УДК 21.548 **doi: 10.20998/2079-3944.2023.2.04**

V. V. CHUMACK, M. A. KOVALENKO, I. Y. KOVALENKO, I. V. TKACHUK, O.L. TYMOSCHUK

MATHEMATICAL SIMULATION OF BRUSHLESS DOUBLE STATOR AXIAL FLUX MAGNETOELECTRIC GENERATOR FOR SMALL POWER ELECTRIC COMPLEXES

This paper presents the design of a magneto-electric generator with an axial magnetic flux (MEGAP) and a double stator, which is used for an autonomous wind-electric complex. Contactless MEGAPs have the advantages of permanent magnet generators: high reliability, efficiency; and generators with electromagnetic excitation: the possibility of adjusting the output parameters (voltage, power) using an additional excitation winding. In order to meet the requirements of a stand-alone multiplier-less wind power plant, a MEGAP structure consisting of a double stator and a single rotor has been investigated. The use of a double stator design allows more efficient use of the active volume of the generator, increasing its power and stabilizing the output voltage of the stator winding. A three-dimensional numerical field mathematical model of MEGAP was developed. The model fully takes into account the design features of the generator under study, namely the presence of an axial flow from the stator winding and the flow generated by the additional winding. With the help of the model, the external characteristics were calculated, which indicates the correspondence of the developed mathematical model to physical processes. The analysis of magnetic induction in the air gap and in other structural elements of the generator under study was carried out. The analysis of the obtained values showed that the geometric dimensions of the generator, which were previously selected, are correct and do not require significant adjustments. In the future, it allows you to use the results of this calculation for the preparation of documentation for the production of the prototype. Static characteristics of MEGAP and values of magnetic parameters in all structural elements were studied. An additional winding is used to stabilize the output voltage when the speed of rotation of the generator changes and at different loads. At a relative power of the additional winding of ≈7%, the output voltage of the generator increases by ≈24%. A more significant result can be achieved by adjusting the current of the additional winding with special controllers.

Keywords: axial flux magnetoelectric generator, double stator, mathematical simulation, axisymmetric model.

В.В. ЧУМАК, М.А. КОВАЛЕНКО, І.Я. КОВАЛЕНКО, І.В. ТКАЧУК, О.Л. ТИМОЩУК

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ БЕЗКОНТАКТНОГО АКСІАЛЬНОГО МАГНІТОЕЛЕКТРИЧНОГО ГЕНЕРАТОРА ІЗ ПОДВІЙНИМ СТАТОРОМ ДЛЯ ЕЛЕКТРИЧНИХ КОМПЛЕКСІВ МАЛОЇ ПОТУЖНОСТІ

В даній роботі представлена конструкція магнітоелектричного генератора з аксіальним магнітним потоком (МЕГАП) та подвійним статором, який використовується для автономного вітроелектричного комплексу. Безконтактні МЕГАП мають переваги генераторів на постійних магнітах: висока надійність, ефективність; і генератори з електромагнітним збудженням: можливість регулювання вихідних параметрів (напруга, потужність) за допомогою додаткової обмотки збудження. Щоб задовольнити вимоги до автономної безмультиплікаторної вітроелектричної установки, досліджено структуру МЕГАП, що складається з подвійного статора та одного ротора. Використання конструкції подвійного статора дозволяє більш ефективно використовувати активний об'єм генератора, підвищити його потужність і стабілізувати вихідну напругу обмотки статора. Розроблено тривимірну чисельну польову математичну модель МЕГАП. Модель повністю враховує особливості конструкції досліджуваного генератора, а саме наявність осьового потоку від обмотки статора та потоку, що утворюється додатковою обмоткою. За допомогою моделі розрахована зовнішня характеристика, що свідчить про відповідність розробленої математичної моделі фізичним процесам. Проведено аналіз магнітної індукції в повітряному проміжку та в інших конструкційних елементах досліджуваного генератора. Аналіз отриманих величин показав, що геометричні розміри генератора, що були вибрані попередньо коректні і не потребують суттєвих коригувань. В подальшому, це дозволяє використовувати результати даного розрахунку для підготовки документації по виготовленню прототипу. Досліджено статичні характеристики МЕГАП та значення магнітних параметрів у всіх елементах конструкції. Додаткова обмотка використовується для стабілізації вихідної напруги при зміні швидкості обертання генератора і при різному навантаженні. При відносній потужності додаткової обмотки ≈7% вихідна напруга генератора зростає на ≈24%. Більш значного результату можна досягти, регулюючи струм додаткової обмотки спеціальними контролерами.

Ключові слова: генератор з аксіальним магнітним потоком, подвійний статор, математичне моделювання, асиметрична модель.

