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Design Methodology of a Multifunctional Screw-Type Energy Converter

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Abstract
This paper examines the method of designing a non-standard electric machine – a three-phase induction motor with a hollow solid rotor, on the surface of which the turns of the screw are located. Such an unusual design makes it possible to turn the main disadvantage of induction machines with a solid rotor, namely the heating of the rotor due to the effect of eddy currents, into an advantage. The heat from the rotor is transferred to the bulk material, which is mixed by the screw, for drying and reducing the moisture content. At the same time, only one device is used to perform three functions – mixing, drying, transportation of bulk material, which, due to the specified functional features, was called a multifunctional energy converter (MFEC). The MFEC design method differs from conventional machines, because it takes into account the peculiarities of determining the parameters of a number of typical methods: an induction motor with a squirrel-cage rotor, an induction motor with a solid internal rotor, and an inductor. In the previous publications of the authors, the complex methodology of designing an induction motor with an external solid rotor was considered in detail, however, in view of the additional theoretical and experimental studies conducted, it needs to be clarified and adjusted. In addition, in this paper, the beginning of the design, the determination of the initial data and the main dimensions of the MFEC is performed in a different way. In particular, the overall dimensions of the MFEC are determined not by the sum of power spent on heating and mixing the material and internal losses in an induction machine (considering the efficiency and power factor), but by the required performance of the unit and the limit dimensions of the installation area. The paper proposes a new approach to determining the dimensions of the stator slot, considering the necessary area for the placement of conductors and the current density in the winding. This paper is one of several publications that aim to reveal the features of design and mathematical modeling of such an atypical class of electric machines as an induction motor with an external hollow solid rotor.

INTRODUCTION

In connection with the lack of a complex of mathematical models of induction machines with a solid rotor, and even more so multifunctional energy converters (MFEC) of the screw type operating in the environment of bulk or viscous materials [1, 2], there is a logical need to create a general approach in the compilation of mathematical models and methods of calculation of induction machines, mainly with an external hollow solid rotor. The peculiarity of such a mathematical description is that the MFEC is considered in connection with the thermal and hydrodynamic processes of the environment, and the output characteristics are determined by the target function of the device: along with the mechanical and thermal dependences of the heating of the MFEC nodes and the environment [3]. MFEC refers to complex energy converters, in which the electromechanical conversion of energy is accompanied by the conversion of electrical P_e or mechanical energy P_{meh} into thermal P_t. In its general form, the MFEC can be imagined as a six-pole with an internal resistance Z_{ec} and two electrical terminals characterized by voltage U_n and frequency f with two mechanical terminals determined by torque M and rotation frequency n, and a thermal circuit characterized by the amount of heat Q and temperature T [4–8].

Traditionally, in MFEC, the energy that is converted into heat is attributed to losses, and the efficiency is the corresponding ratio of electrical and mechanical powers. It depends on the operating mode of the MFEC – generator or motor. Along with this, a new class of MFEC appeared for the implementation

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of technological processes in which thermal energy is used along with mechanical energy [9]. For such a class of MFEC, the issues of optimal design and areas of effective use require their own solution [10]. Solving these problems will contribute to the creation of energy-saving technologies [11–14].

MFEC operating in a closed environment, the working body (fusible or bulk materials) is a kind of cooler, which during its heating absorbs the remaining thermal energy from the surface of the device. A complete consideration of the "MFEC-environment" system is impossible without consideration of the processes in the working environment. On the one hand, the cooling of MFEC and heating of the substance disrupts consideration of thermal processes [15, 16]; from the second, the medium acts as a load on the rotor of the MFEC [17, 18]. From this, it becomes necessary to consider the processes of hydrodynamics to obtain the magnitude of the load moment and mechanical energy losses in a swirling flow of a viscous mass.

The multifunctional energy converter is a combined device that combines in one design the functions of an induction heater and an induction machine with an external hollow solid rotor (Fig. 1–4). Therefore, the method of calculation and design of such devices combines three design methods: induction heaters [19, 20], conventional induction machines (induction machines with squirrel-cage or phase rotors) [21, 22] and induction machines with a solid rotor [23, 24].

During operation, the MFEC can be in one of three main modes: long-term parking under current, rotation, start-up and braking. The most unfavorable from the point of view of electrical and thermal load is the first mode, in which the MFEC is in a state of short circuit, and heat transfer to the environment is carried out only due to thermal conductivity. In this mode, maximum currents flow in the windings of the device.

