Hybrid intelligent multiagent model of heterogeneous thinking for solving the problem of restoring the distribution power grid after failures

Alexander Kolesnikov
Immanuel Kant Baltic Federal University
Kaliningrad Branch of the Federal Research Center
“Computer Science and Control“
of the Russian Academy of Sciences
Kaliningrad, Russia
avkolesnikov@yandex.ru

Sergey Listopad
Kaliningrad Branch of the Federal Research Center
“Computer Science and Control“
of the Russian Academy of Sciences
Kaliningrad, Russia
ser-list-post@yandex.ru

***Abstract*—Problems arising in such dynamic environments as regional power grid have the following features: partial observability, high dimensionality of the state space, interconnection and dependence of solutions on each other, which do not allow correcting the erroneous solution in the future. Abstract-mathematical models are limited and irrelevant to such dynamic environments. For this reason teams of experts of various specialties or their computer models are involved, but even they do not always successfully solve emerging problems. The success of the team depends largely on the ability of the decision maker to organize the process of heterogeneous collective thinking, the diagnosis of collective effects, the problems of group behavior and to choose corresponding model of collective reasoning. Under the conditions of time constraints in practice, it is not possible to organize such a comprehensive collective problem solving process. In this regard, the paper proposes the formalized model and the basic algorithms of a new class of intelligent systems, namely hybrid intelligent systems of heterogeneous thinking. Their main feature is modeling of the discussion management in the expert team by the facilitator with heterogeneous collective thinking methods. These methods will allow the agent modeling facilitator's actions to organize communication and diagnostics of collective effects, problems and adjustment of group behavior, ensuring the relevance of the system to conditions of dynamic directly unobservable environments.**

***Keywords*—heterogeneous thinking; expert team; hybrid intelligent multiagent system**

I. Introduction

If there is a failure in the distribution power grid, the rate of power supply restoration is critical [1], [2]. In order to reduce economic and social losses, the majority of energy supplying organizations develop guidelines and operational procedures for the restoration of power supply. Such guidelines are created based among other on the results of the analysis of previous accidents by expert teams from power engineering organizations, representatives of design institutes who have developed the generation and power grid complex of the organization, as well as representatives of manufacturers of the equipment being operated [3]. The guidelines regulate the sequence of actions-steps of operational personnel for the restoration of power grid modes. However, the emergency conditions of the power system may differ significantly from those adopted during the development of the recovery plan, which reduces the likelihood of success of the actions, leading to unacceptable loads, voltage levels or protection systems [4]. Although, any employee can be called up to the appropriate control room by the request of the operating personnel and must arrive immediately, it is not possible to organize a comprehensive collective solution to the problem due to the limited time to make decisions.

In this regard, the development of intelligent automated systems integrating the knowledge of experts of various specialties, the coordination of several optimality criteria and the consideration of a multitude of restrictions in the context of dynamically directly unobservable environments and lack of time to make decisions are relevant. In addition, in case of technological violations at the facilities belonging to several operators or independent actions, the execution of which is assigned to substation personnel without prior dispatcher's order or permission [5], it is important to ensure a common understanding of the current emergency situation and coordinated work.

To simulate such structures for information preparation and decision-making support it is proposed to combine the hybrid intelligent approach of A.V. Kolesnikov [6], the apparatus of multiagent systems in the sense of V.B. Tarasov [7] and the methods of heterogeneous thinking [8]–[10]. The result should be a new class of intelligent systems, namely the hybrid intelligent multiagent systems of heterogeneous thinking (HIMSHT). The use of HIMSHT for information preparation of decision-making will automate the activities of operational personnel for receiving and processing information about the external environment, the state of the management system, the course of the controlled process, its analysis, modeling of the emergency situation and developing options to eliminate it by simulating collective problem solving using heterogeneous thinking methods. The result of such work is new images, visual forms with a definite semantic load [11], allowing the dispatcher team to see the problem as a whole, its solutions, forecast of the situation development in each case, to adopt an action plan of eliminating the failure and to coordinate actions in its implementation.

