UDC 004:005=111

D.A. Tyzhnenko, A.V. Vasilyeva, P.M. Valov, V.V. Potekhin

INTELLIGENT INFORMATIONAL-MEASURING SYSTEM FOR MONITORING AND OPTIMIZATION OF POWER CONSUMPTION

An intelligent informational-measuring system for monitoring and optimization of power consumption was developed for the use by housing and communal services.

AUTOMATED INFORMATIONAL-MEASURING SYSTEM FOR ACCOUNTING OF POWER CONSUMPTION; AUTOMATED SYSTEM FOR ACCOUNTING AND CONTROL OF POWER RESOURCES; INTELLIGENT INFORMATIONAL-MEASURING SYSTEM; INTELLIGENT EQUIPMENT FOR ACCOUNTING OF POWER RESOURCES; ANALYSIS AND OPTIMIZATION OF POWER CONSUMPTION.

Д.А. Тыжненко, А.В. Васильева, П.М. Валов, В.В. Потехин

ИНТЕЛЛЕКТУАЛЬНАЯ ИНФОРМАЦИОННАЯ СИСТЕМА МОНИТОРИНГА И ОПТИМИЗАЦИИ ПОТРЕБЛЕНИЯ ЭНЕРГОРЕСУРСОВ ДЛЯ ЖИЛИЩНО-КОММУНАЛЬНОГО ХОЗЯЙСТВА

Разработана интеллектуальная информационная система мониторинга и оптимизации потребления энергоресурсов для жилищно-коммунального хозяйства.

АВТОМАТИЗИРОВАННАЯ ИНФОРМАЦИОННО-ИЗМЕРИТЕЛЬНАЯ СИСТЕМА УЧЕТА ЭНЕРГОПОТРЕБЛЕНИЯ; АВТОМАТИЗИРОВАННАЯ СИСТЕМА КОНТРОЛЯ И УЧЕТА ЭНЕРГОРЕСУРСОВ; ИНТЕЛЛЕКТУАЛЬНЫЕ ИНФОРМАЦИОННО-ИЗМЕРИТЕЛЬНЫЕ СИСТЕМЫ; ИНТЕЛЛЕКТУАЛЬНЫЕ УСТРОЙСТВА УЧЕТА ЭНЕРГОРЕСУРСОВ; АНАЛИЗ И ОПТИМИЗАЦИЯ ЭНЕРГОПОТРЕБЛЕНИЯ.

The project task was to develop an informational-measuring system for monitoring and accounting of power consumption and a decision support system for power resource optimization and increase of power efficiency in economy of municipal formations and communal services. The work was achieved through an international cooperation with a scientific research organization from the Republic of South Africa (RSA). The final product is an intelligent informational-measuring system which is used to obtain complete information about the parameters of power consumption. After that the collected information is analyzed for decision support of power use optimization at the farm level (in the RSA), on the one hand, and at the level of small-scale enterprises and management companies (in the Russian Federation), on the other hand.

One of the priorities of the energy strategy is the social orientation in the fuel-power complex development, or, in other words, the increase in level of the population life. At the same time, new market conditions do not emphasize large-scale raise of power source production rate, but more efficient ways of power utilization, which is saving. The support of power infrastructure is carried out by the private management company or the homeowner's association (the HOA). Private households, such as country houses, cottages, town houses, flats, as well as small and middle-size business enterprises, may act as individual consumers [1—3].

Thus, there are two levels of influence upon infrastructure:

level of management company;

separate households owned by private individual.

Let us consider an organization as a system. The system power consumption is formed of the following major items: power consumption by the infrastructure of the system, power consumption for public purposes, power utilization by individual consumers and losses that appear during transfer of electric power:

$$E_{\text{syst}} = E_{\text{infr}} + E_{\text{pp}} + E_{\text{ic}} + E_{\text{losses}}, \quad (1)$$

where E_{syst} – total power consumption by the system, kilowatt-hour (kwh); E_{infr} – power consumption for infrastructure support, kwh; E_{pp} – power consumption for public purposes, kwh; E_{ic} – power consumption by individual consumers, kwh; E_{losses} – electric power losses, kwh.

