1. Vasyl SHYNKARENKO, 2. Anna SHYMANSKA, 3. Viktoriia KOTLIAROVA

ORCID: 1.0000-0002-5054-823X; 2.0000-0003-2481-0908; 3.0000-0002-4182-4175

DOI: 10.15199/48.2025.05.53

Taxonomy and genetic evolution of electromechanical energy converters of the Spherical Genus

Badania taksonomii i ewolucji genetycznej sferycznego rodzaju maszyn elektromechanicznych

Abstract*. The article summarizes the results of structural and systemic studies on the taxonomy and evolution of the Spherical Genus of electrical machines. It is shown that the rank structure of genetic systematics, geometric classes of electrical machines correspond to the taxonomic rank of the Genus. The concept is introduced for the first time and the structure of the generative taxon is given, which determines the hierarchical structure of higher taxon ranks. The genetic programs, evolutionary status and quantitative composition of the Species of spherical machines are determined. A genetic and evolutionary analysis of the processes of historical speciation is carried out with the identification of evolutionary events that testify to the discovery of new Species of spherical electromechanical systems. The results of the implementation of the scenario of Controlled Evolution by purposeful introduction of new Species into the evolution are considered using specific examples. The results of the research determine the innovative potential of the Genus and show the possibility of setting and solving tasks of the Discovery of systems type, which are an integral part of the strategy of Controlled Evolution.*

Streszczenie. *W artykule podsumowano wyniki badań strukturalnych i systemowych dotyczących taksonomii i ewolucji Rodzaju Sferycznych maszyn elektrycznych. Wykazano, że w strukturze rangowej taksonomii genetycznej klasy geometryczne maszyn elektrycznych odpowiadają rzędowi taksonomicznemu Rodzaju. Po raz pierwszy wprowadzono koncepcję i strukturę taksonu generatywnego, który determinuje hierarchiczną strukturę taksonów wyższego rzędu. Określono programy genetyczne, status ewolucyjny i skład ilościowy Gatunków Sferycznych maszyn elektrycznych. Przeprowadzono analizę genetyczno-ewolucyjną procesów historycznej specjacji, identyfikując wydarzenia ewolucyjne świadczące o odkryciu nowych Gatunków sferycznych układów elektromechanicznych. Rezultaty wdrożenia scenariusza ewolucji sterowanej poprzez celowe wprowadzanie nowych gatunków do ewolucji są badane na konkretnych przykładach. Wyniki badań określiły potencjał innowacyjny Rodzaju oraz pokazały możliwość stawiania i rozwiązywania takich zadań jak Odkrywanie Systemów, które stanowią integralną część strategii Ewolucji sterowanej.*

Keywords: spherical electromechanical objects; taxonomy; genetic code; generative taxon; Species; Genus; controlled evolution; evolutionary experiment; innovative potential

Słowa kluczowe: obiekty elektromechaniczne o kształcie sferycznym; taksonomia; kod genetyczny; takson generatywny; Rodzaj; Gatunek; ewolucja sterowana; eksperyment ewolucyjny; potencjał innowacyjny

Introduction

The problem of expanding the diversity and increasing the complexity of electromechanical systems, their integration into the structure of complex technical systems, increasing the volume of accompanying information necessitate their systematization and qualitative change of the knowledge structure itself. An important feature of the modern picture of the physical world is the recognition of the fact that the processes of evolution of anthropogenic systems submit the general system principles of genetically organized systems, regardless of their nature, time of evolution and features of their functioning.

By opening the Genetic Classification of primary sources of the electromagnetic field, electromechanics and mechanics, as independent branches of physics, received their own system model for posing and solving fundamentally new system problems from the genetic to the evolutionary levels of their structural organization [1].

The study of the laws of evolution and the principles of genetic structure formation at the level of arbitrary functional and taxonomic classes of technical systems opens up the possibility of their systematization, genetic analysis and prediction, which is an urgent problem for technical science, education and innovation.

Using the methodology of structural-system research and the setting of evolutionary experiments, the task is set to determine the generic taxonomy, study the mechanisms of expansion of population and Species diversity of objects in the technical evolution of electromechanical energy converters.

In this article, on the example of genetic-evolutionary analysis of electromagnetic and electromechanical systems of the Spherical Genus, the results of such studies are summarized for the first time.