II. Post-emergency power grid supply restoration problem

Emergency is the state of the power grid (PG), associated with changes in the normal operation of equipment, creating the risk of an accident [12]. Emergency sites of the PG should be shut down within milliseconds, and the systems are divided into subsystems unbalanced by load and generation a few seconds later. Supplier shutdowns occur only a few minutes after division, and systems are restored a few hours or days after redemption [13]. PG restoring process is to build up its structure through time coordinating the preparation and input of many interdependent objects that have retained functionality after an emergency, as well as objects restored by personnel actions [14].

Planning for the restoration of the power system is a combinatorial problem that requires extensive knowledge, includes many constraints and conditions, which operator's estimates are necessary further complicating its integrated solution [1]. Three main features attribute this problem to especially interesting for modern planners: partial observability, dimension of the state space, which makes a complete enumeration of states absolutely impossible, the consequences of the actions are difficult to simulate [15]. There are many statements of this problem, and new recovery methods are proposed that are alternative to the commonly used procedures. Most of them consider the problem in a simplified, "game" form, because of which they stop at the stage of development of a prototype [1]. Such "game" power grid supply restoration planning (GSRP) can be represented as follows.

At GSRP, the power grid is represented by a graph $PS =< V, E >$ with three types of nodes V: the power center (supplier) $v^s \in V^s \subseteq V$, the consumer (load) $v^l \in V^l \subseteq V$, and the bus $v^b \in V^b \subseteq V$. The edges E of the graph denote electrical power lines with switches opening or closing the line. Powered lines form a radial structure, i.e. there are no cycles of power lines. The power center is characterized by the maximum generated power, the consumer is characterized by the nominal power consumption and the state (powered/disconnected), and the power transmission line is characterized by the carrying capacity (maximum transmittable power), the state (on/off) and operability (good/accident). It is required to determine which lines need to be turned on/off, and in what order, to ensure the maximum possible amount of power consumption while observing the following operational limitations: maintaining the radial structure of the powered lines; for each line, the total value of loads that are fed from the power center through it should not exceed its carrying capacity; consumers not affected by the initial shutdown should not be turned off as a result of switching.

An example of the grid in GSRP is shown in Fig. 1. As seen in the left part of the figure in the normal state, all the loads are distributed between the two power centers, and there are no rings of switched on lines. When an accident occurs in such network, three consumers, indicated by dashed arrows, are de-energized. On the bottom of the Fig. 1 a situation is shown when all three consumers cannot be powered through one feeder due to an overload. In this case, the out of service part of the power grid is divided into two parts by opening the normally closed switch. After that, it becomes possible to power de-energized consumers from different feeders of the functioning part of the network.

GSRP can be used to test optimization methods for the purpose of their subsequent coarse-grained or fine-grained hybridization to solve the real problem of power grid supply restoration planning (RSRP). Solutions obtained by GSRP problem solving methods without their hybridization are irrelevant to RSRP because of the significantly larger number of object types and their properties that must be taken into account for constructing an acceptable plan in the latter, as well as non-factors in the sense of A.S. Narinyani [16] inherent in RSRP. The need to increase the number of types of objects being modeled is associated, for example, with the impossibility of remote switching in some parts of the power grid, the presence of distributed generation and active consumers, and the need to take power grid physical processes into account. The number of Non-factors of RSRP include, for example, the following: the underdetermined nature of the accident site during recovery planning; the inaccuracy of the amount of power consumed by each client and the distributedly generated power by each source; the fuzziness of the restoration time of the power grid elements; incorrect operation of emergency mode sensors; incomplete power grid model.

Based on the analysis of the papers [1], [15], [17]–[27] devoted to the post-emergency power grid supply restoration, the model of RSRP represented by the tuple was developed:

$$RSRP =< PGE, PGR, PL, RT, RC, VH, RS, ACT >,$$

where PGE is the elements of the power grid; PGR is the set of incident relations between the elements of the