Optimization problem of power consumption can be put in two ways: either minimization of power consumption or cost of power minimization.

All systems of parameter acquisition and control are built according to the same principles. First of all, it is the acquisition of equipment parameters, which are usually presented as electrical signals. After that data are recorded. Finally, the identification of inadmissible parameters is performed followed by a corresponding indication or elaboration of control action. The acquisition system of flow data consists of hardware connected to the technological setting and software, which realizes procedures for recording and storing the acquired data, including error handling and control of characteristics values. In case of multiple settings hardware items may be duplicated, therefore every hardware item receives a unique identification number or address [4–8].

The multiagent approach was proposed as a method of power distribution control.

Multiagent systems can be successfully applied to solving various control problems. These systems can be viewed as a set of intelligent agents that can interact with each another. The effective work organization is gained by development and implementation of algorithms, which allows a group of agents to fulfill tasks, which cannot be fulfilled by agents individually.

The situation at a point of time t_i is formed by states of all system variables which they have at a point t_i and which they had in the past (at points of time $t_j, j \in \{0, ..., i-1\}$). The situation may also be defined as a logical term that is made of a starting situation (usually defined as S_0) and all situation, which result from the starting situation through application of some actions to it. The situation constitutes the fact that a combination of events is true or false at the same time in a certain place. For example, the situation S can be defined as $S = e_i \wedge \overline{e_j}$. The situation instances group into the situation classes, where $S_{CL} = \{S_\perp, S_0, ..., S_k\}$ is a set of situation classes. The situation class is a classification of situations into semantically equivalent groups. For example, the situation class S can be defined as $S = e_i \wedge (e_j \vee \overline{e_j})$, if e_j does not correspond to any of the actions that are possible in this situation class.

A group of agents can «feel» similar events by monitoring the state of the system and forming probabilistic distributions of origins for certain events and situations. An identical set of plans P, containing a special plan P_i for every situation in the class S_i is assigned to each group member. The plan $P_\perp$, that corresponds to the class $S_\perp$, forms a situation, when all agents in the group do not react to events. Plans are organized into a hierarchy. At the top level of the hierarchy are the most common situations, whereas specific situations are at the bottom levels of the tree structure.

Function $U : P \times S_{CL} \to R$ defines usefulness of a plan execution command for a situation class. As a situation class is unique for all system positions in the working environment (WE) and does not depend on other locations, we can consider only one position of the system in the WE. Therefore, in order to simplify mathematical notation, we delete, where it is possible, the index, that is responsible for the location of the system in the WE. Thus, the function U must satisfy the following constraints:

$$s \in S_i \text{ and } s \in S_j \text{ and } S_i \subseteq S_j \to U(P_i, S_i) \geq U(P_j, S_i); \quad (2)$$

$$s \notin S_i \text{ and } s \in S_j \text{ and } S_i \subseteq S_j \to U(P_i, S_j) < U(P_j, S_j); \quad (3)$$

$$U(P_\perp, S_\perp) = 0. \quad (4)$$

Let R denote a group of N autonomous agents R_j $(j = \overline{1, N})$, , which cooperate in a specified environment E. State of each agent $R_j(t) \in R(j = \overline{1, N})$ at the time instant t is defined by the following vector-function:

$$R_j(t) = [r_{1,j}(t), r_{2,j}(t), \ldots, r_{h,j}(t)]^T, \quad (5)$$

where $r_{i,j}(t)$ $(i = \overline{1,h})$ are state variables of agent j.