Introduction. Axial-flux magneto-electric generators (AFMEG) are widely used in various fields: transport [1], renewable energy sources [2-4], fans [5], pumps [6], aviation technology [7], robotics, etc. [8, 9]. AFMEG are also used as a low-speed high-torque drive, since they have a compact structure that allows their integration with various devices [10, 11].

AFMEG combine the advantages of permanent magnets generators with the ability to adjust the output parameters (voltage, power) using an additional winding [12]. Such generators have a number of fundamental advantages compared to generators of a traditional design: high power density, low axial length and a large diameter; minimal pulsations of the electromagnetic torque, low rotor rotation speed [13].

Depending on the stator and rotor configuration, AFMEGs are structurally: one-sided or two-sided, single-stator or multi-stator, and others [14, 15]. In this paper, AFMEG with a double stator and a single rotor is considered. This design makes it possible to use the full volume of permanent magnets and active materials of the generator and to increase the power density of the generator.

In the paper [16] presents a three-dimensional model of a cylindrical permanent magnets magnetoelectric generator. This model does not take into account saturation, and the rotation of the rotor is simulated by discrete numerical calculations. Mathematical models of axial flux permanent magnet generators with various configurations are presented in [17, 18]. However, they lack information about the mathematical simulations of AFMEG with an additional excitation winding. Another task is the calculation of the parameters and characteristics of such generators during rotor rotation.

Authors in works [19, 20] consider various constructions of axial magnetic flux machines with an without a magnetic core. In order to reduce the weight of multi-stator and multi-rotor designs of generators, the authors in works [21, 22] developed mathematical models designed for the analysis and comparison of various variants of the design of such generators.

In this paper developed a three-dimensional numerical axisymmetric field mathematical model of AFMEG with a double stator, implemented by the finite element method, and an analysis of its parameters and characteristics was carried out.

The development of brushless AFMEGs for wind generating systems, small hydroelectric power plants and systems for converting low-potential mechanical energy into electrical energy in general is a relevant direction. In such generators constructions, the role of the main magnetic flux regulator is performed by an additional winding. The change of the amplitude of the main magnetic flux in the air gap occurs due to the use of a constructive technique: part of the permanent magnets on the rotor is replaced by a soft magnetic material called a magnetic shunt. The absence of mathematical models for evaluating parameters and characteristics of AFMEG with a double stator also determines the relevance of such work.

The relevance of the work is the development of non-contact AFMEGs for wind generating systems, small hydroelectric power plants and systems for converting low-potential mechanical energy into electrical energy in general is a relevant direction. In structures of this type, the role of the regulator of the main magnetic flux is performed by an additional winding. The change in the amplitude of the main magnetic flux in the air gap occurs due to the use of a constructive method: a part of the permanent magnets on the rotor is replaced by a magnetically soft material called a magnetic shunt. To date, the absence of mathematical models for evaluating AFMEG with a double stator also determines the relevance of developing such a model.

Purpose of work is the development of a three-dimensional axisymmetric field mathematical model of AFMEG with a double stator and the analysis of its parameters and characteristics.

To evaluate the parameters and characteristics of a magnetoelectric generator with an axial magnetic flux, it is necessary to develop a mathematical model that takes into account the change in the load of the studied generator without regulation and when the current of the additional winding changes.

Research object.

Cross-section of the investigated AFMEG shows on the Fig. 1.