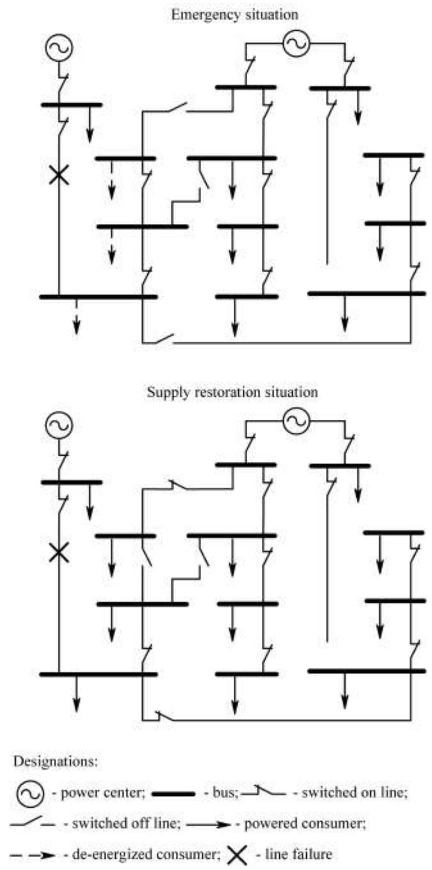

Figure 1. Examples of graphs in the “game” planning of the supply restoration

power grid; PL is the set of locations; RT is the set of routes between locations; RC is the set of repair crews; VH is the set of vehicles; RS is the set of resources to restore the power supply; ACT is the set of actions to restore the power supply. The following elements of the power grid are distinguished:

$$PGE =< PGE^{ps}, PGE^{co}, PGE^{bu}, PGE^{sw}, PGE^{pl} >,$$

where PGE^{ps} is the power source of distributed generation, PGE^{co} is the consumer, PGE^{bu} is the bus, PGE^{sw} is the switch, PGE^{pl} is the power line. The power source of distributed generation is characterized by the following properties: operability (healthy/accident), state (disconnected/connected), history of generation of active power, history of generation of reactive power, nominal voltage, parameters of the transition process at cold start, location. The consumer is characterized by the following properties (it is assumed that consumers can generate and deliver excess electricity to the grid): state (disconnected/connected), priority, history of generation and consumption of active power, history of generation and consumption of reactive power, nominal voltage, cold start transient parameters, location. A bus, a switch and a power line are characterized by the following general properties: operability, long-term allowable current, allowable transmitting active power, allowable transmitting reactive power, coefficient of allowable overload for a given time, location. A switch is additionally characterized by the following properties: switch state (on, off, or disabled with no turn on), switch type (remote/local), synchronization ability. Power line has properties: voltage loss, active power loss, reactive power loss.

Location $pl \in PL$ is the geographical coordinates and/or address of power grid element of set PGE, car depot or resource warehouse. The route $rt \in RT$ is described by the initial location, final location, travel time, the expected delay in travel in the form of statistical or fuzzy variable. The repair crew $rc \in RC$ is characterized by the following properties: the number of employees, the level of admission. The vehicle $vh \in VH$ has the following properties: the depot location, the maximum number of passengers, carrying capacity, the dimensions of the cargo compartment. Properties of resource $rs \in RS$ for the restoration of the power grid are the weight, the dimensions, and the location. The action $act \in ACT$ on the restoration of the power grid is characterized by the following properties: the object of restoration, the duration, the expected repair delay, described by statistical or fuzzy variables, the level of personnel admission, the necessary resources.

It is required to make a power grid restoration plan, which includes the sequence of turning on and off the switches, the sequence of trips of repair crews to perform switching and repair work.

Criteria for optimality of the plan are following: minimizing the shutdown time of the priority consumers, maximizing the total recovered load, maximizing the reliability of the power system (the stability of the power system to subsequent accidents).

The following restrictions apply to the plan: the preservation of the radial structure of the network of powered lines; for each line, the total value of loads that are supplied from a source of distributed generation through it should not exceed its carrying capacity; active power balance must be maintained; reactive power balance must be maintained; voltage and frequency values must be within acceptable limits; consumers not affected by the initial outage should not be turned off as a result of the switch; the repair actions must be carried out by teams that have the appropriate admission if the necessary resources are available in their vehicle; vehicle capacity is never exceeded; brigade working time is limited; vehicles must return to their depot; when forcibly dividing the grid to islands, the communication lines between the islands must have synchronization equipment for the subsequent merge of the islands.