For a long time, it was believed that spherical electrical machines (SEMs) have no commercial and, therefore, no practical value due to the high complexity of manufacturing the magnetic system and unsatisfactory integral characteristics. A characteristic trend in the evolution of electromechanical systems (EM-systems), which has been observed over the past decades, is a significant increase in the amount of information on the results of research, development and practical application of SEMs [2-4].

Due to their properties such as the central symmetry of the magnetic field, the ability to provide controlled multi-coordinate motion, high control accuracy, implementation of direct drive, and high structural adaptability, they are widely used in control systems of spacecraft and microsatellites [5], in electromagnetic systems of thermonuclear fusion reactors [6], in orientation and guidance systems of unmanned aerial and ground autonomous objects [7,8], in physical experiments on modelling planetary magnetism [9,10], in the kinematics of industrial and anthropomorphic robots [11], in traction electric drives [12], as generators for converting sea wave energy [13], in precision drives of rotary platforms, surveillance and vision devices [14], etc.

Unexplored parts of the general problem

Despite significant progress in the study and development of individual varieties of SEMs, available sources of information, well-known monographs and review publications are actually limited to theoretical analysis of internal physical processes, description of individual technical solutions and assessment of their possible applications.

The methodology and organization of research in such an evolutionary concept, in technical sciences, was first initiated in electromechanics, where the theoretical and methodological principles of genetic systematics of EM-objects were first developed [1,15].

The purpose of this study is to determine the mechanisms of formation of new Species in technical evolution of spherical electric machines and electromagnetic systems, as a necessary condition for transition from the concept of Observed Evolution to the strategy of Guided Evolution. The object of research is the processes of innovative structure formation of spherical electric machines. The subject of research is taxonomy, genetic programs of structure formation, methods of identification and analysis of evolutionary events, which testify to the discovery and evolution of new Species, which determine the innovative potential of SEM.

The research methods include structural-system approach, provisions of the theory of genetic evolution of EM-systems, systemic modelling, methods of genetic systematics, technology of genetic prediction, evolutionary experiments [1,16].

Taxonomy of the Spherical Electric Machines Genus

The results of previous studies have established that the principles of genetic taxonomy constitute an integral component of the Genetic Organizes Systems (GOS), the function of the Generative System in which the periodic structure of the Genetic Classification of primary sources of the electromagnetic field performs [1,15,17].

The structure of taxonomic ranks of an arbitrary functional class of EM- systems is determined by the Generative Taxon (GT), which has a direct connection with the structure of small periods, groups and subgroups of Genetic classification, the structure of universal genetic codes, micro- and macrogenetic programs of structure formation (Fig. 1).

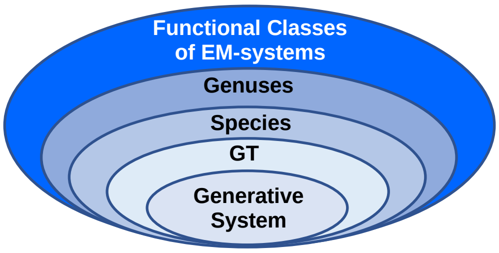


Fig.1. Hierarchy of the main taxonomic ranks of Genetic Taxonomy of arbitrary functional classes of EM-systems

The taxonomy of an arbitrary functional class of spherical (SP) EM-systems can be represented by a hierarchy of the following interconnected ranks

$$R_T = < G_T \to T_S \to T_G > \subset C_{SP} \qquad (1)$$

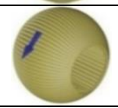
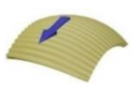
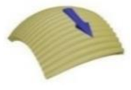
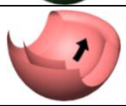
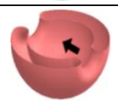
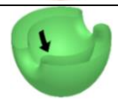
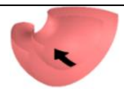
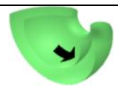
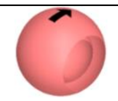
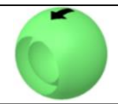
where: G_T - rank of the Generative Taxon; T_S - rank of the Species; T_G - rank of the Genus. The structure of each rank contains a finite set of corresponding taxons.

The hierarchy of taxonomic ranks R_T is invariant with respect to the level of complexity, functional purpose and time of evolution of functional classes of EM-systems.