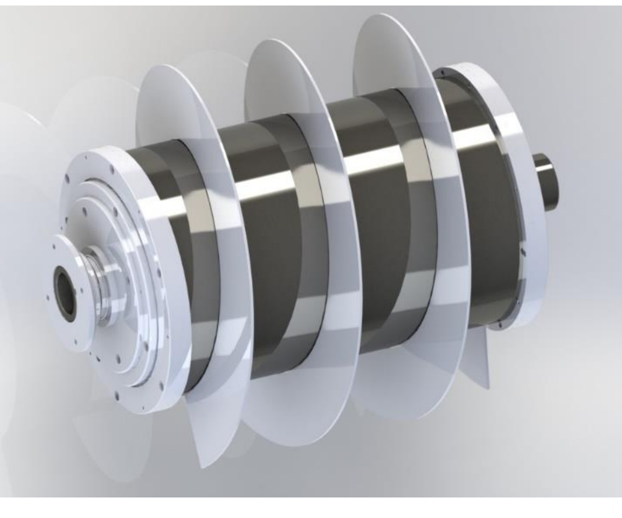

Figure 1. Appearance of a screw-type multifunctional converter

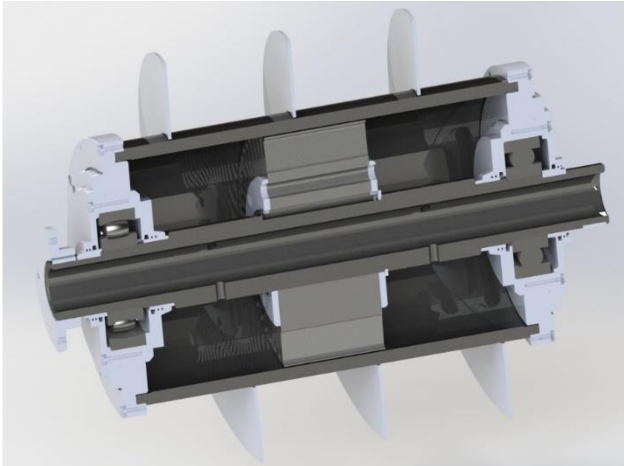

Figure 2. Longitudinal section of a screw-type multifunctional converter

For long-term and reliable operation of the MFEC, it is necessary that already at the design stage the device is designed for maximum overload, and this mode of maximum load is chosen as a long-term operating mode. For example, the winding is selected according to the short-circuit current. In dynamic modes, the MFEC works in the area of large slips (0.35–0.5) and the current multiplicity of the starting and dynamic modes will not differ much. In addition, in order to maintain a constant heat flow from the surface of the MFEC rotor, it is envisaged to adjust the supply voltage in the direction of increase, which, in turn, will lead to an increase in the currents in the windings. Thus, the currents in the windings in different operating modes of the MFEC will be approximately at the same level, and the calculation of the windings based on the short-circuit current will not lead to excessive consumption of copper, insulation, steel, etc.

The technical task for the design of the MFEC contains the rated data of the designed machine, instructions on its mode of operation, the structural form of execution, and the degree of protection against the influence of the environment. In addition, additional requirements may be set, for example, supply voltage regulation, two-stator version, integration with the air-cooling system and heating elements on the frame.

Thus, the aim of this paper is to reveal the design methodology of the MFEC from the initial input data to obtaining the operating characteristics. Achieving this aim will allow to proceed both to the production of experimental prototypes of MFEC, and to the development of mathematical and simulation models of non-stationary operating modes of the device under load.

MAIN PART

In contrast to previous studies [1–3, 9, 10], the design of the MFEC will be carried out in two stages:

