Development brushless direct current electric motor of the Pilger mill drive for the technology of seamless pipes manufacturing based on the magnetic system with claw-poles

Bakhtiyor Kosimov\textsuperscript{1,2}, Sergey Gandzha\textsuperscript{1} Dilshod Aminov\textsuperscript{1,2}, Azamdzhon Davlatov\textsuperscript{1}, Dilovar Gulov\textsuperscript{1}, Ilhom Abdulloev\textsuperscript{1}

\textsuperscript{1}South Ural State University, Chelyabinsk, Russia
\textsuperscript{2}Tajikistan Power Energy Institute, Khushoniyon, Tajikistan

Abstract. Currently, metallurgical industry contains a large number of morally and physically outdated electrical equipment that requires modernization. It requires a large capital expenditure to replace it. For this reason, it is slow to implement, long-term use for the purpose of payback, and slow to withdraw from manufacturing. In this regard, the new equipment must be innovative and in many respects ahead of the existing level of development of the industry. The article suggests such a solution. To replace the existing collector motor of the pilger mill drive for the manufacturing of seamless pipes, which has been operating since 1928 and is in a critical condition, a large-sized low-speed brushless motor with a large built-in inertial mass is proposed, which has a permanent magnet magnetic system and claw-poles. Such a technical solution for drives of this class has not been used in the world. The motor eliminates the existing 120-ton flywheel, improves reliability due to contactless current supply, and reduces operating costs by eliminating excitation losses. The motor design allows its Assembly without additional tooling, which is very important for large motors with permanent magnets. To develop a unique motor, a design system consisting of a synthesis subsystem and an analysis subsystem was created. The synthesis subsystem implements multi-level single-criteria optimization. As a result of its operation, the optimal geometry is determined based on the selected criterion. The analysis system confirms the calculation reliability using simplified optimization methods and finally removes technical risks before manufacturing an industrial design. It is based on the well-developed Ansys Electronics Desktop and Ansys Icepak systems for CAE electric machines. The analysis has several stages, which includes electromagnetic and thermal analysis. It is based on the well-developed for CAE systems electric machines Ansys Electronics Desktop and Ansys Icepak. The analysis has several stages, which includes electromagnetic and thermal analysis. The effectiveness of the design system was tested on a real project that was performed for the Chelyabinsk rolling mill. This approach is recommended for the design of other similar types of brushless direct current drive. Key words: pilger mill, CAE systems, synthesis, analysis, thermal analysis, brushless direct current motor, claw-poles, magnetic system, tangential magnets, two-dimensional model, three-dimensional model.
1 Introduction

The Ural region is traditionally one of the centers of heavy industry. Historically, large-scale mechanical engineering and metallurgy have developed here for more than two centuries. These trends are still present today. A feature of the development of this industry is inertia. First of all, this is due to the large capital costs of modernizing production. Scientific developments and innovative solutions are much slower to be implemented in this area than in other industries. This can explain the fact that many heavy industry enterprises in Russia still use pre-war and post-war equipment. In this regard, it is very important that technical solutions for this industry are significantly ahead of time and innovative. They will be slowly implemented and then work for a long time until moral and physical wear and tear.

One such example is the current pilger mill drive at the Chelyabinsk pipe rolling plant for the production of seamless pipes of various diameters that are used in the oil and gas sector. The drive has been operating since 1928. The main parameters of the synchronous collector motor from Siemens are shown below, and its General appearance is shown in Fig. 1:

- rated power of 2.75 MW;
- rated voltage power supply 6 kV DC;
- rated speed of 35 rpm.

The electric drive rotates a massive flywheel with a diameter of 9 m and a weight of 120 tons. Continuous electric motor operation has led to physical and moral wear and tear. Numerous defects were found that could cause an accident. As obvious problems can be noted the appearance of microcracks on the motor shaft due to shock load, which can lead to the destruction of the shaft. Taking into account the 3-shift operation of the drive, special attention should be paid to solving issues of energy efficiency and energy saving of the new electric motor and its drive. The key task of the enterprise at present is to replace the existing collector electric motor with a more modern, reliable, energy-efficient contactless electric motor.