The Generative Taxon in the taxonomy of the SEM Genus is determined by a finite set of electromagnetic chromosomes of the basic level C_0 and a set of chromosomes of the isotope level S_I (Table 1), which are identified within the small period of the GC

$$G_{TSP} = < C_0, C_I > \qquad (2)$$

Table 1. Structure and genetic information of the Generative Taxon of the SEM Genus

Genetic code	3D-model of initial field sources	Symmetry group & active surface topology	Winding type	Type of EEE
Initial sources of magnetic field (Base level)				
SP 0.0y		Sym.closed without edge (*x*,*y*-sym.)	Circular *y*-oriented	None
SP 0.0x		Sym. closed without edge (*x*,*y*-sym.)	Circular *x*-oriented	None
SP 0.2y		Dysym. closed with edges (*x*-asym.)	Surface type *y*-oriented	T
SP 2.0x		Dysym. closed with edges (*y*-asym.)	Circular *x*-oriented	L
SP 2.2y		Asym. unclosed with edges (x,*y*-asym.)	Surface type *y*-oriented	L&T
SP 2.2x		Asym. unclosed with edges (x,*y*-asym.)	Surface type *x*-oriented	L&T
Initial sources of magnetic field (Isotopes level)				
¹SP 0.2y		Dysym. closed with edge (*x*-asym.)	Surface type *y*-oriented	T
¹SP 2.0x		Dysym. closed with edges (*y*-asym.)	Circular *x*-oriented	L
¹SP 2.2y		Asym. unclosed with edges (x,*y*-asym.)	Surface type *y*-oriented	L&T
¹SP 2.2x		Asym. unclosed with edges (x,*y*-asym.)	Surface type *x*-oriented	L&T
²SP 0.2y		Dysym. closed with edges (*x*-asym.)	Surface type *y*-oriented	T
²SP 2.0x		Dysym. closed with edges (*y*-asym.)	Circular *x*-oriented	Ll
²SP 2.2y		Asym. unclosed with edges (x,*y*-asym.)	Surface type *y*-oriented	L&T
²SP 2.2x		Asym. unclosed with edges (x,*y*-asym.)	Surface type *x*-oriented	L&T
³SP 0.2y		Dysym. closed with edges (*x*-asym.)	Surface type *y*-oriented	T
³SP 2.0x		Dysym. closed with edges (*y*-asym.)	Circular *x*-oriented	L

In Table 1: Sym. – Symmetrical, Dysym. – Dissymmetrical, Asym. – Asymmetrical; EEE – edge electromagnetic effects, L – longitudinal, T – transverse, L&T – longitudinal and transverse edge electromagnetic effects.

The primary sources of the magnetic field of the generating taxon G_{TSP} determine the quantitative composition and genetic information of the corresponding Species of the base level and Twin Species according to the principle of "one code - one Species".

Analysis of Table 1 clearly shows that the spherical generic geometry is endowed with the property of polymorphism, which allows the existence of a wide range of variability of forms, especially at the level of isotope sources.

An arbitrary primary source of the magnetic field of the base level S_0 and a set of isotope sources are related to each other by the homeomorphism relation

$$f : (S_0) \rightarrow ({}^1S, {}^2S, {}^3S, \ldots, {}^nS), \; n = \overline{1, \; \infty} \tag{3}$$

The specified topological property determines the identity of the genetic codes of the basic field source and the sources-isotopes (Table 1).

For example, the basic field source with the genetic code SP 0.2y performs the function of generating relative to a number of isotopes within the generic space of the formation of G_{SP}

$$SP\ 0.2y \rightarrow ({}^1SP\ 0.2y;\ {}^2SP\ 0.2y;\ {}^3SP\ 0.2y;\ \ldots) \subset G_{SP} \tag{4}$$

Therefore, the main method of synthesizing EM-structures on the elemental basis of chromosomes-isotopes is the methods of topological transformations, provided that the ancestral geometry is preserved. The structures-descendants synthesized on isotopes acquire the status of objects and the corresponding Twin Species [17].

Generic features of spherical electric machines

The spatial geometry and topology of primary sources of the electromagnetic field organizes the structure of small and large periods of the GC, determines the generic taxonomy of the genosystematics of EM-systems and also belongs to the main components of genetic information. The belonging of an arbitrary EM-object to the corresponding Genus is identified by the first component of its genetic code. This means that the boundaries of generic taxa and their systemic properties are uniquely determined by the symmetry and topology of the element-information basis of small periods of the GC.