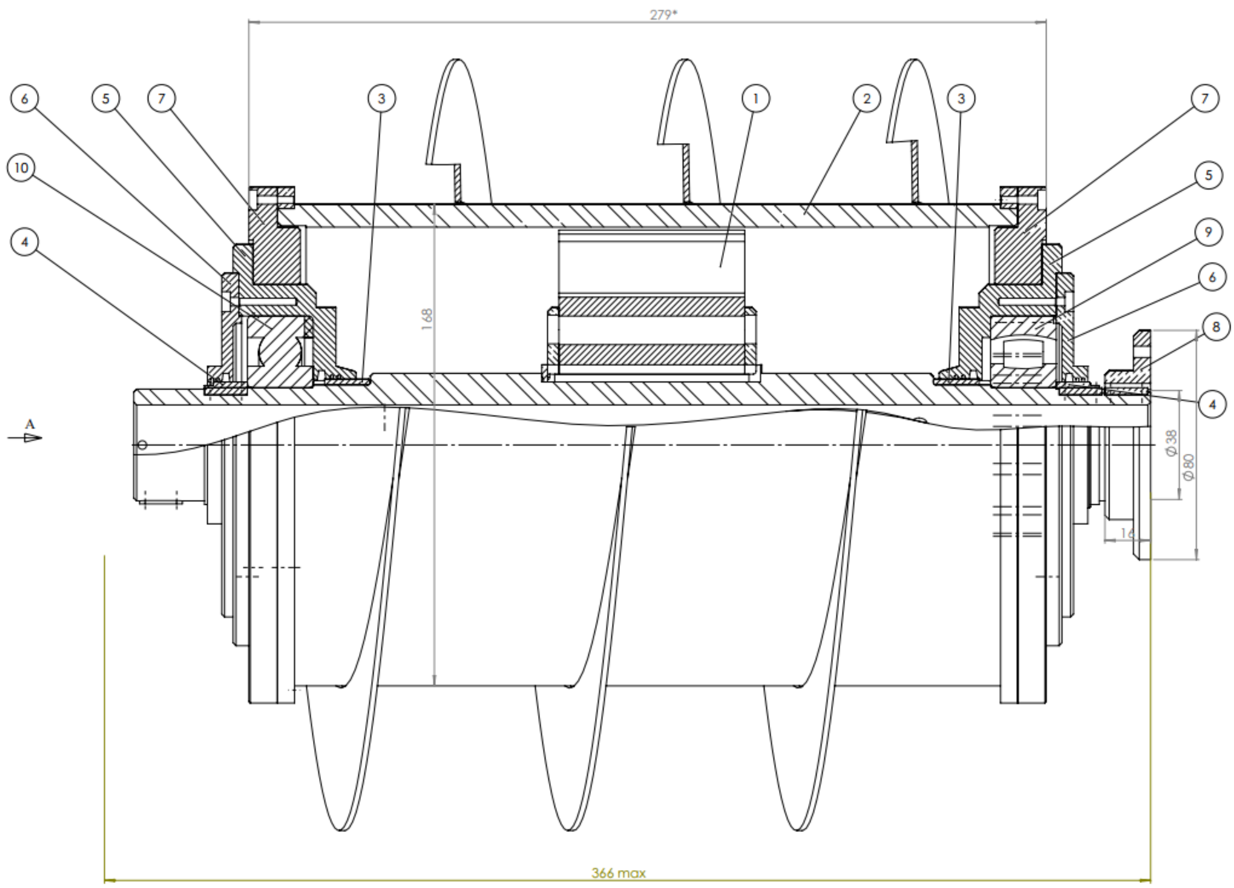

Figure 3. Assembly drawing of a screw-type multifunctional converter (view 1): *1* – stator; *2* – rotor; *3* – sleeve for the capsule; *4* – sleeve under the cover; *5* – capsule; *6* – cover; *7* – shield; *8* – flange; *9* – roller bearing; *10* – ball bearing

