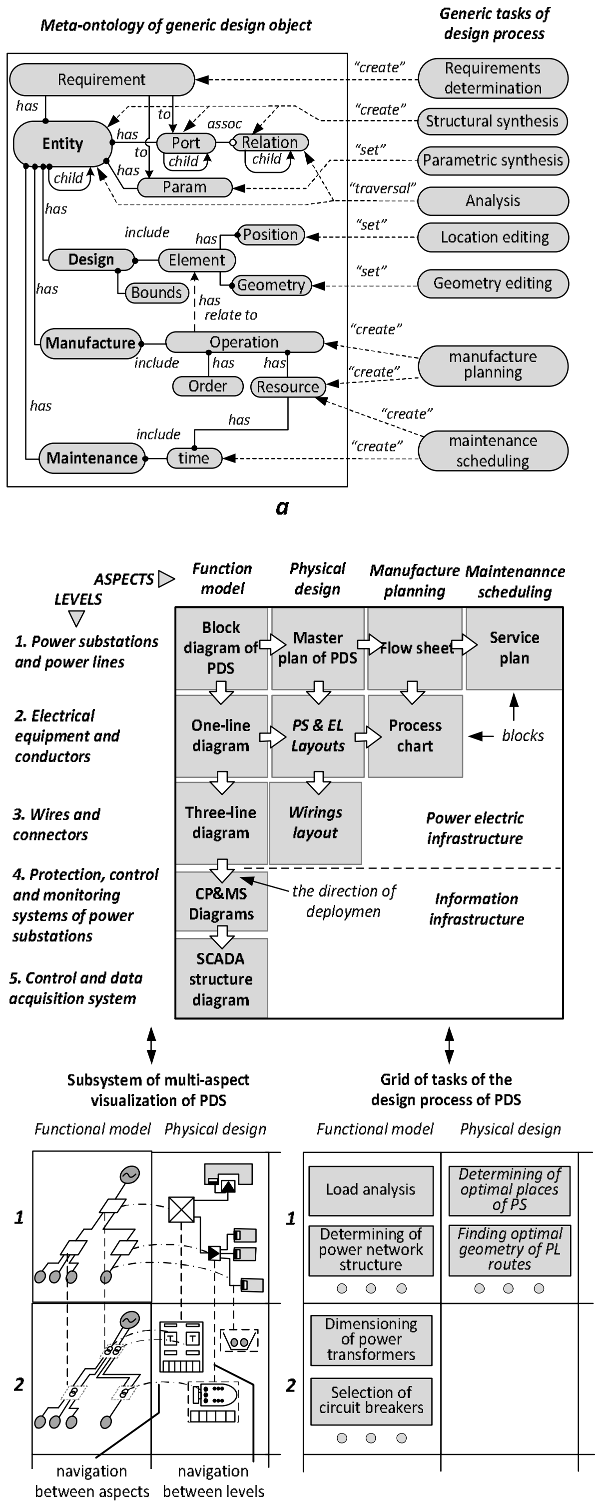

Fig. 5. Multi-aspect information model of electric power distribution system: a – class diagram of meta-ontology, b – structure and deployment of domain ontology.

At the first stage, the group of ***IA*1-*IA3*** via a user's interface in a dialogue form delegates the development of input information to a design engineer. The design engineer enters the information on electric power consumers and possible power sources, and represents them on the master plan. The design engineer also prepares a list of requirements and restrictions to EPDS as a whole. The results of this stage correspond to the formation of the initial state of IMDO ($M^{(o)}$).

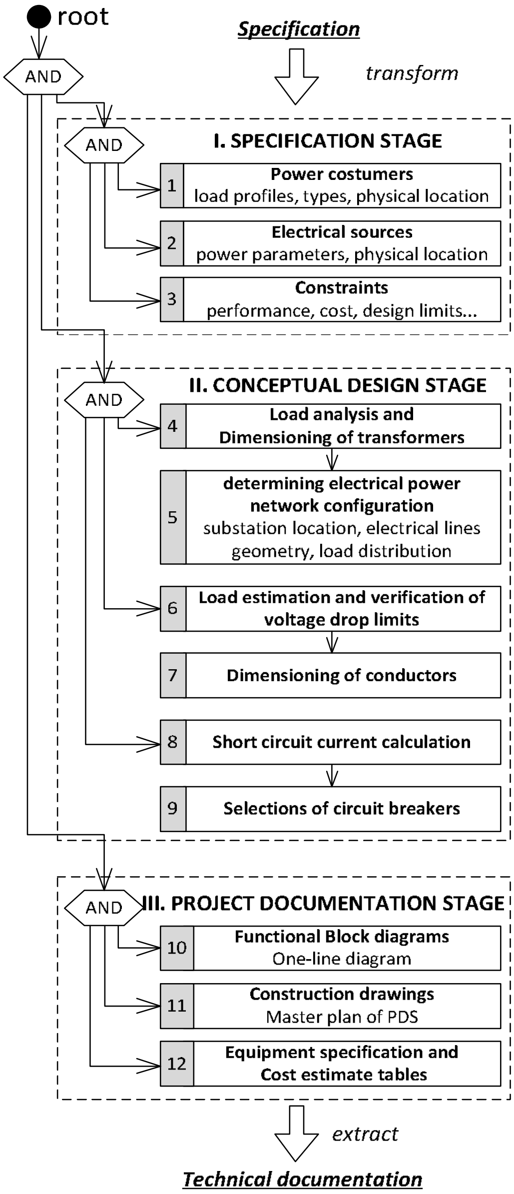

Fig. 6. Structure of MAS for conceptual design of an electric power distribution system.