The state of an agent group is obtained by the following vector-function:

$$R(t) = (R_1(t), R_2(t), \ldots, R_N(t)). \quad (6)$$

State of the WE around agent j at the time instant t is obtained by the following equation:

$$E_j(t) = [e_{1,j}(t), e_{2,j}(t), \ldots, e_{w,j}(t)]^T, \quad (7)$$

where $e_{i,j}(t)$ $(i = \overline{1,w})$ are parameters of the environment that surrounds agent j.

Hence, state of the WE, where intelligent agent operate at the time instant t, provided that the environment is stationary, is defined by the following expression:

$$(t) = (E_1(t), E_2(t), \ldots, E_N(t)). \quad (8)$$

If agents are absent, then $E_i(t) = E_i =$ $=$ const.

The WE and agents, cooperating within the WE, together comprise a system called the «agents-environment group». State of the «agents-environment group» system at a time instant t can be viewed as a system state, defined by a couple $S_c = (R, E)$.

States of the «agents-environment group» system can be described as points in a $(N(h+w))$ – dimensional state space $\{S_c\}$. The initial system state can be considered as the situation $S_c^0 = (R^0, E^0)$, that is defined by the following vector-functions:

$$R^0 = R(t_0), E^0 = E(t_0), \quad (9)$$

which corresponds to the time instant t_0 of the work start of the agent group. Thereafter the final state of the system is denoted as $S_c^f = (R^f, E^f)$ and is described by the following expressions:

$$R^f = R(t_f), E^f = E(t_f), \quad (10)$$

which corresponds to the time instant t_f of the end of work of the agent group.

The «agents-environment group» state at a present instant t' is called the current system state. This state $S_c^{t'} = (R^{t'}, E^{t'})$ is defined by the following equations:

$$R^{t'} = R(t'), E^{t'} = E(t'), \quad (11)$$

which corresponds to the current time instant t'.

A group of agents R is acting somehow translating the system from the initial state into the ending state. It is assumed, that every agent $R_j \in R$ $(j = \overline{1,N})$ is capable of performing some actions that can be described by the following vector-functions:

$$A_j(t) = [a_{1,j}(t), a_{2,j}(t), \ldots, a_{m,j}(t)]^T. \quad (12)$$

A set of actions that are available for the agent $R_j \in R$ can be described as points in a m-dimensional action subspace $\{A_j\}$.

A set of actions that can be executed by a group of agents is the union of all actions that can be executed by each agent individually

$$\{A_c\} = \{A_1\} \cup \{A_2\} \cup \ldots \cup \{A_n\}. \quad (13)$$

A set of actions $A_j(t)$ that is necessary to achieve the common goal for a group of agents is the control action of the agent group R. Actions that are executed by a group of agents at the time instant t can be described by the following expression:

$$A_c(t) = (A_1(t), A_2(t), \ldots, A_N(t)). \quad (14)$$

Changes in the state of the system can be described by a system of differential equations of the following form:

$$S_c(t) = f_c(S_c(t), A_c(t), g(t), t). \quad (15)$$

In this case, states and actions of the agent group can be constrained as follows (in general case):

$$S_c(t) \in \{S_c^p(t)\} \subset \{S_c\}, \quad (16)$$

where $\{S_c^p(t)\}$ is a set of admissible states of the system «agents-environment group» at the time t, and

$$A_c(t) \in \{A_c^p(t)\} \subset \{A_c\}, \quad (17)$$

where $\{A_c^p(t)\}$ is a set of admissible actions of the system «agents-environment group» at the time t.

Taking into consideration the above definitions, the control task of the agents group comes to finding in a time interval $[t_0, t_f]$ such actions $\overline{A_j}(t)$ for every agent $R_j \in R$ that satisfies the system of relations (15), initial conditions (9), final conditions (10), constraints (16), (17) and an extreme is provided for the functional:

$$Y_c = \Phi(S_c^f, t_f) + \int_{t_0}^{t_f} F(S_c(t), A_c(t), g(t), t)dt, \quad (18)$$

$$Y_c = \Phi(R_1^f, R_2^f, \ldots, R_N^f, E^f, g(t_f), t_f) + \Psi, \quad (19)$$

$$\Psi = \int_{t_0}^{t_f} F(R_1(t), R_2(t), \ldots, R_N(t), E(t), A_1(t), A_2(t), \ldots, A_N(t), g(t), t)dt, \quad (20)$$

which defines the goal of agents group work and quality of control process.