The genetic organization of the SEM (provided that there is a solid-state rotor and δ = const) allows the implementation of structures with one-, two-, and three-coordinate rotational motion of the spherical rotor. The number of degrees of freedom is determined by the minimum number of independent variables (generalized coordinates) necessary for a complete description of the dynamic state of the EM-system. Therefore, the possibility of implementing controlled multi-coordinate rotational motion can be considered as a unique property of the objects of the Genus.

A characteristic topological property of magnetically oriented spherical active surfaces of EM-objects is the presence of singular points of the vector electromagnetic field. In topology, a singular point of the vector field is a point at which the vector field is zero. In the structure of the genetic code, the direction of the magnetic orientation vector is determined by the third component of genetic information, which can have one of two values: x - or y - orientation. The presence of zones with singular points is directly related to both the nature of the distribution of the vector magnetic field and the topology of surface and ring distributed windings (Fig. 2).

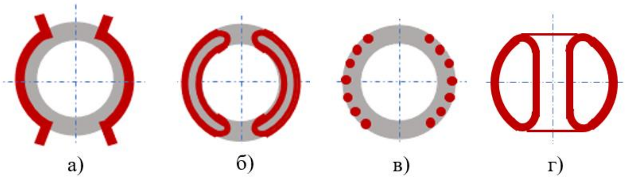


Fig. 2. Arrangement of sections of distributed windings (cross-sections) in the zone of singular points of the spherical active surface: a) surface y-oriented windings (SP 0.2y); b) ring y-oriented (SP 0.0y); c) ring x-oriented (SP 2.0x); d) ring y-oriented windings with D-shaped sections (^{1}SP 0.0y)

Specific generic features also include the chromosomal anomaly of twin chromosomes of group 2.2, which eliminates the difference in their x-y-orientation (SP 2.2x ≈ SP 2.2y). This chromosomal property, which occurs only in the structure of the Generative Taxon of the Flat Genus and the Spherical Genus, is represented in technical evolution by populations of electric machines with OZ-rotational symmetry of active parts, which played the role of archetypes of a new direction of their adaptive structure formation [16].

Generic macrogenetic program

The macrogenetic program of EM-objects of the Spherical Genus G_{SP}, within the first large period of the GC, can be represented by two finite subsets of primary sources of the electromagnetic field

$$(P_{SPB},\ P_{SPI}) \subset G_{SP} \tag{5}$$

where: P_{SPB} – sources of basic level

$$P_{SPB} = \langle SP\ 0.0y;\ SP\ 0.0x;\ SP\ 0.2y;\ SP\ 2.0x;\ SP\ 2.2y;\ SP\ 2.2x \rangle \tag{6}$$

P_{SPI} – isotope sources

$$\begin{aligned} P_{SPI} = \langle &({}^1SP\ 0.0y,\ {}^2SP\ 0.0y,\ \ldots,\ {}^nSP\ 0.0y); \\ &({}^1SP\ 0.0x,\ {}^2SP\ 0.0x,\ \ldots,\ {}^nSP\ 0.0x); \\ &({}^1SP\ 0.2y,\ {}^2SP\ 0.2y,\ \ldots,\ {}^nSP\ 0.2y); \\ &({}^1SP\ 2.0x,\ {}^2SP\ 2.0x,\ \ldots,\ {}^nSP\ 2.0x); \\ &({}^1SP\ 2.2y,\ {}^2SP\ 2.2y,\ \ldots,\ {}^nSP\ 2.2y); \\ &({}^1SP\ 2.2x,\ {}^2SP\ 2.2x,\ \ldots,\ {}^nSP\ 2.2x) \rangle \end{aligned} \tag{7}$$

The structure of the macrogenetic program contains complete information about genetically admissible generating sources of the field, which are invariant to the level of technical evolution and the level of complexity of the descendant objects and determine the structure of the corresponding Species.

Another important function of macrogenetic programs is their prognostic function [16,17]. For an arbitrary functional class of evolving EM-objects, the following relation is valid

$$C_S = C_H + C_F, \tag{8}$$

where: C_S – finite set of genetically admissible Species; C_H - finite set of Species, objects of which are historically involved in the evolution of the studied class; C_F - implicit Species, objects of which are not yet present in the evolution of the class at the time of its study.

Results of evolutionary experiments

The main task of experimental studies is to verify the reliability of the principles and models of genetic structure formation of SEM at the object and Species levels [15].

The correspondence of genetic programs to real processes of technical structure formation at the object and species levels was determined by methods of identification of genetic codes and taxonomic affiliation for each SEM object, identified according to the results of patent information research.