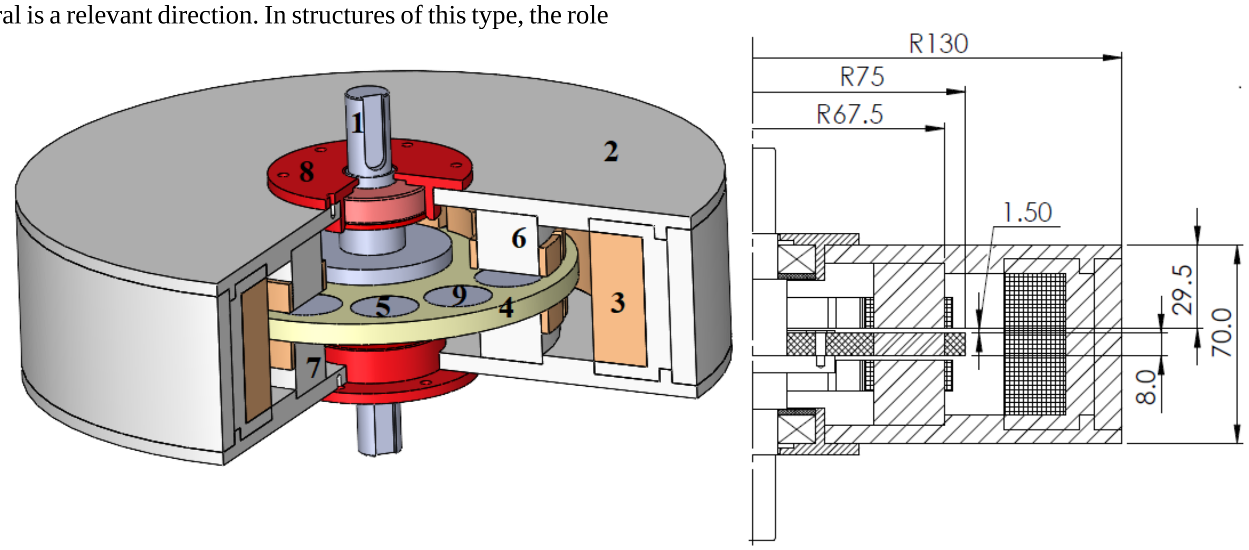

Fig. 1 – AFMEG configuration example

On fig. 1 shown: 1 – generator shaft; 2 – housing, made of magnetically conductive material; 3 – additional excitation winding; 4 – generator rotor made of non-magnetic material; 5 – permanent magnets, NdFeB N38H type; 6, 7 – two stators with an armature winding; 8 – flanges with bearings; 9 – magnetic shunts.

The magnetic shunt is made of soft magnetic material. The shunt forms a path for closing the main magnetic flux of permanent magnets on the one side, and forms a path for closing the magnetic flux for the additional winding.

The main parameters of the studied AFMEG are given in Table. 1.

Table 1 – Parameters and characteristics of studied AFMEG

№	Parameter	Value	Unit
1	Output power	700	V·A
2	Rated voltage	48	V
3	Number of phases	3	–
4	Rated speed	≤1000	rpm
5	Pole pairs	6	–
6	Permanent magnets type	NdFeB N38H	–
7	Diameter/axial permanent magnets length	25/8	mm
8	Power factor	0,9	–
9	Magnetic core diameters	135/85	mm
10	Axial stator length	23,0	mm
11	Axial rotor length	8,0	mm
12	External generator diameter	270,0	mm
13	Air gap value	0,5	mm
14	Efficiency	92	%
15	Number of stator slots	18	–
16	Steel brand	3416	–

Mathematical model. In order to reduce the computation time and time spent on each iteration of the numerical calculation, increase the efficiency of numerical methods, an axisymmetric model was developed in this work. The model has 2 types of symmetry: spatial (sectoral) symmetry and mirror symmetry relative to the plane perpendicular to the rotation axis. This makes it possible to reduce the geometry of the complete calculation area to the one shown in Fig. 2.

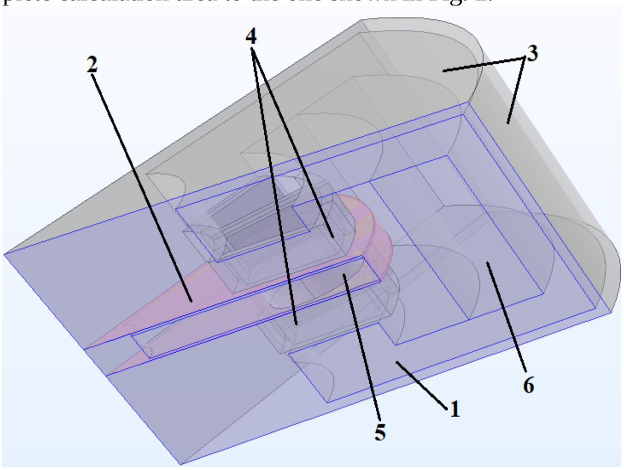

Fig. 1. Axisymmetric AFMEG

In Fig. 2 shows the corresponding boundary conditions of the developed model and individual structural elements:

1 – periodic boundary conditions, set at the boundaries of symmetric sectors of the calculation domain:

$$\boldsymbol{A}_{12} = -\boldsymbol{A}_{21} \tag{1}$$

2 – boundary conditions between the stator and the rotor. Must coincide with boundary conditions (1). 3 – zero boundary conditions of the first kind for the tangential component of the magnetic potential are set for this boundary of the calculation domain:

$$\mathrm{n}\times\boldsymbol{A}=0 \tag{2}$$

4 – armature winding. 5 – generator rotor with permanent magnets and magnetic shunts. 6 – additional excitation winding.

To reduce each iteration calculation time, a combined approach is used: for non-electroconductive areas, the solution is solved with respect to the scalar magnetic potential V_m. The classical equations for the electromagnetic field are used for the vector magnetic potential $\boldsymbol{A}$.