Actions $\overline{A_j}(t)$ $(j = \overline{1, N})$ are optimal for the group of agents R to achieve the common goal.

It is obvious, that existence of the condition for the control action, that translates the system from one state to the other, is not enough to execute a control problem of a group of agents, which works in a dynamic nondeterministic environment. It is also necessary for the control action to be found within such a short interval that guarantees the system state $S_c(t) = (R(t), E(t))$ does not considerably change it. Therefore, in addition to the system agents state and the action constraints there must be specified time constraints, which determine the amount of time available for the search of action $\overline{A_j}(t)$ $(j = \overline{1, N})$. Put it another way, a condition $t_p \le \tau_p$ must be satisfied, where t_p is the necessary time for the search of the control action, and τ_p is the maximum time that is allotted for the search of the control action. Time τ_p depends on many factors. Firstly, it depends on the speed of the processes that take place in the environment. Secondly, the maximum time τ_p depends on the state changes of the agents group. Finally, changes in the environment influence the maximum possible time for searching for the control action. An agent group is called controlled if there is such a solution to the problem of a group control which described above. It can be found in time $t_p \le \tau_p$ [9]

The developed multiagent system for the control of power consumption and distribution, just as a physical system of the power distribution, holds a hierarchical structure. At the root of the structure there is a management company, which performs monitoring of the whole system and controls its work. Nodes of the next levels of the structure are responsible for power distribution from the management company to the private consumers of the power. In the following individual consumers of the electric power are located from the root level of the hierarchy. The alternative power can be supplied at any level of the system structure, starting from the power distributing management com-