The date of appearance of a new Species, as a macroevolutionary event, is identified by genetic analysis methods by the priority date (description, patenting or technical implementation) of its first structural representative (microevolutionary event).

From the point of view of the theory of genetic speciation, the evolutionary event that determines the initial evolution of a new Species is simultaneously accompanied by a change in its evolutionary status. The “implicit” Species acquires the status of the “real-informational” Species.

The task of the second stage of evolutionary experiments is to confirm the reliability of the "guided evolution" scenario, the implementation of which is carried out by methods of genetic prediction and structure formation at the level of objects and Species of SEM.

The initial information for setting up predictive experiments is the genetic codes of implicit Species, which are determined by the results of the analysis of macrogenetic programs.

According to the results of genetic analysis of the results of patent information research, it was established that the evolution of inductive machines of the Spherical genus lasts 140 years (Fig. 3).

If the initial period of the evolution of the Genus (from 1885 to 1940) was represented only by objects of one Species (SP 0.2y), then at present, the technical evolution of SEM is represented by a variety of objects of 8 Species. Among them, objects of 6 Species that arose historically (SP 0.2y, SP 2.0x, SP 2.2x and SP 2.2y, ^{1}SP 2.0x, ^{1}SP 0.0y) and objects of two Species (SP 0.0x and ^{1}SP 0.2y), which were first introduced into technical evolution purposefully.

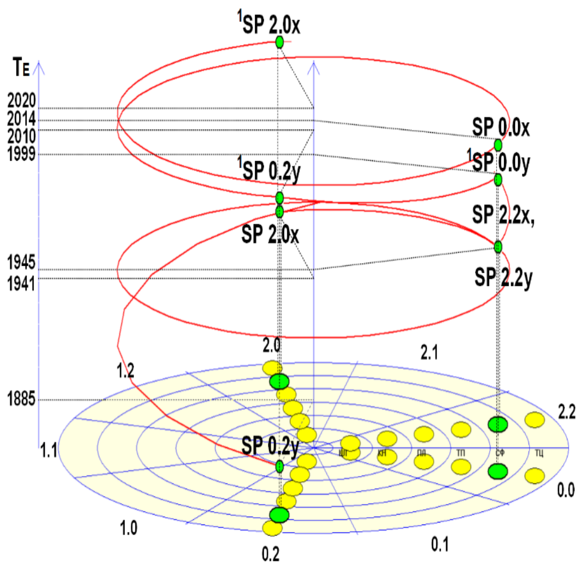


Fig. 3. Macroevolutionary process of Species composition expansion in the structure of the Genus of SEM according to evolutionary experiments. The evolutionary trajectory visualizes the nodal evolutionary events of the emergence of new Species and their genetic codes (T_E = 140 years, N_S = 8)

The nodal events of the macroevolutionary trajectory (Fig. 3) identify the dates of evolutionary events, reproduce the sequence of the appearance of new Species (with an indication of their genetic codes) in the evolution of the SEM, and also determine the coordinates of their parental chromosomes in the structure of the macrogenetic program of the Genus.

The evolution of an arbitrary Species begins simultaneously with the appearance of its first representative (the archetype of the Species), the description, priority and authors of which are determined through documented open access information sources, and its genetic code and evolutionary status are identified by genetic analysis methods.

Microevolution of an arbitrary Species can be considered as a multi-level process of implementing its own genetic program, which is independently carried out by different researchers and reproduced in the form of specific evolutionary events (innovations).

The results of evolutionary experiments confirm that the long-term historical process of structure formation of spherical EM-systems, both at the object and species levels, occurs in strict accordance with their generic (macrogenetic) and intraspecific (microgenetic) programs.

Discovery of new Species and implementation of Guided Evolution scenario

The methodology of setting and solving multi-level problems of the "systems discovery" type is a fundamentally new direction in the study of EM-systems, which integrates methods of analyzing macrogenetic programs, genetic prediction technology, setting up evolutionary experiments with active use of the researcher's cognitive space.

The final result of solving problems of this level is the guaranteed discovery and "launch" into the evolution of new systems not only at the level of new EM-objects, but also at the level of their populations, homologous series or Species. It has been experimentally established that the vast majority of SEM Species (87.5%) have arisen over the past 80 years.