To solve the RSRP, it is proposed to model the

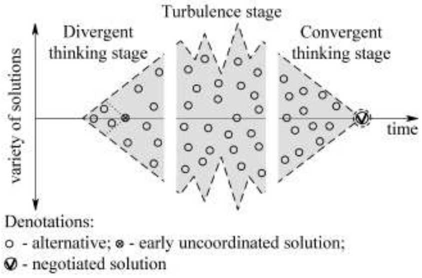

Figure 2. Rhombus of group decision making by S. Keiner, K. Toldi, S. Fisk, D. Berger

collective decision-making by the operating personnel of the energy supplying organization, power engineers, logisticians, and labor protection specialists with the HIMSHT.

III. Team decision making in power grid management

When solving new, previously not encountered problems, teamwork in general case consists of the following stages: formulation, analysis of the problem, data collection and interpretation, search for solutions, analysis of the effectiveness of solutions and final choice, presentation of results, implementation of the solution, monitoring and evaluation of results [28]. The problem solving process is superimposed on the process of forming and developing the team as a single entity. The latter consist of the stages: formation, turbulence, refinement of proposals and preparation of alternatives, decision making and disbandment [29], [30], which is consistent with team decision making model by S. Keiner, K. Toldi, S. Fisk, D. Berger (Fig. 2) [9].

At the first stage, members of the team get to know each other, exchange official information about each other, make suggestions on the teamwork, adhere to generally accepted points of view, and propose obvious solutions [30]. If the problem has an obvious solution, the discussion ends, otherwise the divergent thinking process begins, within which a non-judgmental discussion and the generation of a large number of solutions are encouraged [9]. If the team managed to go beyond the boundaries of traditional opinions, the process of discussion goes into the turbulence stage, when conflicts could arise between team members due to conflicting solutions. By conflict we will understand the situation of the disagreement of two or more experts about knowledge, belief, opinions, i.e. cognitive conflict [31]. The conflict is a distinctive feature of the turbulence stage, which allows the facilitator to take measures to develop mutual understanding and bring together the experts' points of view.

At the stage of finalizing proposals and preparing alternatives, experts formulate specific proposals from valuable ideas and "grind" them until all the discussion participants come to a final solution embodying all the diversity of points of view. This stage is characterized by "convergent thinking", i.e. the classification of ideas, their generalization, and making assessments. During decision-making and disbandment stage the team integrated problem solution is developed, taking into account the opinions of all the participants in the discussion.

The rhombus of group decision-making model can be used by the facilitator or his model to identify the current situation of decision-making and to attempt to steer the discussion in the required direction, activating the appropriate thinking style in the team.

IV. Formal model of the hybrid intelligent multiagent system of heterogeneous thinking in collective operational work

Formally HIMSHT is defined as follows:

$$himsht =< AG^*, env, INT^*, ORG, \{ht\} >,$$

$$act_{himsht} = \left(\bigcup_{ag \in AG^*} act_{ag} \right) \cup$$

$$\cup act_{dmsa} \cup act_{htmc} \cup act_{col},$$

$$act_{ag} =< MET_{ag}, IT_{ag} >, \; ag \in AG^*,$$

$$\left| \bigcup_{ag \in AG^*} IT_{ag} \right| \geqslant 2,$$

where $AG^* = \{ag_1, ..., ag_n, ag^{dm}, ag^{fc}\}$ is the set of agents, including expert agents (EA) ag_i, $i \in \mathbb{N}$, $1 \leqslant i \leqslant n$, decision-making agent (DMA) ag^{dm}, and facilitator agent (FA) ag^{fc}; n is the number of EA; env is the conceptual model of the external environment of HIMSHT; $INT^* = \{prot, lang, ont, dmscl\}$ are the elements for structuring of agent interactions: $prot$ is the interaction protocol; $lang$ is the message language; ont is the domain model; $dmscl$ is the classifier of collective solving problem situations, identifying the stages of this process (Fig. 2); ORG is the set of HIMSHT architectures; $\{ht\}$ is the set of conceptual models of macro-level processes in the HIMSHT: ht is the model of the collective problem solving process with heterogeneous thinking methods (Fig. 2); act_{himsht} is the function of the HIMSHT as a whole; act_{ag} is the function of EA from the set AG^*; act_{dmsa} is the FA's function "analysis of the collective problem solving situation"; act_{htmc} is FA's function "choice of heterogeneous thinking method"; $act_{col} =< met_{ma}, it_{ma} >$ is the collective dynamically constructed function of HIMSHT with multiagent method met_{ma} and intelligent technology it_{ma}; $met_{ag} \in MET_{ag}$ is the problem solving method; $it_{ag} \in IT_{ag}$ is the intelligent technology, with which the method met_{ag} is implemented; "$\cup$" is the union operation over tuples or sets.