2 Requirements for a new drive

According to the terms of the customer, when replacing the electric motor in question, the main components and assemblies of the existing drive must remain unchanged, namely:
- two-roll cage with variable cross-section gauge;
- feeding mechanism.

Therefore, only the electric motor and the massive flywheel must be replaced. The customer's requirements for new equipment are listed below:
- the new unit should not exceed the dimensions of the manufacturing room facility where it should be placed;
- to increase reliability and reduce operating costs the new drive must have a contactless current supply;
in order to be able to roll pipes of different diameters, the drive speed adjustment must be within the range of 30-45 rpm, while ensuring the stability of the selected speed;
it is necessary to reduce operating losses by increasing the efficiency of the drive;
the time it takes to replace the old drive with a new drive should not cause continuous production to stop for a long time;
the proposed electric motor and its control system should have the lowest possible cost.

3 Selecting the basic motor option for the pilger mill drive

Analysis of trends in the development of modern electrical engineering allows us to choose a brushless electric drive as the most prospective one [1-5]. This is due to the fact that the power and reliability of brushless machines are steadily increasing, including in aggressive environments. At the same time, the price of such drives is reduced and becomes affordable for medium-sized enterprises. This is facilitated by the development of production of high-power high-coercivity permanent magnets and power electronics for high currents and voltages. Currently, the development of controlled current frequency converters at a power of tens and hundreds of megawatts does not present practical problems. A well-established vector control, which is effective from the point of view of mass and energy indicators. Various designs with efficient magnetic systems for the inductor have appeared. These positive trends allow us to design and produce valve engines and generators for tens and hundreds of megawatts.

But practice shows that powerful and large-sized brushless direct current (BLDC) machines are produced with electromagnetic excitation without permanent magnets. This is due to the technology of manufacturing machines with permanent magnets, which have a large diameter. When assembling an electric machine, when the inductor is inserted into the armature, very strong magnetic forces occur. When using powerful magnets, these forces can reach several tons. The rotor is attracted to the stator walls, and assembly becomes almost impossible. Theoretically, it is possible to design equipment for the assembly of such electric machines, but calculations show that the cost of these devices can be ten times higher than the cost of the motor itself. The same problems occur when disassembling the inductor for routine maintenance and repair work.

Investigations to solve this technological problem led to the selection and analysis of the brushless machine with claw-poles [6-8]. The design of an inductor with claw-poles with a permanent magnet is shown in Fig. 2

It should be noted that the magnetic system with claw-poles cannot be considered effective. It has a large scattering flux that saturates the magnetic core, but does not participate in energy conversion. With this disadvantage, this design has a great advantage. The inductor can be assembled directly in the electric machine itself in parts using the following technology:

1. Initially, a shaft with the lower clip of claw-poles is inserted into the anchor. This part of the magnetic system at this stage of assembly does not contain permanent magnets and, for this reason, will not be attracted to the walls of the anchor;
2. At the second stage of assembly, a permanent magnet is mounted in the inductor. Depending on its size, it can be glued together in separate parts, or it can be mounted as a whole;
3. At the third stage, the upper cage with claw-poles is inserted into the inductor. Under the action of the electromagnetic forces of a permanent magnet, it must be drawn into the inductor;
4. At the last final stage, the bearing mounting shield completes the assembly.

The build technology is shown in fig. 3
Fig. 3. Technology motor Assembly (1-installation of the stator Assembly, 2-installation of the first half of the claw-rotor, 3,4 - installation of a permanent magnet, 5-installation of the second half of the claw-rotor, 6-final Assembly of the motor).

This technology of Assembly of the claw-poles brushless motor (CPBM) does not require expensive equipment and special devices and is offered for the first time.

By optimizing the geometry and choosing the correct size of the circled permanent magnet, the magnetic system can be made efficient enough with a large working magnetic flux.

Magnetic systems with claw-poles are well studied [9-13], but this applies to electric drives of low and medium power. The development of multi-megawatt brushless machines with a bore diameter of several meters is unique for engineering practice. In this regard, the task of theoretical research and practical implementation of such a design in real production has become urgent.