The second stage is performed in semi-automatic mode. For the duration of (During) this stage, IMDO is expanded (getting detailed and complemented) from the initial state ($M^{(o)}$) with the help of ***IA4-IA9.*** Here, the participation of a design engineer is limited to the supervision of the design process and, if necessary, to making strategical project decisions which cannot be formalized in principle. At this stage, it is possible to perform multi-variant design scenarios with the presence of coordinative agents of multi-variant design. The result of this stage is a comprehensive image of the design object ($M^{(k)}$).

At the third stage, ***IA10-IA12*** traverse a graph and extract required information resulting in preparing, in the form acceptable for a design engineer, the detailed design documentation which contains functional diagrams, construction drawings, equipment specifications, and an estimate of costs.

6. Software implementation of the multi-agent iCAD for electric power distribution systems

Software implementation of iCAD for EPDS is performed using the C++ programming language and is based on a three-layer architecture (Fig. 7), which includes: a data layer, a business logic layer, and a presentation logic layer.

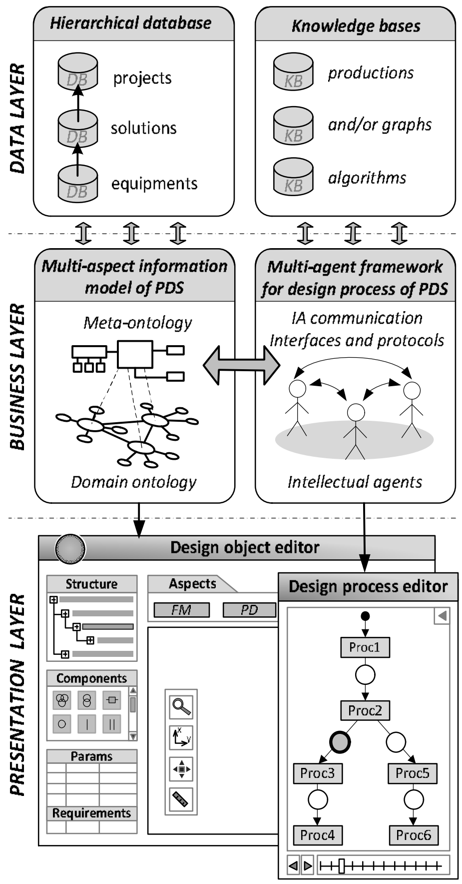

Fig. 7. Software architecture of iCAD of an electric power distribution system.

The business logic layer is formed from the subsystems of the EPDS multi-aspect information model and multi-agent framework of EPDS automation. The ontological approach described in Section 4 is the basis for implementing the multi-aspect EPDS information model. The implementation of the multi-agent framework is based on the interface protocol and approaches to IA coordination explained in Section 3. The multi-agent framework solves the problems of unified software interfaces and protocols of interaction between dissimilar design subsystems (CAD/CAM/CAE) and IA with different knowledge databases. This allows removal and addition of individual IAs without affecting the organization of the entire system.

The multi-aspect information model of EPDS implements the format of a unified representation of the subject area concepts, allowing the use of the common principles for various types of databases involved in projects, technical solutions, electrical equipment and other information, related to the design. The presentation logic layer is based on the interactive interface of a user.

At the user interface level, the structure of a multi-agent system can be represented in the form of a project tree that describes not only a static scheme of the design process, but also reflects its dynamics by visualizing an active IA, as well as the state of the design object at any given point of time.

From the user's point of view, EPDS iCAD intensifies a creative activity of a design engineer by organizing his or her optimal interaction with the design system. The EPDS iCAD eliminates the need for manual formation of input and output information linking various design subsystems. This provides an efficient way to perform a functional analysis and economic evaluation of the project.

From the developer's point of view, the multi-agent approach to the EPDS iCAD software provides such high software quality characteristics as scalability, flexibility and enhanceability in comparison with the traditional CAD systems. This in turn can significantly reduce the cost of the development and support of iCAD software that will assure its economic benefits.

7. Conclusions

1) The conceptual principles for the creation and implementation of software for intellectual computer aided design based on the multi-agent approach has been developed for the first time.

2) A multi-aspect information model of EPDS has been created.

3) A multi-agent iCAD of EPDS has been developed and implemented.

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ФОРМАЛІЗАЦІЯ ПРОЦЕСУ ПРОЕКТУВАННЯ ЕЛЕКТРОПОСТАЧАЛЬНИХ СИСТЕМ НА ПІДСТАВІ МУЛЬТИАГЕНТНОГО ПІДХОДУ

Андрій Парфенюк, Петро Гоголюк, Ілля Ґрінберґ

Викладено концептуальні засади формалізації процесу проектування електропостачальних систем на засадах мультиагентного підходу. Вибрано архітектуру мультиагентного середовища, описано протоколи взаємодії та способи координації інтелектуальних агентів. На підставі онтологічного підходу сформовано мультиаспектну інформаційну модель електропостачальної системи. Здійснено програмну реалізацію інтелектуальної системи проектування електропостачальних систем.

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