To implement the FA function "analysis of the collective problem solving situation", the concepts of compatibility of the partial solutions proposed by EA, the intensity of the conflict between them, and the stage of the problem solving process are introduced. Solution compatibility cmp is problem-depended scalar function describing the possibility of simultaneous implementation of two partial solutions.

The intensity of the conflict between the two agents is based on the compatibility of the partial problem solutions offered by them:

$$cnf(ag_i, ag_j) = \sum_{k=1}^{N_i} \sum_{l=1}^{N_j} cmp(dec_k, dec_l)(N_i N_j)^{-1}, \quad (1)$$
$$r_1^{res\ res}(dec_k, ag_i) \circ r_1^{res\ res}(dec_l, ag_j),$$

where N_i, N_j are the number of private solutions found by agents ag_i and ag_j, respectively; $r_1^{res\ res}$ is the relation "to be found by" between the private solution and the agent who proposed it; "$\circ$" is the operation of gluing concepts.

The conflict intensity in HIMSHT as a whole described by the expression

$$cnf_{himsht} = \sum_{i=1}^{n} \sum_{j=i+1}^{n} 2cnf(ag_i, ag_j)(n-2)!(n!)^{-1}, \quad (2)$$

where "!" is factorial.

The conflict intensity between agents or in HIMSHT as a whole is used as a universe of the linguistic variable "conflict", which is then used in the implementation of the function "choice of heterogeneous thinking method" act_{htmc}. The linguistic variable "conflict" is represented by the expression

$$cnfl = < \beta, T, cnf, G, M >, \quad (3)$$

where $\beta =$ "$conflict$" is the name of the linguistic variable; $T = \{$"$absent$", "$minor$", "$moderate$", "$sharp$"$\}$ is the term-set of its values, i.e. the names of fuzzy variables; $cnf = [0, 1]$ is the universe of fuzzy variables; $G = \emptyset$ is the procedure for the formation of new terms using the elements of the set T; $M = \{\mu_{absent}(cnf)$, $\mu_{minor}(cnf)$, $\mu_{moderate}(cnf)$, $\mu_{sharp}(cnf)\}$ is the procedure that assigns meaningful content to each term of T by composing a fuzzy set.

The value of the character variable "stage of the problem solving process" stg, defined on the set $STG = \{$"$divergent$", "$turbulence$", "$convergent$"$\}$, is calculated according to the rules:

$$stg = \text{"}divergent\text{"} \wedge (cnfl = \text{"}moderate\text{"} \vee$$
$$\vee cnfl = \text{"}sharp\text{"}) \rightarrow stg = \text{"}turbulence\text{"}, \quad (4)$$
$$stg = \text{"}turbulence\text{"} \wedge (cnfl = \text{"}absent\text{"} \vee$$
$$\vee cnfl = \text{"}minor\text{"}) \rightarrow stg = \text{"}convergent\text{"}. \quad (5)$$

The algorithm of the FA's function "analysis of the collective problem solving situation" is the sequence of steps:

1) set the initial values: $stg =$ "$divergent$", $cnf(ag_i, ag_j) = 0$, $cnf_{himsht} = 0$, $cnfl =$ "$absent$";
2) expect messages;
3) if a message is received about HIMSHT termination, then the end;
4) if a message is received about the solution dec_k developed by the EA ag_i, then proceed to step 5, otherwise the abort execution with error;
5) determine $cnf(ag_i, ag_j)$ for each EA ag_j by (1), where $j \in \mathbb{N}$, $1 \leqslant j \leqslant n$, $j \neq i$;
6) calculate cnf_{himsht} and $cnfl$ by (2) and (3), respectively;
7) determine the stage stg of the problem solving process according to the rules (4) and (5);
8) go to the step 2.