The process of the emergence of new species in the evolution of the genus occurred in the following chronological sequence: 1885 - SP 0.2y; 1941 - SP 2.0x; 1945 - SP 2.2xy; 1999 - ^{1}SP 0.0y; 2010 - ^{1}SP 0.2y; 2014 - SP 0.0x; 2020 - ^{1}SP 2.0x (Fig. 4).

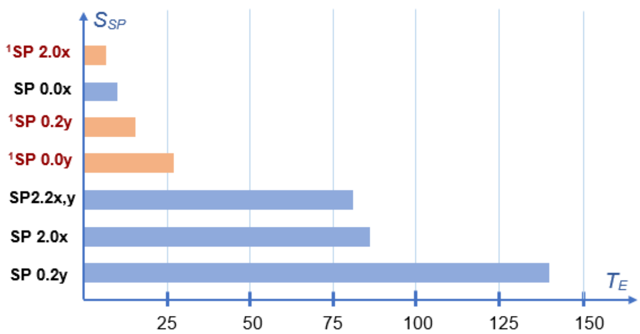


Fig. 4. Duration of time of evolution of basic Species (blue) and twin Species (pink) of electromagnetic and electromechanical systems of the Spherical Genus

If the average time interval for the appearance of a new Species in the historical evolution of the SP Genus is $t_c \approx 27$ years, then using the technology of genetic prediction and synthesis it is reduced to 1-2 years (actually determined by the time required for the development and patenting of original technical solutions).

Innovative Potential of the Spherical Electric Machines Genus

A potential source of innovation is SEM macrogenetic programs. Genetic programs contain complete and systematized information both on known Species that appeared in the process of evolution and on implicit Species that have not yet been involved in the evolution of the studied class. For the first time, it has become possible to predict and purposefully introduce into technical evolution not only genetically synthesized EM-objects, but also their populations, Species and homologous series, information about which can be obtained only from the results of the analysis of macrogenetic programs.

Implicit SEM Species constitute a new subject of research, both from the point of view of implementing innovative projects such as “System Discovery” and from the point of view of innovative educational technologies with the possibility of forming individual educational trajectories in electrical and mechanical engineering [16].

The structural potential of Twin Species, the existence of which is predicted theoretically and confirmed by the results of evolutionary experiments, requires further analysis. With the discovery of the law of hybridization of EM-structures and the development of a methodology for the synthesis of hybrid objects, Hybrid Species and SEM objects remain a promising direction in innovative structure formation, the analysis of which constitutes an independent research direction [18].

Conclusions

The evolution of technical objects is a process of competitive innovation, which occurs at all levels of their structural organization. The results of the research show that the methodology of genetic taxonomy is an effective scientific tool and a necessary condition for setting and solving tasks related to the systematization of knowledge and the implementation of innovative projects under the “Systems Discovery” scenario, which are an integral part of the “Guided Evolution” strategy.

As is known, genetic information is endowed with the highest prognostic value. In a systematized form, it is presented in the structure of generative systems and in genetic programs. The results of the research confirm that the long historical process of structure formation of the Genus of spherical EM-systems, both at the object and population, Species and Genus levels, occurs in strict accordance with their genetic programs. But a systemic vision of such a process, with the possibility of genetic analysis, prediction and management of innovations (at the level of objects, Species and homologous series), is available only to that category of researchers who possess the methodology of genetic and evolutionary research.

Given the rapid development of digital technologies and artificial intelligence, we can expect that the adaptation of their capabilities to deciphering and analyzing genetic programs of complex technical systems will allow us to radically change traditional ideas and methodological approaches to implementing a strategy for managing knowledge and innovations.

***Authors**: prof. Vasyl Shynkarenko, Department of Electromechanics of National Technical University of Ukraine “Ihor Sykorskyi Kyiv Polytechnical Institute”, 37 Peremogy ave., build. 20, Kyiv, 03056, Ukraine, E-mail: svf1102@gmail.com; PhD Anna Shymanska, Department of Electromechanics of National Technical University of Ukraine “Ihor Sykorskyi Kyiv Polytechnical Institute”, 37 Peremogy ave., build. 20, Kyiv, 03056, Ukraine; Faculty of Electrical and Computer Engineering, Cracow University of Technology, Warszawska,24, 31-155 Krakow, Poland, E-mail: shym.anna@gmail.com; Viktoriia Kotliarova, Department of Electromechanics of National Technical University of Ukraine “Ihor Sykorskyi Kyiv Polytechnical Institute”, 37 Peremogy ave., build. 20, Kyiv, 03056, Ukraine, E-mail: sharik_2004@ukr.net;*