4 Statement of the CPBM synthesis and analysis problem

A special feature of the pilger mill drive is the low speed of the shaft rotation at high impact loads. Operating conditions do not allow the use of a step-up gearbox for the motor due to high dynamic moments, so the motor has large dimensions. It is impossible to apply the similarity theory in this case, when an optimally designed low-power motor proportionally increases in size to a given power. In electrical engineering, this technique is not used. This is due to sharply nonlinear relationships between the linear dimensions of the engine, electromagnetic loads and its electromagnetic power.

The design of large-capacity and large-size motors is associated with high capital costs. It is impossible to lead a project along the traditional path: creating and researching a mock-up model, a prototype, or a serial product. Modern development of computer technology and software allows you to go through these stages on a digital double before making a real motor. To do this, you need to create a design system for synthesizing the optimal geometry and analyzing the resulting electronic prototype.

For synthesis, it is necessary to choose the most suitable method of nonlinear programming for this mathematical model.

For better analysis of electrical machines of this class, you can use well-developed and proven CAE systems based on the finite element method, such as Ansys Electronics Desktop. Such a design system for designing the CPBM was created. The functional diagram of the design system is shown in the following figure:

Fig. 4. Functional diagram of the design system for a brushless machine with the claw-like magnetic system

Division of the project system into two parts: synthesis and analysis is explained by the following reasons. Geometry optimization involves a large number of iterations when changing independent variables. Depending on the selected...
method, the number of mathematical model calculation cycles can be up to several thousand. It is clear that optimal
design methods can only work with a very simplified model with a large number of restrictions [14,15]. It is impossible
to leave this model as the final one, even after the optimization procedure, because of the high risks of capital
expenditures for the development of design and technological documentation and sample production. A thorough
analysis of the results obtained on the basis of more accurate methods of digital duplicates is necessary. This task is
performed by the analysis system.

The length of the article does not allow us to describe both systems in detail. The work of the synthesis system is
presented in a number of already published articles [16]. Briefly note that the synthesis system is based on the method
of substitution schemes. The optimal design problem is formulated as a multi-level single-criteria problem. For the
algorithm for iterating through independent variables, a method is chosen that combines the Gauss-Seidel coordinate
descent method when moving to the optimum with the Fibonacci method when choosing a step. The algorithm has a
built-in method of penalty functions when searching for an optimum on the boundary.

We will describe the construction of the analysis system and the results of its work in more detail, since several
innovative solutions were adopted during its development.

As it was noted, the Ansys Electronics Desktop software package was selected for the analysis system out of numerous
possible options [17-20]. It contains a large number of well-developed methods of typical designs of electric machines.
CPBM is included in the list of these machines. The software package allows you to make a preliminary analysis of this
machine in RMxprt mode. This mode makes the calculations based on the method of equivalent circuits. To do this, just
fill in table forms with the machine geometry, materials, and parameters of the nominal mode, which greatly facilitates
the analysis of the machine. However, it should be noted that in the latest version of the program, you can only analyze
the generator mode of operation. For the pilger mill drive requires an analysis of the motor operation. Due to the
specifics of the drive operation, it may differ significantly from the generator mode, which leads to technical risks when
introducing the drive into production.

The software package allows you to deploy the task in a 3D model. The program does this automatically when you
select Create Maxwell 3D Design mode. It is not possible to expand the problem of analyzing a gate machine into a 2D
model, since the machine geometry does not have flat symmetry.

At this stage of creation of the system, the developers encountered a very big problem. Test calculations showed that
when using the Ansys Electronics Desktop program for a 3D model in the mode of solving the transient dynamic
problem for a machine with a claw-like magnetic system, the waiting time for the results of calculating the main
characteristics was from 8 to 15 hours. It should be noted that a powerful University supercomputer was used to solve
the problem. The procedure of parallelizing the problem solution to several processor cores did not significantly
improve the result. One of the probable reasons was the fact that the formation of the design grid came from an air gap
of several millimeters, and the dimensions of the entire engine were more than 6 meters. The grid generator divided the
calculated area into a very large number of elements. At the same time, for the convergence of the process, the grid was
repeatedly rebuilt.