The FA's function "choice of heterogeneous thinking method" is implemented using a fuzzy knowledge base about the effectiveness of heterogeneous thinking methods depending on the characteristics of the problem, the stage of its solution and the current solution situation in HIMSHT. This fuzzy knowledge base should be developed based on the results of the computational experiments to be carried out with algorithms that implement these methods. By now the comparative analysis of the approaches proposed in HIMSHT and implemented in hybrid intelligent multi-agent systems, that increased efficiency by more than 7% solving complex transport-logistic problem [32], suggests the advantages of the former and their greater relevance to the problems in dynamic environments.

Thus, thanks to the FA, which initiates the use of various methods of heterogeneous thinking, and EAs, which implement various technologies of artificial intelligence, the HIMSHT dynamically rebuilds the algorithm of its functioning, each time developing a hybrid intelligent solution method that is relevant to the dynamic problem. HIMSHT combines the representation of the heterogeneous functional structure of a problem with heterogeneous collective thinking of intelligent agents, which creates conditions for solving the problem without simplifying in the dynamic environment of the regional power grids.

V. Conclusion

In this paper, the main stages of solving problems by the team of experts engaged in operational activities are reviewed, and the thinking styles of participants are highlighted in these stages. The formalized model of the HIMSHT and algorithms that simulate heterogenous thinking processes are proposed for the relevant modeling of the problem solving process in a small team of experts. The proposed HIMSHT moves an imitation of collective development of operational actions to the field of synergetic informatics, when interaction of agents is necessary for obtaining a result greater than the sum of the work carried out individually. This leads to self-organizing, social management models, each element of which is developing, obtaining data and knowledge from other elements. This reduces the cost of developing and operating the system. The use of such systems in operational dispatching (operational and technological) management will make it possible to develop solutions relevant to the problems that arise in the complex, dynamic environments of regional power grids.

ACKNOWLEDGMENT

The reported study was funded by RFBR according to the research project No. 18-07-00448A.

REFERENCES

[1] M.I. Uspenskiy, and I.V. Kyzrodev, *Metody vosstanovleniya elektrosnabzheniya v raspredelitel'nykh setyakh* [*Methods for restoring electrical supply in distribution networks]*, Syktyvkar, 2010. (in Russian)

[2] *Avtomatizatsiya dispetcherskogo upravleniya v elektroenergetike* [*Automation of dispatching control in electric power industry*], Yu.N. Rudenko, and V.A. Semenova (eds.), Moscow: Izdatel'stvo MEI, 2000. (in Russian)

[3] Avariya v energosisteme Kaliningradskoy oblasti [Accident in the power system of the Kaliningrad region]. Available at: http://allabc.ru/energetika/2212-avariya-v-energosisteme-kaliningradskoj-oblasti.html. (accessed 25.12.2018) (in Russian)

[4] A.L. Barabashi, and E. Bonabo, "Bezmasshtabnyye seti [Non-scale networks]" in *V mire nauki* [*In the world of science*], 2003, No 8, pp.54-63.

[5] A.A. Filatov, *Obsluzhivaniye elektricheskikh podstantsiy operativnym personalom* [*Maintenance of electrical substations operational staff*], Moscow: Energoatomizdat, 1990. (in Russian)

[6] A.V. Kolesnikov, *Gibridnye intellektual'nye sistemy. Teoriya i tekhnologiya razrabotki* [*Hybrid intelligent systems: theory and technology of development*], Saint Petersburg: Izdatel'stvo SPbGTU, 2001. (in Russian)

[7] V.B. Tarasov, *Ot mnogoagentnykh sistem k intellektualnym organizatsiyam: filosofiya, psikhologiya, informatika* [*From multiagent systems to intelligent organizations: philosophy, psychology, and informatics*]. Moscow: Editorial URSS, 2002. (in Russian)

[8] H. Gardner, *Multiple Intelligences* – The Theory in Practice. New York: Basic Books, 1993.

[9] S. Kaner, L. Lind, C. Toldi, S. Fisk, and D. Beger, *The Facilitator's Guide to Participatory Decision-Making*, San Francisco, CA: Jossey-Bass, 2011.