For all non-conductive parts (air, rotor and some parts of the housing), a system of equations is used with respect to the scalar magnetic potential V_m:

$$\begin{cases} -\nabla\cdot(\mu_0\nabla V_m - \mu_0\boldsymbol{M}) = 0 \\ \nabla\cdot\boldsymbol{B} = 0 \\ \boldsymbol{B} = \mu_0\cdot\mu_r\cdot\boldsymbol{H} \\ \boldsymbol{H} = -\nabla V_m \end{cases} \tag{3}$$

where: μ_0, μ_r – the magnetic permeability of the vacuum and the relative permeability of the material; V_m – scalar magnetic potential; $\boldsymbol{B}$ – vector of magnetic induction; $\boldsymbol{H}$ – magnetic field vector; $\boldsymbol{M}$ – the magnetization vector.

The permanent magnets electromagnetic field is also solved with respect to the scalar magnetic potential, but the equation takes a different form, taking into account the properties of permanent magnets:

$$\begin{cases} \boldsymbol{B} = \mu_0\cdot\mu_m\boldsymbol{H} + B_r \\ B_r = \|B_r\|\dfrac{e}{\|e\|} \end{cases} \tag{4}$$

where: μ_m is the permanent magnet magnetic permeability; B_r – residual magnetization of a permanent magnet; e – residual magnetization permanent magnets vector (x, y or z axis).

Stator magnetic core, generator housing and the shaft are made of a magnetic material, which is characterized by a nonlinear relationship between the magnetic induction $\boldsymbol{B}$ and the magnetic field $\boldsymbol{H}$. The electromagnetic field equation for these areas and the nonlinearity of the ferromagnetic material are described by the following equations:

$$\begin{cases} \nabla\times\boldsymbol{H} = \boldsymbol{J} \\ \boldsymbol{B} = \nabla\times\boldsymbol{A} \\ \boldsymbol{E} = -\dfrac{\partial\boldsymbol{A}}{\partial t} \\ \boldsymbol{J} = \sigma\boldsymbol{E} \\ \boldsymbol{B} = f(\|H\|)\dfrac{\boldsymbol{H}}{\|H\|} \end{cases} \tag{5}$$

where: $\boldsymbol{J}$ is the current density vector; $\boldsymbol{E}$ is the electric field vector; σ is the material electrical conductivity.

The first four equations of the system (5) are valid for the three-phase generator armature winding. At the same time, the current density in the armature windings, induced EMF and other winding parameters are determined by the following equations system:

$$J_e = \frac{N(V_e + V_{ind})}{S_c\cdot R_c}$$

$$R_c = \int_A \frac{N\cdot L}{\sigma_c\cdot a_c\cdot S_c}dA \tag{6}$$

$$V_{ind} = N\cdot\sum\frac{L}{S_c}\cdot\left(\int_{S_c}E_{zA}ds - \int_{S_c}E_{zx}ds\right)$$

where: J_e is the current density in the armature winding, which depends on the value of the load and the type of the generator's operation; N is the number of turns in the armature winding; S_c is the cross-sectional area occupied by the conductor winding; R_c is the stator winding phase resistance; L is the average length of one stator winding turn; σ_c, a_c – stator winding electrical conductivity and the cross-sectional area of the elementary conductor; V_{ind} is the value of the induced EMF in the stator winding; V_e is the output generator voltage depending of load; E_{zA}, E_{zX} – electric field in the phase zones "A" and "x".

To ensure a single solution of the differential equations (3-6) system, an additional condition is set for all regions with vector magnetic potential $\boldsymbol{A}$:

$$\nabla\cdot(\sigma\boldsymbol{A}) = 0 \tag{7}$$

Simulation results. In the simulation, the rated rotation speed of the rotor is equal to 500 rpm. In Fig. 3 shows the magnetic flux density (background coloring) distribution and the line of the main magnetic flux (arrows) for the start computation time and at the time 0.02 s. The current in the excitation winding is equal to I_e=0 A.