Of the existing standard designs of brushless machines in the Ansys Electronics Desktop software package, the closest
to a claw- poles brushless motor was the design of a BLDC type brushless machine with tangential poles. This brushless
machine has a similar armature. The inductors of these machines differ, but there are no electric or magnetic losses in
the inductor. The above suggests that in cases of choosing an identical magnetic flux in the inductor of a brushless
machine with a tangential excitation system, and a completely identical armature, you can get almost a twin machine for
analyzing the main characteristics.

At the same time, BLDC analysis can be performed in a two-dimensional problem statement, which reduces the
calculation time to 25-45 minutes.

When writing the program of synthesis and analysis of the projected electric machine with claw- poles, the justified
principles of replacement were made at the stage of synthesis and analysis, the description of which is discussed below.

5 Description of the software package for designing brushless machines with claw-
poles (CPBM)

Implementation of the task starts with the synthesis. At this stage, the optimal geometry of the machine and the winding
data of a real CPBM are determined. The obtained results of optimization calculations based on a pre-prepared script
are transmitted to the Ansys Electronics Desktop program. The correctness of the calculated data is checked in the
RMxprt mode, which is based on this construction. At the same time, the accuracy of solving the optimization problem
is checked for the main parameters (efficiency, losses, flow in the gap, moment, induced by EMF in phases).

If the marked basic parameters differ in the synthesis and analysis subsystem, the procedure is repeated with the
correction of these data in the synthesis subsystem, since the analysis subsystem is considered a reference.

After optimization for the main parameters without leaving the RMxprt mode, the real machine with claw-poles
CPBM is replaced by a machine analogous to BLDC. For replacement, the data obtained from the claw-poles model is
transmitted to the model of a brushless machine with a tangential excitation system. In this case, the internal diameter of
the armature of the BLDC machine is selected so that the main magnetic flux passing from the rotor to the stator
coincides with the magnetic flux of the CPBM armature.
At the same time, we check the identity of the characteristics of both machines. After all tasks are completed, the machine automatically switches from RMxpert mode to Maxwell 2D Design mode. In this mode, the machine geometry is constructed and analysis is performed using the finite element method. The calculation time of the electromagnetic field parameters is 20-40 minutes.

At the final stage, a three-dimensional (3D) model of the claw-poles machine CPBM is analyzed with the corresponding real parameters. The calculation time is several hours, but it is quite acceptable for a one-time calculation.

Below is shown one of the tabs of the developed optimization program implemented in the programming language Delphi for an example of a brushless motor with a claw-like magnetic system with the following parameters: 2.5 MW, 600 V, 40 rpm to drive the pilger mill.

Figure 4 shows the results of the first stage (the synthesis program). The program is an author's development and is written in the Delphi programming language. It determines the optimal geometry of the machine according to the customer's technical specification.

To check the correctness of the parameters calculated at this stage, they are passed to the Ansys Electronics Desktop program in RMxpert mode using a pre-prepared script.

The results of calculating the claw-poles brushless machine in RMxpert mode are shown in Fig. 5.
To obtain the results of calculating the data of the brushless motor with the tangential inductor (BLDC), we take the same parameters (stator dimensions and winding data) of the corresponding machine with claw-poles (CPBM) as the initial data. In this case, the magnetic flux of the twin machine is selected using the internal diameter equal to the magnetic flux of the machine with claw-poles (CPBM).

The analysis results of the calculated data of the brushless machine with a tangential system in RMxpert mode are shown in Fig. 6.

Follow-up actions are performed in Maxwell 2D Design. To perform this action, the design of a brushless DC motor with permanent magnets (BLDC) is deployed in a flat two-dimensional model. This model has an analogy with a machine with claw-poles, i.e. it has the same anchor and magnetic flux. Simulating an electronic circuit for performance analysis is performed in the Ansys Citrix Circuit.

Simulation results of the BLDC motor with tangential magnets in Maxwell 2D Design, as well as the diagrams of its simulator are shown in Fig. 7.
The calculated curve of the electromagnetic moment is shown in Fig. 8

![Electromagnetic torque curve](image)

**Fig.8.** Electromagnetic torque curve

At the final stage, after the final determination of the optimal geometry and winding data, the transition to the RMxprt mode for the machine with claw-poles takes place. From this mode, using the options of the Ansys Electronics Desktop program, a real three-dimensional model of the machine is built for the final analysis and construction of the main characteristics.