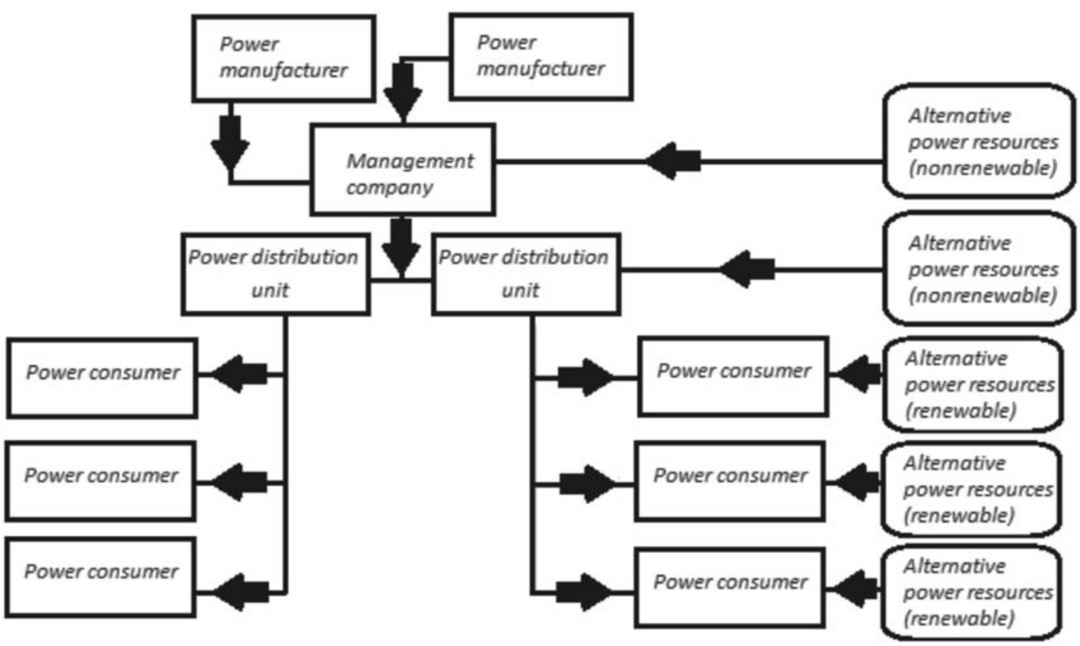

Fig. 1. Hierarchical structure of the system

pany and finishing at the individual consumers level. Trunk electricity is provided only through the management company, which is distributed between all other system members (Fig. 1).

The hierarchy of the multiagent system is almost tree-like with the only difference of additional channels of power transfer between direct descendants of one agent. The extra channels are used either to balance the volume of the power or as reserved transfer channels in case of failure of the main power channels.

The WE of the system is deterministic. The actions of the agents in the environment have a fixed effect and there is no need for an agent to check the steps of its action or to check the fullness of the action every time, when a certain action has been performed.

Moreover, the WE of the system is dynamic, so it can be changed not only by actions of the agents, but also by external forces. Dynamism of the system is shown through appearance of random disturbances in the work of the system, such as the outage of power channels and agents.

Furthermore, the WE of the system is continuous. Thus, the system has an infinite number of states, and it complicates the functioning of the agents. This problem is solved by the approximation of an infinite number of states into a finite set of states that can be perceived by agents in the system.

Finally, the WE is a real-time environment, therefore time characteristics of the system are the key features that are considered while estimating both agents and the whole systems efficiency. During the work of the system time constrains are imposed on the agents response time and on the query time [10].

In the given multiagent system the following agent roles can be singled out:

power manufacturer;

access point to the electricity trunk;

alternative nonrenewable power manufacturer;

alternative renewable power manufacturer;

power distributor;

local area network (LAN) switch;

metropolitan area network (MAN) switch;

power consumer.

The structure of the intelligent agent depends a lot on the roles that are assigned to it during the system development. Every intelligent agent possesses only hardware for the control. In this project control hardware is based on the industrial programmable logical controllers (PLC), manufactured by Siemens. The PLC models in use are Simatic S7-200/300/400.

All agents have the identical basic structure and functionality (Fig. 2). On the one hand, every agent is capable of decision making and can forecast its future volumes of power consumption. On the other hand, the agents can execute different actions depending on their place in the system hierarchy.

System can be divided into two main parts: central control body (CCB) and agents. Every agent cooperated with the local PLC and with the CCB. Agents basically read data from PLC and send it to the main system. Moreover, they have a local database for data storage. The