[10] E. de Bono, *Parallel Thinking: From Socratic to De Bono Thinking*, Melbourne: Penguin Books, 1994.

[11] B.A. Dushkov, A.V. Korolov, and B.A. Smirnov, *Osnovy inzhenernoy psikhologii* [*Fundamentals of engineering psychology*]. Moscow: Akademicheskiy prospect, 2002. (in Russian)

[12] V.V. Krasnik, *Potrebiteli elektricheskoy energii, energosnabzhayushchiye organizatsii i organy Rostekhnadzora. Pravovyye osnovy vzaimootnosheniy* [*Consumers of electrical energy, energy supplying organizations and bodies of Rostechnadzor. Legal basis of relationships*], Moscow: NTS ENAS, 2005. (in Russian)

[13] M.M. Adibi, and L.H. Fink, "Overcoming Restoration Challenges Associated with Major Power System Disturbances" in *Power and Energy Magazine, IEEE*, 2006, Vol. 4(5), pp. 68-77.

[14] O.A. Masterova, and A.V. Barskaya, *Ekspluatatsiya elektroenergeticheskikh sistem i setey* [*Operation of power systems and networks*], Tomsk: TPU, 2006. (in Russian)

[15] S. Thiebaux, and M.-O. Cordier, "Supply Restoration in Power Distribution Systems — A Benchmark for Planning under Uncertainty" in *Proceedings of the 6th European Conference on Planning (ECP-01)*, Toledo, 2001, pp. 85-96.

[16] A.S. Narinyani, "Inzheneriya znaniy i NE-faktory: kratkiy obzor-08 [Knowledge Engineering and Non-Factors: A Brief Overview-08]" in *Voprosy iskusstvennogo intellekta* [*Artificial Intelligence Issues*], 2008, No, pp.61–77. (in Russian)

[17] I.V. Kyzrodev, and M.I. Uspensky, "Avtomatizatsiya vosstanovleniya elektrosnabzheniya v raspredelitel'nykh setyakh [Automating the restoration of power supply in distribution networks]" in *Izvestiya Komi nauchnogo tsentra UrO RAN* [*Izvestiya Komi Scientific Center, Ural Branch of the Russian Academy of Sciences*], 2010, No 2, pp. 84-91. (in Russian)

[18] V. Kumar, H.C.R. Kumar, I. Gupta, and H.O. Gupta, "DG integrated approach for service restoration under cold load pickup" in *IEEE Transactions on Power Delivery*, 2010, Vol. 25(1), pp 398-406.

[19] P. Hentenryck, and C. Coffrin, "Transmission system repair and restoration" in *Mathematical Programming*. Ser. B, 2015, Vol. 151, pp. 347–373.

[20] W. Chen, M. Tsai, and H. Kuo, "Distribution system restoration using the hybrid fuzzy-grey method" in *IEEE Transactions on Power Systems*, Vol. 20(1), pp. 199–255.

[21] S. Jayasinghe, and K. Hemapala, "Multi agent based power distribution system restoration – a literature survey" in *Energy and Power Engineering*, 2015, Vol. 7, pp. 557-569.

[22] J.W. Feltes et al., "Some considerations in the development of restoration plans for electric utilities serving large metropolitan areas" in *IEEE Transactions on Power Systems*, 2006, Vol. 21, pp. 909-915.

[23] M. Gholami, J. Moshtagh, and N. Ghadernejad, "Service restoration in distribution networks using combination of two heuristic methods considering load shedding" in *Journal of Modern Power Systems and Clean Energy*, 2015, Vol 3(4), pp. 556–564

[24] P. Gomes, A.C.S. de Lima, and A. de P. Guarini, "Guidelines for Power System Restoration in the Brazilian System" in *IEEE Transactions on Power Systems*, 2004, Vol. 19(2), pp. 1159 – 1164.

[25] S.-J. Lee, S.-I.Lim, B.-S. Ahn, "Service Restoration of Primary Distribution Systems Based on Fuzzy Evaluation of Multi-Criteria" in *IEEE Transactions on Power Systems*, 1998, Vol. 13(3), pp. 1156 – 1163.