Three-dimensional model in Maxwell 3D Design mode is shown in figure 9.

![3D modeling of the machine with a claw-like magnetic system (CPBM)](image)

**Fig. 9.** 3D modeling of the machine with a claw-like magnetic system (CPBM)

Electromagnetic moment curve of the machine with the claw-like magnetic system calculated for a three-dimensional model in Maxwell 3D Design mode is shown in Fig. 10.

![Electromagnetic moment curve](image)

**Fig. 10.** Electromagnetic moment curve of the machine with a claw-like magnetic system in a three-dimensional model from the Maxwell 3D Design mode

Figure 10 shows that the calculated torque curve of a claw-like magnetic system (CPBM) motor is almost identical to the same curve for the motor BLDC (see figure 8).

Fig. 11 shows the design system stages in the form of the following algorithmic scheme for a clearer understanding of its functioning.

![Algorithmic scheme](image)

**Fig. 11.** Algorithmic scheme of the project system functioning.

Thus, using this design system, it is possible to perform synthesis and multi-stage analysis of the electric machine with a claw-like magnetic system.
6 Thermal analysis of the state CPBM using the Ansys Icepak software package

Calculation of the thermal state of high-power brushless DC motors is a very important step in the analysis. Its evaluation requires the use of precise modern programs based on the finite element method. These calculations are labor-intensive, but they significantly reduce the technical risks before manufacturing a prototype [18-20]. The following positive trend should be noted when creating modern CAE systems. It is now possible to combine different programs into a single model to solve a related problem through the Ansys Workbench shell. Let's use this opportunity and create a calculated thermal model based on the following calculation scheme. Initially, we will perform CPBM electromagnetic state calculation in the program Ansys Electronics Desktop. Based on the results of this calculation, we will more accurately determine the losses in steel and copper of the armature winding. Next, we will pass the data to the Workbench shell. It is a link to the heat calculation program. In the next step, we will pass the data directly to the Icepak thermal field calculation program.

Thus, the related magnetodynamic and thermodynamic tasks are solved. This calculation scheme is shown in Fig. 12

![Thermal calculation scheme](image)

In the Icepak program, the final configuration of the thermal task is performed:
- materials are refined taking into account their thermodynamic properties;
- set the size of the area where the heat exchange is performed;
- set the speed of the cooling agent and the nature of its movement (laminar, turbulent);
- the calculation grid is set up.

Thermal calculation is performed in an iterative way, during which the partition grid is refined into finite elements and the convergence of the computational process is determined.

As a result of the calculation, the temperature in each element that the motor model is divided into is determined. Thus, we can calculate the temperature field in contrast to the integral temperature, which is determined by the method of equivalent thermal substitution schemes. The temperature distribution for the 3D model is shown in figure 13. The figure shows the maximum calculated temperature of 359 degrees Kelvin. When converted to degrees Celsius, this value will be 86°C.

![Temperature field of CPBM calculated in the Ansys Icepak software package](image)

Thus, thermal calculation by the finite element method gives an accurate picture of the CPBM heating.

Positive simulation results finally remove technical risks for development results of CPBM that allows you to move onto the final stage – the creation of three-dimensional solid models and developing design documentation for the creation of a prototype.

**Analysis of results.** Modern applications of the CAE system allow you to calculate and analyze the parameters and characteristics of electrical machines.

It should be noted that these programs require very high performance and large computer resources. Not every engineer and researcher can afford such opportunities. One of the main problems during the calculation is the duration of the calculation process.
Practice shows that the developer of electric machines does not always need to complicate the calculation model. To obtain accurate results of three-dimensional objects can be represented in the form of two-dimensional models that do not require large computational resources.

This approach was applied to the brushless machine with a claw-like magnetic system. After the synthesis stage, where the simplified model was optimized with a substitution scheme, the results of optimization data were analyzed in the Ansys Electronics Desktop software environment, where the problem of calculating the magnetic field for a two-dimensional model (Maxwell 2D Design) and a three-dimensional model (Maxwell 3D Design) was solved sequentially.