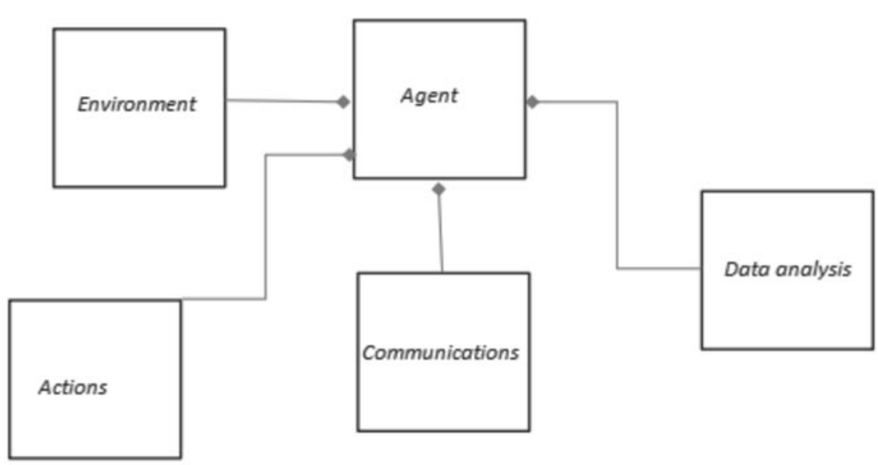

Fig. 2. Basic agent structure

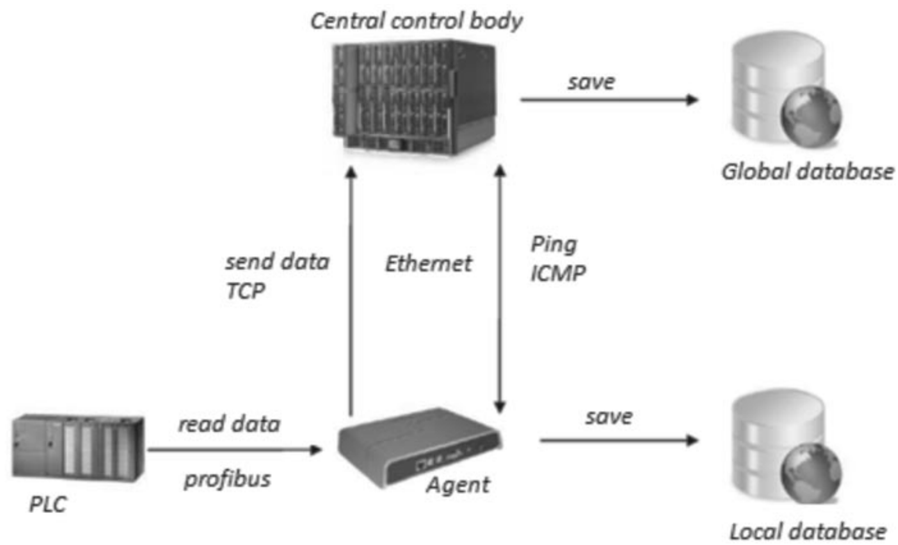

Fig. 3. General structure of an agent

general structure of the agent is depicted in Fig. 3.

The central control body receives data from the agents and stores them in a global database. In addition to this, CCB can check for the link to the agents and can produce reports about possible errors.

The agents as well as the central control body were developed in C# programming language, hence the target platform is the Windows operating system (OS). Nevertheless, it is also possible to use a Linux system provided the specific software called Mono is installed. It allows to run extern C# programs under Linux OS. Communication programming was achieved through Zero Message Queue (0MQ) platform for TCP utilization and with the use of LIBNODAVE library for communication with PLC. The user interface was developed in CSS-framework TwitterBootstrap.

The decision support system structure is presented in Fig. 4. The user of the electric power (operator) interacts with the system via a mobile application or a web-interface and, after the operator the information has been processed by the analyst, he or she receives feedback with