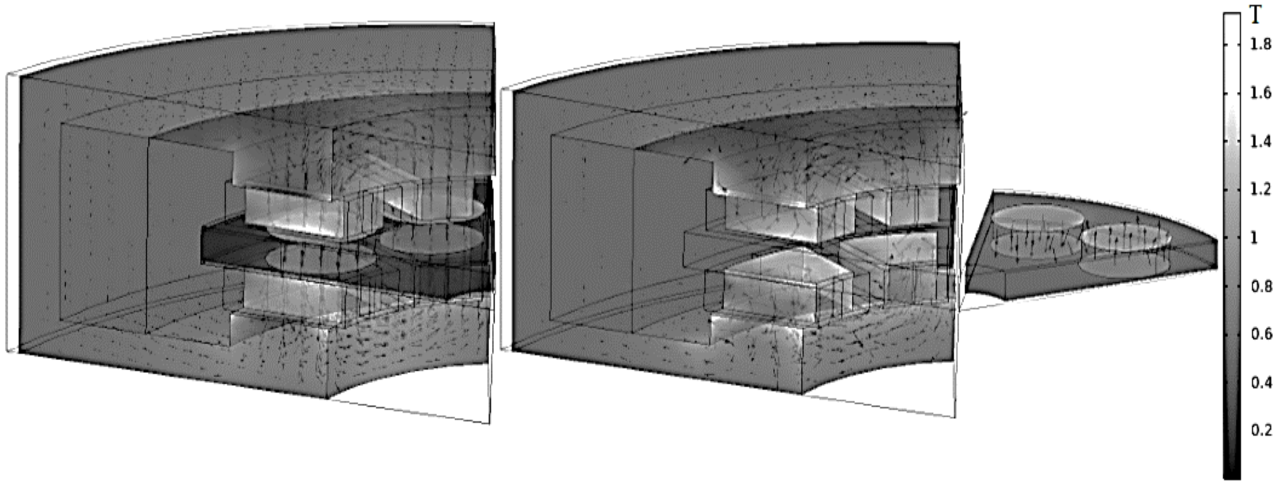

Fig. 2. Magnetic flux density and magnetic field distribution in computation area

The average value of the magnetic flux density in the stator teeth is ≈1.49 T, in the stator yoke ≈1.04 T, in the air gap ≈0.376 T. The calculated values of the magnetic flux density in the structural elements are within the acceptable range, which indicates the correct basic geometric dimension's selection. For elected soft iron material, the maximum induction level in the teeth is equal to ≈1.9 T. This allows to use an additional winding for increasing main magnetic flux and provides an appropriate range of voltage regulation.

When the current is applied to the additional winding in the housing of the generator, a significant magnetic induction of ≈1.28 T is appearing. At the same time, the aver-age induction value in the stator teeth increases to ≈1.91 T, in the stator yoke to ≈1.54 T, in the air gap to ≈0.477 T.

Permanent magnets on the rotor and magnetic shunts are arranged in such an order and in such a way that the following path is formed for closing the main magnetic flux of permanent magnets (at Ie=0 A): permanent magnet-air gap 1-stator tooth 1 -stator yoke 1-generator housing 1-back housing-generator housing 2-stator yoke 2-stator tooth 2-air gap 2-permanent magnet. This characteristic of the main magnetic flux circuit is caused by the fact that the structural elements of the generator (case, back of the case) are unsaturated and, accordingly, at Ie=0 A, the magnetic resistance of this section is significantly less than expected due to the air gap and magnetic shunt. This is a feature of the magneto-electric generator with an axial magnetic flux and a double stator.

Numerical calculations of the studied generator were carried out for two modes of operation: when the current in the excitation winding is Ie=0 A, and when the current is supplied to the additional winding Ie=1 A.

In fig. 4 shows the distribution of the magnetic induction and the main magnetic flux when the current is supplied to the additional winding with a value of Ie=1 A.

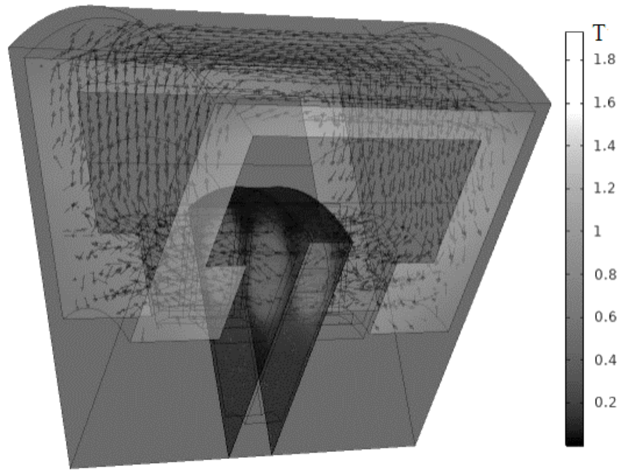

Fig. 4. Magnetic flux density and magnetic flux distribution in AFMEG

When the current is applied to the additional winding in the case (capsule) of the magnetic core of the generator under study, a significant magnetic induction of ≈1.28 T appears. At the same time, the average induction value in the stator teeth increases to ≈1.91 T, in the stator yoke to ≈1.54 T, in the air gap to ≈0.477 T.

On Fig. 5 shows the distribution of the axial component of the magnetic induction Bδ in the air gap δ for two cases: 1 – when current in the additional winding is Ie=0 A; 2 – when current in the additional winding Ie=1 A.