Differences in the main parameters (efficiency, electromagnetic moment, speed, magnetic flows, rotation EMF) of the design system functional scheme for the brushless machine with a claw-like magnetic system are presented below:
- the error between the calculated parameters obtained in the Delphi and RMxprt program for the machine with claw-poles was from 5 to 9 %;
- the error between the results in RMxprt for the machine with claw-poles and the RMxprt results for a brushless machine with tangential magnets was 3-5 %;
- the error between the results of the calculation in Maxwell 2D mode for the brushless motor with tangential magnets and the results of the calculation in Maxwell 3D for the machine with claw-poles was 5-7 %;
- the error between the synthesis stage results and the analysis stage results in the Maxwell 3D Design machine with claw-poles was 9-12%.

The resulting calculation accuracy for such a complex magnetic system as the machine with claw-poles should be considered a good result. This approach can be recommended for the development of other types of electric machines that do not have flat symmetry.

7 Conclusion

Morally and physically obsolete equipment of metallurgical production requires replacement with drives that contain innovative solutions. The money invested in modernization takes a long time to pay off, and not every production can afford to replace it frequently. This raises the challenge of introducing advanced innovative solutions that will work for a long time.

The article offers a technical solution that has not yet been used in the world. As a drive motor for the pilger mill drive for the seamless pipes manufacturing is proposed to use a low-speed direct-drive brushless DC motor with a large diameter and the required inertial mass with claw-poles and a powerful permanent magnet as the drive motor for pilger mill. This solution allows you to remove the existing 120-ton flywheel by reducing the dimensions, since the necessary inertial mass is embedded in the rotor, increase efficiency by eliminating excitation losses, and reduce operating costs due to the absence of a collector unit. This offer contains a large number of technical risks. For their reduction have been developed the design system for the creation of electric machines of this class. The system contains two main parts: a synthesis subsystem and an analysis subsystem. The synthesis subsystem determines the optimal geometry of the machine based on the implementation of the multi-level single-criteria optimization problem based on the Gauss-Seidel method, the Fibonacci method, and the punitive function method. The analysis subsystem is a multi-step process using the well-established CAE complex Ansys Electronics Desktop. At the same time, minimal computer resources and estimated time are used, since at the intermediate stage a flat problem is analyzed, and only at the final stage a three-dimensional problem is analyzed. Also, the three-dimensional model thermal analysis of the machine by the finite element method in the program Ansys Icepak confirmed the possibility of using CPBM as a pilger mill drive.

The design system was actively used in the pilger mill drive development for the seamless pipes manufacturing at the Chelyabinsk pipe rolling plant.

The work was performed at SUSU with the financial support of the Russian Science Foundation (project № 14-19-00327). The author is grateful to the University leadership for the opportunity to conduct this research.

Acknowledgment

The work was carried out at the SUSU with the financial support of the Russian Science Foundation (project № 14-19-00327). The authors thank the officials for the opportunity to carry out this study.

References

1. A.F. Desanti, I. Sidharta, H. Erwananto and others, “Design of Performance and Parameter Measurement System for Brushless Direct Current (BLDC) Motor”, Proceeding - 2018 International Seminar on Intelligent Technology and Its Application, ISITIA 2018, pp. 175-179.
2. H.-S. Park, S.-W. Park, D.-Y. Kim and J.-M. Kim, “Hybrid phase excitation method for improving efficiency of 7-phase BLDC motors for ship propulsion systems”, Journal of Power Electronics, 2019, 19(3), pp. 761-770.
3. S. Gandzha, D. Aminov and B. Kosimov, “Design of Brushless Electric Machine with Axial Magnetic Flux Based on the Use of Nomograms”, 2018, Proceedings - 2018 International Ural Conference on Green Energy, UralCon 2018, 8544320, pp. 282-287.

4. Gandzha, S.A. The choice of the optimal design of the electric motor of the Pilgerstan drive for the technology of manufacturing seamless pipes. Gandzha, B.I. Kosimov, D.S. Aminov // Bulletin of SUSU. Series "Energy". - 2019. - T. 19, No 1. - P. 5-17. DOI: 10.14529 / power190101.