REFERENCES

[1] Shynkarenko V. Fundamentals of the theory of evolution of electromechanical systems, *Kyiv.: Naukova dumka*, 2002, 288
[2] Kleymilson N. Souza, Ricardo Silva Th.,Tobias R. Fernandes, Victor P. B. Aguiar, Felipe Bandeira Silva A new topology of a spherical actuator, *13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference,* 2015, 1-4 doi:10.1109/cobep.2015.7420290
[3] Bruno Dehez, G. Galary, D. Grenier, Benoit Raucent Development of a Spherical Induction Motor With Two Degrees of Freedom, *IEEE Transactions on Magnetics* 42(8), 2006, 2077 – 2089 doi:10.1109/TMAG.2006.876473
[4] Kaminski G., Smak A. Induction motors with spherical rotor *ICEM’04 Conf.Proc.* 2004, 4
[5] Yusheng Liang, Jie Zhang, Liming Yuan Stator Winding Design and Optimization of an Induction Reaction Sphere for Microsatellite Attitude Control *23rd International Conference on Electrical Machines and Systems (ICEMS),* 2020, 1215 – 1219 doi:10.23919/ICEMS50442.2020.9290778
[6] Antonov A. E. Electric machines of magnetoelectric type. Fundamentals of theory and synthesis, Kyiv: IED NASU, 2011, 216
[7] Kun Bai, Kok-Meng Lee Permanent Magnet Spherical Motors: Model and Field Based Approaches for Design, *Sensing and Control Springer Nature Singapore Pte Ltd., Springer,* 2018, 170 ISBN: 978-981-10-7961-0
[8] T. -L. Wu, J. -H. Chen and S. -H. Chang A six-DOF prismatic-spherical-spherical parallel compliant nanopositioner, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 2008, vol. 55, no. 12, 2544-2551; doi: 10.1109/TUFFC.2008.970
[9] Petukhov I.S. Electromagnetic moments of control of the precessional thrust of a three-stage electric machine *Technical Electrodynamics,* 2023, no. 4, 52-61; doi: 10.15407/techned2023.04.052
[10] Yan, L., Chen, I.M., Lim, C.K., Yang, G., Lee, K.M. Design, Modeling and Experiments of 3-DOF Electromagnetic Spherical Actuators *Mechanisms and Machine Science,* 2011, vol 4. Springer, Dordrecht doi.org/10.1007/978-94-007-1646-91
[11] A. Bhatia, M. Kumagai and R. Hollis Six-stator spherical induction motor for balancing mobile robots *IEEE International Conference on Robotics and Automation (ICRA)*, 2015, 226-231 doi: 10.1109/ICRA.2015.7139004
[12] Antonov A. E. Two-coordinate electric machines for tracking systems, Kyiv: IED NASU, 2000,191
[13] Yun Liu; Shishi Li; Chen Liu; Yao Wang; Yuhao Zhou; Haiping Yi Spherical electret generator for water wave energy harvesting by folded structure *45th Annual Conference of the IEEE Industrial Electronics Society*, 2019, Vol. 1, 812-815 doi: 10.1109/IECON42759.2019
[14] Masaaki Kumagai, Ralph L. Hollis Development and Control of a Three DOF Spherical Induction Motor *IEEE International Conference on Robotics and Automation (ICRA)*, 2013, 1520 – 1525 doi: 10.1109/ICRA.2013.6630773
[15] Avgustynovych A. A. Theoretical problems of creating genetic systematics of electrical machine species, Kyiv: IED NASU, 2008, 20 p.
[16] Shynkarenko V., Makki A., Kotliarova V., Shymanska A. Genetic Organization and Evolution of Electromechanical Objects with Adaptive Geometry of Active Zone, *Advances in Science Technology and Engineering Systems Journal 5(5):512-525* doi:10.25046/aj050564
[17] Shynkarenko V., Kotliarova V., Shymanska A., Krasovskyi P. Macrogenetic program of distributed windings of electromechanical converters *Przegląd ektrotechniczny*, 9 (2004) doi:10.15199/48.2024.09.20
[18] Shynkarenko V., Makki A., Kotliarova V., Shymanska A. Modular Principle in the Structural Organization and Evolution of Electromechanical Objects, *International Conference on Modern Electrical and Energy Systems (MEES)* doi:10.1109/MEES.2019.8896446