[26] Y. Besanger, M. Eremia, and N. Voropai, "Major grid blackouts: Analysis, classification, and prevention" in *Handbook of Electrical Power System Dynamics: Modeling, Stability, and Control*, New Jersey: Wiley – IEEE Press, 2013, pp. 789-863.

[27] N.I. Voropay, and Buy Din' Tkhan', "Vosstanovleniye sistemy elektrosnabzheniya s raspredelennoy generatsiyey posle krupnoy avarii [Restoration of the power supply system with distributed generation after a major accident]" in *Promyshlennaya energetika* [*Industrial Energy*], 2011, No 8, pp.12-18. (in Russian)

[28] M.V. Samsonova, and V.V. Yefimov, *Tekhnologiya i metody kollektivnogo resheniya problem: Uchebnoye posobiye* [*Technology and methods of collective problem solving: Textbook*], Ul'yanovsk: UlGTU, 2003. (in Russian)

[29] A.N. Zankovskiy, *Organizatsionnaya psikhologiya: Uchebnoye posobiye dlya vuzov po spetsial'nosti «Organizatsionnaya psikhologiya»* [*Organizational psychology: Textbook for high schools on the specialty "Organizational psychology"*], Moscow: Flinta: MPSI, 2002. (in Russian)

[30] *Organizatsionnoye povedeniye: Uchebnik dlya vuzov* [*Organizational Behavior: A Textbook for Universities*], G.R. Latfullin, and O.N. Gromova (eds.), Saint-Petersburg: ZAO Izdatel'skiy dom «Piter», 2004. (in Russian)

[31] A.Y.C. Tang, G.S. Basheer, "A Conflict Resolution Strategy Selection Method (ConfRSSM) in Multi-Agent Systems" in *International Journal of Advanced Computer Science and Applications*, 2017, Vol. 8(5), pp. 398–404.

[32] A.V. Kolesnikov, I.A. Kirikov, S.V. Listopad, *Gibridnye intellektual'nye sistemy s samoorganizatsiey: koordinatsiya, soglasovannost', spor* [*Hybrid intelligent systems with self-organization: coordination, consistency, dispute*], Moscow: IPI RAN, 2014. (in Russian)

ГИБРИДНАЯ ИНТЕЛЛЕКТУАЛЬНАЯ МНОГОАГЕНТНАЯ МОДЕЛЬ ГЕТЕРОГЕННОГО МЫШЛЕНИЯ ДЛЯ РЕШЕНИЯ ЗАДАЧИ ВОССТАНОВЛЕНИЯ РАСПРЕДЕЛИТЕЛЬНОЙ ЭЛЕКТРОСЕТИ ПОСЛЕ АВАРИЙ

Колесников А.В., Листопад С.В.

Проблемы, возникающие в таких динамических средах как региональная распределительная электросеть, обладают следующими особенностями: частичная наблюдаемость, высокая размерность пространства состояний, взаимосвязь и зависимость решений друг на друга, не позволяющие исправить ошибочное решение в будущем. Абстрактно-математические модели ограничены и нерелевантны таким динамическим средам, в связи с чем привлекаются коллективы экспертов различных специальностей или их компьютерные модели, но и они не всегда успешно решают возникающие проблемы. Успех работы коллектива во многом зависит от способности лица, принимающего решения, организовать процесс гетерогенного коллективного мышления, диагностику коллективных эффектов, проблем группового поведения и выбор на их основе соответствующей модели коллективных рассуждений. В условиях временных ограничений при решении практических проблем организовать такое всестороннее коллективное решение проблемы не представляется возможным. В этой связи в работе предлагается формализованная модель и основные алгоритмы нового класса интеллектуальных систем – гибридные интеллектуальные системы гетерогенного мышления. Особенность данного класса интеллектуальных систем – моделирование действий фасилитатора по управлению дискуссией команды экспертов методами гетерогенного коллективного мышления. Их применение позволит агенту, моделирующему действия фасилитатора, организовать коммуникацию и диагностику коллективных эффектов, проблем и корректировку группового поведения, обеспечив релевантность системы рассматриваемым проблемам в условиях динамических непосредственно ненаблюдаемых сред.

Received 09.01.19