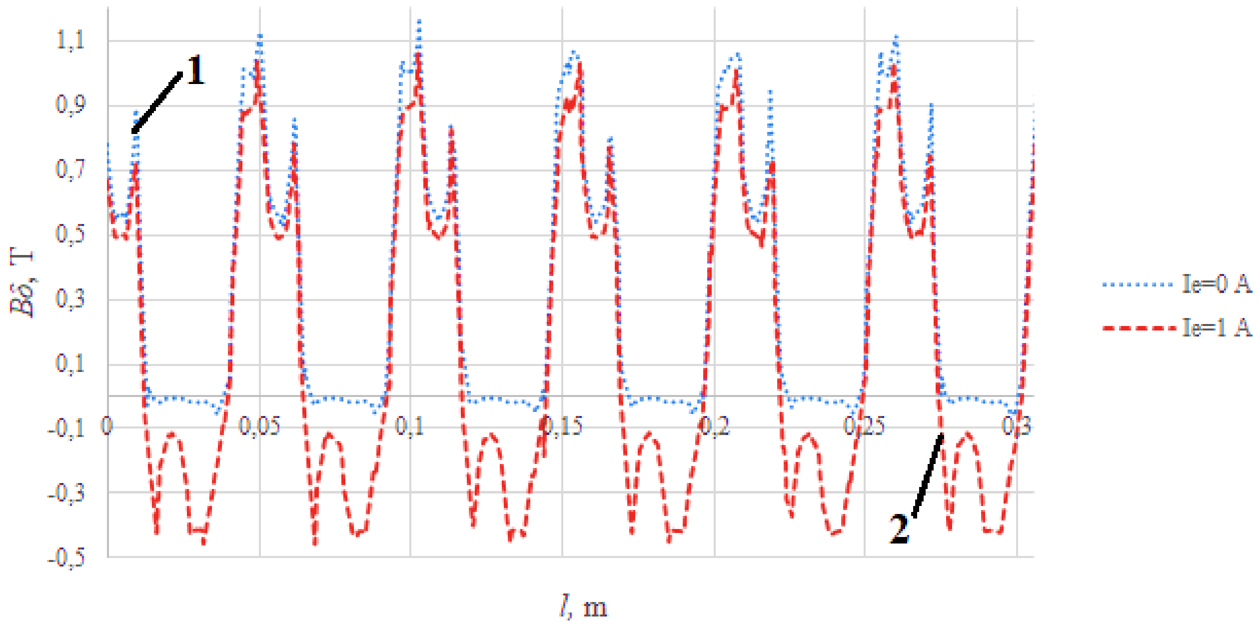

Fig. 5. Magnetic flux density distribution in the air gap: curve 1: I_e=0 A, curve 2: I_e=1 A

When a current is applied to the additional winding Ie=1 A (Fig. 5, curve 2), a path appears path for additional winding magnetic flux circulation through magnetic shunts: yoke of the housing - generator housing 1 - stator yoke 1 - stator tooth 1 -air gap 1-magnetic shunt-air gap 2-stator tooth 2-stator yoke 2-generator housing 2- yoke of the housing.

The magnetic flux of the additional winding partially reduces the main magnetic flux under the poles with permanent magnets (Fig. 5, curve 1, 2) and magnetizes the magnetic shunts in the rotor. So, the average value of the EMF in the air gap increases, and therefore the magnitude of induced EMF in the armature windings also increases. Due to the design of the generator with a double stator and armature windings connection scheme, an EMF has almost sinusoidal shape, which will be proved in the following authors works.

As part of this work, the external characteristic was calculated for a power factor is cosφ=1 when the current of the additional winding is 0A and at Ie=1 A. It simulated by the equations system (6). Fig. 6 shows the external (load) characteristics of the studying generator.

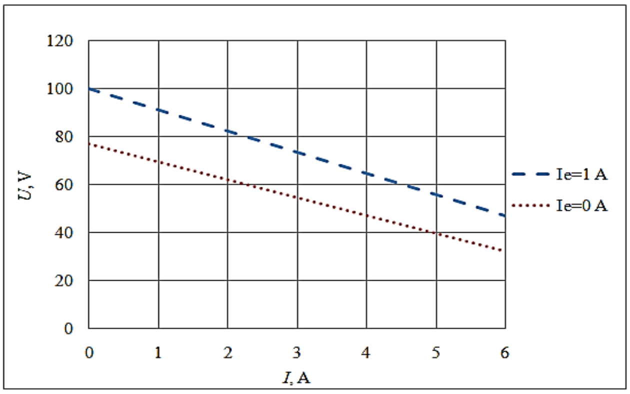

Fig. 6. Load characteristics of AFMEG

According to Fig. 6, when supplying direct current to the additional winding, the output voltage of the generator increases by ≈24%. For more rigid stabilization of the output voltage, it is necessary to synthesize the current control law of the additional winding. This task will be considered in the next works.

Conclusions.

A three-dimensional mathematical model of AFMEG with a double stator has been developed, which allows to obtain electromagnetic field distribution and allows analyzing its parameters and characteristics.