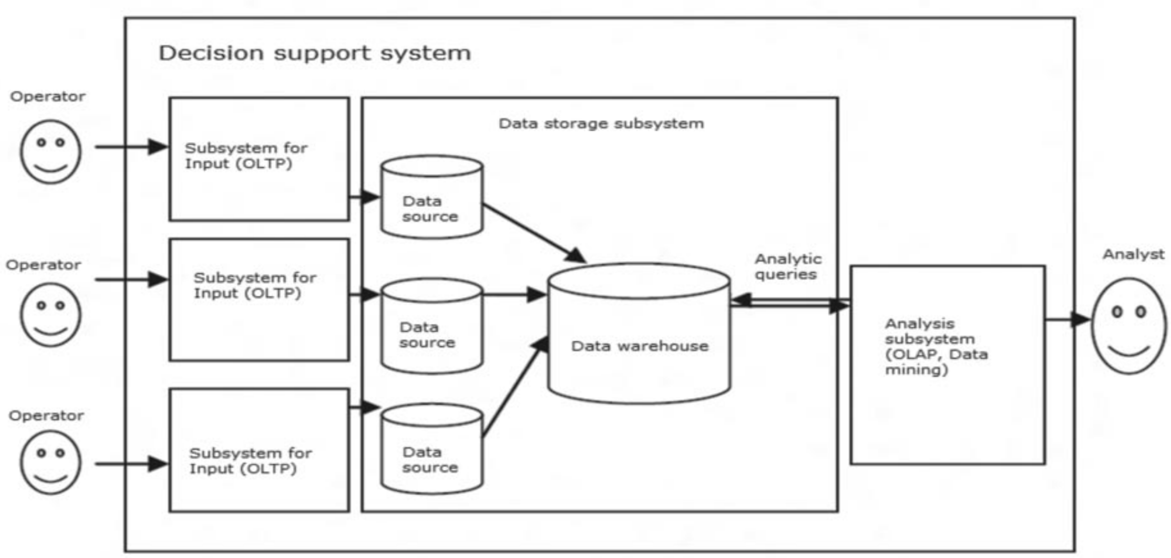

Fig. 4. Decision support system

possible solutions that are directed to minimize the overall payment for electricity.

There are a few interfaces available in the system for the end user:

add/edit device record;

add power consumption data;

report settings (visualization settings);

power consumption reports;

forecast of power consumption/saving.

Development and introduction of the intelligent informational-measuring system for monitoring and optimization of power consumption, which can control distribution, consumption and accounting of electric power, is a promising task.

Within the project we conducted experiments, completed the test bed and patented it as a know-how.

REFERENCES

1. **Wenzel T.P.** Energy Data Source Book for the U.S. Residential Sector, Sept. 1997.
2. **Denisenko V.V.** Kompyuternoye upravleniye tekhnologicheskim protsessom, eksperimentom, oborudovaniyem. Moscow: Goryachaya liniya – Telekom Publ., 2009, 608 p. (rus)
3. **Mylnikov L.A.** Mikroprotsessornyye sistemy sbora i obrabotki dannykh dlya avtomatizatsii kontrolya bystroizmenyayushchikhsya parametrov tekhnologicheskikh protsessov. Perm: PGTU Publ., 2009. (rus)
4. **Barsegyan A.A., Kupriyanov M.S., Stepanenko V.V., Kholod I.I.** Tekhnologii analiza dannykh: Data Mining, Visual Mining, Text Mining, OLAP. St. Petersburg: BKhV-Petersburg Publ., 2008. (rus)
5. **Codd E.F., Codd S.B., Salley C.T.** Providing OLAP (on-line analytical processing) to User-Analysts: An IT mandate. Technical Report, 1993.
6. **Larson B.** Razrabotka biznes-analitiki v Microsoft SQL Server 2005, per. s angl. Moscow: Piter Publ., 2008, 688 p. (rus)
7. **Berger A., Gorbach I.** Microsoft SQL Server 2005 Analysis Services: OLAP i mnogomernyy analiz dannykh. St. Petersburg: BKhV-Petersburg Publ., 2007, 908 p. (rus)
8. Process Automation Handbook. London: Springer, 2007, pp. 351–363.
9. **Loginov A.L., Potekhin V.V., Akulov D.V., Khritonenkov A.K., Poletayev I.G.** Intellektualnaya sistema upravleniya avtonomnoy vetroelektrostantsiyey. *Nauchno-tekhnicheskiye vedomosti SPbGPU. Informatika. Telekommunikatsii. Upravleniye.* St. Petersburg: SPbGPU Publ., 2013, No. 5(181), pp. 50–57. (rus)
10. **Shkodyrev V.P.** Innovatsionnyye tekhnologii v zadachakh upravleniya bolshimi raspredelennymi sistemami. *Nauchno-tekhnicheskiye vedomosti SPbGPU. Nauka i obrazovaniye. Ustoychivoe razvitie i energetika.* St. Petersburg: SPbGPU Publ., 2012, No. 3-1(154), pp. 73–77. (rus)