5. Gandzha, S.A. Comparative Analysis of Pilgerstan Drive Electric Motors for Seamless Pipe Manufacturing Technology. The choice of the optimal design / S.A. Gandzha, B.I. Kosimov, D.S. Aminov, R.R. Nimatov // Bulletin of PNRPU “Electrical engineering, information technologies, control systems”. - 2019. No 30, - P. 79-101.

6. G. R. Omri, A. Ibala and A. Masmoudi, “Characterization on the no-and on-load operations of an improved claw pole machine”, 2018, 13th International Conference on Ecological Vehicles and Renewable Energies, EVER 2018, pp. 1-8.7.

7. R. Rebhi, A. Ibala and A. Masmoudi, “MEC-based sizing of a hybrid-excited claw pole alternator”, 2015, IEEE Transactions on Industry Applications, 51(1), 6837424, pp. 211-223.8.

8. S. Gandzha, D. Aminov, and B. Kosimov, “Development of engineering method for calculation of magnetic systems for brushless motors based on finite element method”, 2019, International Conference on Industrial Engineering, Applications and Manufacturing, ICIEAM 2019, 8742976.9.

9. F. G. Zhang, H.-J. Bai and Y. Liu, “Leakage magnetic calculation on claw pole machine with outer permanent magnet rotor”, 2009, Dianji yu Kongzhi Xuebao/Electric Machines and Control, 13(4), pp. 548-552.10.

10. A. Njeh, H. Trabelsi, “New design of the claw-pole transverse flux permanent magnet machine”, 2018 15th International Multi-Conference on Systems, Signals and Devices, pp. 1311-1316.11.

11. B. Cristian, O. Constantin, O.Chiver and others “The advantages of numerical analysis for claw pole alternator”, 2014, EPE 2014 - Proceedings of the 2014 International Conference and Exposition on Electrical and Power Engineering, 6969928, pp. 353-357.12.

12. F. Jurca, C. Martis, “Claw-Pole generator parameters and steady-state performances analysis”, 2013, International Review on Modelling and Simulations, 6(1), pp. 41-48.13.

13. Bramerdorfer, G. Tolerance Analysis for Electric Machine Design Optimization: Classification, Modeling and Evaluation, and Example // IEEE Transactions on Magnetics – 2019, – 55(8), – 8688464.15.

14. Wang, Q., Li, J., Qu, R., Lu, Y. Design and Optimization of a Permanent Magnet Synchronous Machine for Low Vibration and Noise Applications // ICEMS – 2018 21st International Conference on Electrical Machines and Systems – 8549128, – P. 280-284.16.

15. Gandzha S., Bakhtiyor K., Aminov D. Development of a system of multi-level optimization for Brushless Direct Current Electric Machines // International Ural Conference on Electrical Power Engineering (Ural Con) 2019. 1-3 Oct. 2019 Chelyabinsk, Russia. DOI: 10.1109/URALCON.2019.8877650.17.

16. Gandzha S., Aminov D., Bakhtiyor K. Development of Engineering Method for Calculation of Magnetic Systems for Brushless Motors Based on Finite Element Method // 2019 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), ECF Paper 25-29 March 2019 Sochi, Russia, DOI: 10.1109 / ICIEAM.2019.8742976.18.

17. S. Gandzha, D. Aminov, I. Kiessh and B. Kosimov, “Application of Digital Twins Technology for Analysis of Brushless Electric Machines with Axial Magnetic Flux”, Proceedings – 2018 Global Smart Industry Conference, GloSiC 2018, 8570132.19.

18. P. Zheng, Q. Wu, J. Zhao and others “Performance analysis and simulation of a novel brushless double rotor machine for power-split HEV Applications”, 2012, Energies, 5(1), pp. 119–137.20.

19. Gandzha S., Kosimov B, Aminov D. Application of the Ansys Electronics Desktop Software Package for Analysis of Claw-Pole SynchronousMotor // Machines,-2019 / – https://doi.org/10.3390/machines7040065