The model fully takes into account the design features of AFMEG generator: end-effects, axial magnetic flux of stator winding and magnetic flux of additional winding. Was calculated the external characteristics, which indicates the correspondence of the developed mathematical model to physical processes.

The analysis of magnetic induction in the air gap and in structural elements of the generator was carried out. The analysis of the obtained values showed that the geometric dimensions of the generator, which were previously selected, are correct and do not require significant adjustments. In the future, it allows you to use the results of this calculation for the preparation of documentation for the production of the prototype. Using of an additional winding makes it possible to stabilize the external characteristics of a generator with permanent magnets within wide limits up to 25-35% from no load value.

References

1. Zheng Ma, Jingwei Ai, Yamei Yue, Kun Wang, Bin Su, A superhydrophobic magnetoelectric generator for high-performance conversion from raindrops to electricity, Nano Energy, Volume 83, 2021, 105846, ISSN 2211-2855, https://doi.org/10.1016/j.nanoen.2021.105846.
2. Radwan-Pragłowska, N., Wegiel, T., Borkowski, D. (2020). Modeling of Axial Flux Permanent Magnet Generators. Energies, no. 13 (21), 5741-5745. https://doi.org/10.3390/en13215741.

3. Sadullaev, N & Nematov, Sh & Sayliev, F. (2022). Evaluation of the technical parameters of the generator for efficient electricity generation in low-speed wind and water flows. Journal of Physics: Conference Series. 2388. 012142. 10.1088/1742-6596/2388/1/012142.
4. S. Djebarri, J. F. Charpentier, F. Sciuller and M. Benbouzid, "Design and Performance Analysis of Double Stator Axial Flux PM Generator for Rim Driven Marine Current Turbines," in *IEEE Journal of Oceanic Engineering*, vol. 41, no. 1, pp. 50-66, Jan. 2016, doi: 10.1109/JOE.2015.2407691.
5. M. A. Noroozi Dehdez and J. Milimonfared, "A Novel Radial–Axial Flux Switching Permanent Magnet Generator," in IEEE Transactions on Industrial Electronics, vol. 69, no. 12, pp. 12096-12106, Dec. 2022, doi: 10.1109/TIE.2021.3128901.
6. F. Yu et al., "Design and Multiobjective Optimization of a Double-Stator Axial Flux SRM With Full-Pitch Winding Configuration," in IEEE Transactions on Transportation Electrification, vol. 8, no. 4, pp. 4348-4364, Dec. 2022, doi: 10.1109/TTE.2022.3173938.
7. J. Zhao, Y. Wang, J. Li and H. Hu, "Comparative Study on Torque Performance of Five-phase Single-Stator and Double-Stator Permanent Magnet Synchronous Motors," in CES Transactions on Electrical Machines and Systems, vol. 6, no. 1, pp. 46-52, March 2022, doi: 10.30941/CESTEMS.2022.00007.
8. Sun, Y. & Yu, F. & Yuan, Y. & Huang, Z. & Huang, Y. & Zhu, Z. (2019). A Hybrid Double Stator Bearingless Switched Reluctance Motor. Diangong Jishu Xuebao/Transactions of China Electrotechnical Society. 34. 1-10. 10.19595/j.cnki.1000-6753.tces.L80363.
9. Cendoya, M. & Talpone, Juan & Puleston, P.F. & Barrado, José Antonio & Martinez-Salamero, L. & Battaiotto, P.E. (2021). Management of a Dual-Bus AC+DC Microgrid Based on a Wind Turbine with Double Stator Induction Generator. Wseas transactions on power systems. 16. 297-307. 10.37394/232016.2021.16.30.
10. Li, Zheng et al. 'Design and Analysis of Underwater Power Generation Characteristics of Deflected Double-stator Switched Reluctance Generator'. 1 Jan. 2022: 1 – 20.
11. Widyanto, Aji & Ariwidayat, Rahmat & Husnayaian, Faiz & Rahardjo, Amien & Utomo, A.R. & Ardita, I. (2022). Designing Air-Cored Axial Flux Permanent Magnet Generator with Double Rotor. ELKHA. 14. 46. 10.26418/elkha.v14i1.53048.
12. Ostroverkhov, M., Chumack, V., Falchenko, M., & Kovalenko, M. (2022). Development of control algorithms for magnetoelectric generator with axial magnetic flux and double stator based on mathematical modeling. *Eastern-European Journal of Enterprise Technologies*, 6 (5 (120), 6–17. https://doi.org/10.15587/1729-4061.2022.267265.
13. V.M. Golovko, M.Ya. Ostroverkhov, M.A. Kovalenko, I.Ya. Kovalenko, D.V. Tsyplenkov Mathematical simulation of autonomous wind electric installation with magnetoelectric generator. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu. 2022, (5): 074 – 079. https://doi.org/10.33271/nvngu/2022-5/074.
14. Setyawan, E. Y., Soleh, C., Krismanto, A. U., Sujana, I. W., Djiwo, S., & Prihatmi, T. N. (2022). Design and Performance Analysis of Double Axial Flux Permanent Magnet Generator. *Trends in Sciences*, 19 (6), 3049. https://doi.org/10.48048/tis.2022.3049
15. Prasetijo, Hari. (2022). Pengaruh Inti Stator Terhadap Performa Generator Magnet Permanen Fluks Aksial Satu Fasa. JRST (Jurnal Riset Sains dan Teknologi). 6. 165. 10.30595/jrst.v6i2.13668.
16. Wirtayasa, Ketut & Irasari, Pudji & Kasim, Muhammad & Widiyanto, Puji & Hikmawan, Muhammad. (2019). Load characteristic analysis of a double-side internal coreless stator axial flux PMG. Journal of Mechatronics, Electrical Power, and Vehicular Technology. 10. 17. 10.14203/j.mev.2019.v10.17-23.
17. Lee, J.-Y.; Lee, J.-H.; Nguyen, T.K. Axial-Flux Permanent-Magnet Generator Design for Hybrid Electric Propulsion Drone Applications. *Energies* **2021**, 14, 8509. https://doi.org/10.3390/en14248509
18. Tokgoz, Furkan. (2022). Analytical Modelling and Multi-Objective Optimization of Axial-Flux Permanent Magnet Machine with Various PCB Stators and Development of a GaN Switched Integrated Motor Drive PCB Motor.
19. Kastawan, I & Rusmana,. (2020). Pengujian pembangkitan tegangan generator axial-flux permanent magnet (AFPM) tiga-fasa ganda. Jurnal Teknik Energi. 6. 503-509. 10.35313/energi.v6i2.1713.
20. Asfirane, S., Hlioui, S., Amara, Y., Gabsi, M. (2019). Study of a Hybrid Excitation Synchronous Machine: Modeling and Experimental Validation. Mathematical and Computational Applications, 24 (2), 34. doi: https://doi.org/10.3390/mca24020034
21. Wardach, M., Bonislawski, M., Palka, R., Paplicki, P., Prajzendanc, P. (2019). Hybrid Excited Synchronous Machine with Wireless Supply Control System. Energies, 12 (16), 3153. doi: https://doi.org/10.3390/en12163153
22. Biletskyi, Yu. O., Shchur, I. Z. & Kuzyk, R.-I. V. "Passivity-Based Control System for Stand-Alone Hybrid Electrogenerating Complex". *Applied Aspects of Information Technology*. 2021; Vol. 4 No. 2: 140–152. DOI: https://doi.org/10.15276/aait.02.2021.2.