СПИСОК ЛИТЕРАТУРЫ

1. **Wenzel T.P.** Energy Data Source Book for the U.S. Residential Sector. Sept. 1997.
2. **Denisenko V.V.** Компьютерное управление технологическим процессом, экспериментом, оборудованием. М.: Горячая линия–Телеком, 2009. 608 с.
3. **Мыльников Л.А.** Микропроцессорные системы сбора и обработки данных для автоматизации контроля быстроизменяющихся параметров технологических процессов. Пермь: Изд-во ПГТУ, 2009.
4. **Барсегян А.А., Куприянов М.С., Степаненко В.В., Холод И.И.** Технологии анализа данных: Data Mining, Visual Mining, Text Mining, OLAPM. СПб.: БХВ-Петербург, 2008.
5. **Codd E.F., Codd S.B., Salley C.T.** Providing OLAP (on-line analytical processing) to User-Analysts: An IT mandate. Technical Report. 1993.
6. **Ларсон Б.** Разработка бизнес-аналитики в Microsoft SQL Server 2005. Пер. с англ. М.: Питер, 2008. 688 с.
7. **Бергер А.** Microsoft SQL Server 2005 Analysis Services: OLAP и многомерный анализ данных. СПб.: БХВ-Петербург, 2007. 908 с.
8. Process Automation Handbook. London: Springer, 2007. С. 351–363.
9. **Логинов А.Л., Потехин В.В., Акулов Д.В., Хритоненков А.К., Полетаев И.Г.** Интеллектуальная система управления автономной ветроэлектростанцией // Научно-технические ведомости СПбГПУ. Информатика. Телекоммуникации. Управление. СПб.: Изд-во СПбГПУ, 2013. № 5(181). С. 50–57.
10. **Шкодырев В.П.** Инновационные технологии в задачах управления большими распределенными системами, Научно-технические ведомости СПбГПУ. Наука и образование. Устойчивое развитие и энергетика. СПб.: Изд-во СПбГПУ, 2012. № 3-1(154). С. 73–77.

TYZHNENKO, Denis A. *St. Petersburg State Polytechnical University.*
195251, Polytekhnicheskaya Str. 21, St. Petersburg, Russia.
E-mail: tyzhnenkod@mail.ru

ТЫЖНЕНКО Денис Александрович – *студент кафедры систем и технологий управления Санкт-Петербургского государственного политехнического университета.*
195251, Россия, Санкт-Петербург, ул. Политехническая, д. 21.
E-mail: tyzhnenkod@mail.ru

VASILYEVA, Anastasiia V. *St. Petersburg State Polytechnical University.*
195251, Polytekhnicheskaya Str. 21, St. Petersburg, Russia.
E-mail: vasilyeva.anastasia@bk.ru

ВАСИЛЬЕВА Анастасия Владимировна – *студентка кафедры систем и технологий управления Санкт-Петербургского государственного политехнического университета.*
195251, Россия, Санкт-Петербург, ул. Политехническая, д. 21.
E-mail: vasilyeva.anastasia@bk.ru

VALOV, Pavel M. *University of Waterloo.*
200 University Ave. West Waterloo, ON, Canada N2L 3G1.
E-mail: valov.pm@gmail.com

ВАЛОВ Павел Михайлович – *аспирант кафедры David R. Cheriton School of Computer Science University of Waterloo, магистр.*
N2L 3G1Canada, ON, Waterloo, 200 University Ave. West.
E-mail: valov.pm@gmail.com

POTEKHIN, Vyacheslav V. *St. Petersburg State Polytechnical University.*
195251, Polytekhnicheskaya Str. 21, St. Petersburg, Russia.
E-mail: slava.potekhin@gmail.com

ПОТЕХИН Вячеслав Витальевич – *доцент кафедры систем и технологий управления Санкт-Петербургского государственного политехнического университета, кандидат технических наук.*
195251, Россия, Санкт-Петербург, ул. Политехническая, д. 21.
E-mail: slava.potekhin@gmail.com