Надійшла (received) 11.10.2023

Відомості про авторів / About the authors

Чумак Вадим Володимирович (***Chumak Vadim Vladimirovich***) – кандидат технічних наук, доцент, Національний технічний університет України "Київський політехнічний інститут імені Ігоря Сікорського", доцент кафедри електромеханіки, тел.: (050) 208-38-43; ORCID: https://orcid.org/0000-0001-8401-7931; e-mail: chumack_kpi@ukr.net.

Коваленко Михайло Анатолійович (Kovalenko Mykhaylo) – кандидат технічних наук, доцент, Національний технічний університет України "Київський політехнічний інститут імені Ігоря Сікорського", доцент кафедри електромеханіки, тел.: (067) 656-36-51; ORCID: https://orcid.org/0000-0002-5602-2001; e-mail: kovalenko_ma@i.ua.

Коваленко Ірина Яківна (Kovalenko Iryna Yakivna) – асистент, Національний технічний університет України "Київський політехнічний інститут імені Ігоря Сікорського", аспірант кафедри нетрадиційних та відновлювальних джерел енергії, тел.: (097) 939-96-73; ORCID: https://orcid.org/0000-0003-1097-2041; e-mail: 2048141@ukr.net.

Ткачук Ігор Валерійович (Tkachuk Ihor) – аспірант кафедри електромеханіки, Національний технічний університет України "Київський політехнічний інститут імені Ігоря Сікорського", тел.: (097) 988-51-24; ORCID: https://orcid.org/0000-0002-5717-2458; e-mail: baja0073@gmail.com.

Тимощук Оксана Леонідівна (Tymoshchuk Oksana) – кандидат технічних наук, доцент, кафедра математичних методів системного аналізу навчально-наукового Інституту прикладного системного аналізу, Національний технічний університет України "Київський політехнічний інститут імені Ігоря Сікорського", тел .: 093-437-89-14; ORCID: https://orcid.org/0000-0003-1863-3095; e-mail: oxana.tim@gmail.com.