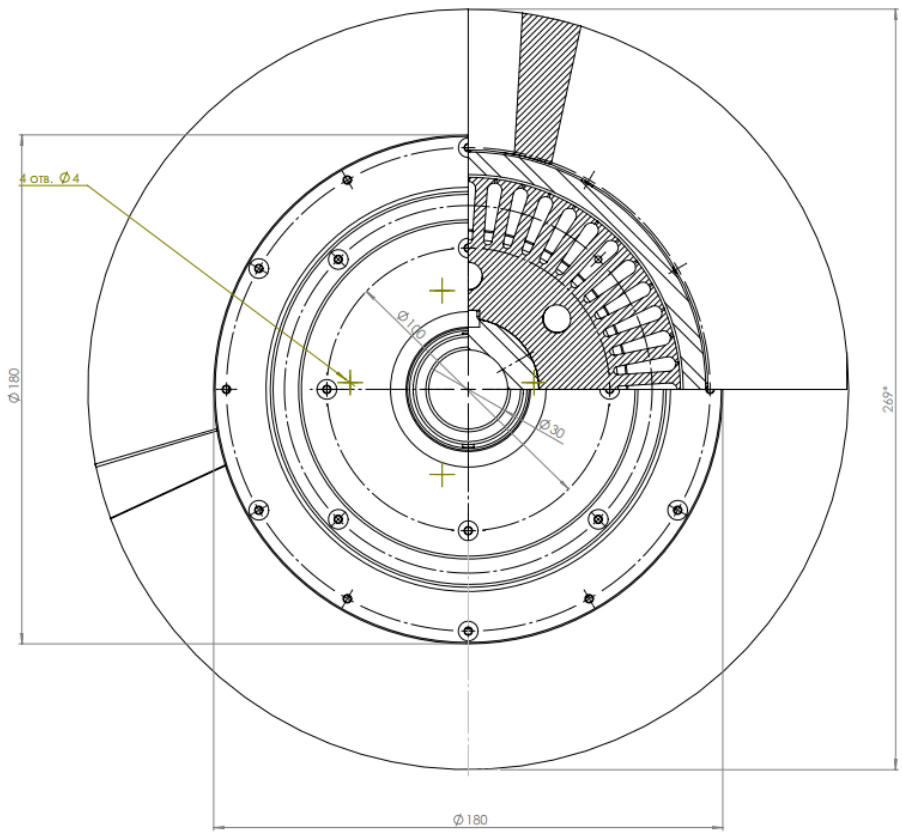

Figure 4. Assembly drawing of a screw-type multifunctional converter (view 2)

Table 1. Initial data for the design of the MFEC

Parameter Name	Designation	Note
Rated output power, W	P_2	It is determined by the total thermal and hydrodynamic loads and the sum of electrical and mechanical losses
Rated phase voltage, V	U_n	Accepted from the standard range
Number of poles	p	Under the conditions of frequency control, it is recommended to take the smallest possible value
Operation frequency, Hz	f	Accepted for steady rotation mode
The outer diameter of the stator*, m	D	It is determined by the great height of the axis of rotation and power from the reference book [27]
Efficiency	η	It is determined by the majestic power from the directory [27]
Power factor	$\cos\varphi$	It is determined by the majestic power from the directory [27]
Magnetic flux density in the air gap, Tl	B_d	It is determined by the magnitude of the outer diameter of the stator from the reference book [27]
The air gap between the stator and the rotor, m	δ	It is determined by the size of the outer diameter of the stator and technical conditions [27]
Specific electric loading, A/m	A	It is determined by the magnitude of the outer diameter of the stator from the reference book [27]
Induced voltage factor	k_E	It is determined by the magnitude of the outer diameter of the stator from the reference book [27]
Current density, A/m²	J	Accepted according to the guide, depending on the cooling conditions [27]
Winding factor	k_w	It is accepted according to the recommendations from the handbook [27]
Magnetic flux density in the stator teeth, Tl	B_z	It is accepted according to the recommendations from the handbook [27]
Magnetic flux density in the stator yoke, Tl	B_a	It is accepted according to the recommendations from the handbook [27]
Steel lamination factor	k_c	It is accepted according to the recommendations from the handbook [27]
Rotor thickness, m	h	It is determined taking into account the minimum values of the penetration depth of the electromagnetic field at the adopted network frequency and mechanical strength requirements

* - in MFEC, the outer diameter of the stator visually looks like the outer diameter of an external rotor. That is, in MFEC, the toothed zone is not inside the package, but on its outer surface. Meanwhile, the axis of rotation, since the rotor is a thin-walled tube, is almost the same as in conventional machines. In this case, depending on the height of the rotation axis, the recommended value of the outer diameter (which is proportional to the output power) is selected from the guide [27], and the inner diameter of the stator is not calculated.

1) determination of geometric dimensions and winding data;
2) calculation of parameters and characteristics (not considered in this paper).

This paper focuses on the first stage, since the second one has already been implemented in previous works in the ANSYS RMxprt software package [25, 26]. Directly, the ANSYS RMxprt program is not intended specifically for design – it is based on a form in which geometric dimensions, material properties, winding data are entered, on the basis of which the active and inductive resistances of the machine, electromagnetic loads, losses, characteristics, etc. are further determined. But the specified input data still need to be determined in advance, which is the task of this paper.

The input data, which are specified at the beginning of project work, are given in the Table 1.

Despite the fact that the information on the selection of initial data in the handbooks is indicated for the standard series of induction motors with a squirrel-cage rotor, as practice shows, this is enough for a starting "run" in the calculations for determining the parameters of the so-called "basic" machine. Of course, this approach is not acceptable for "manual" calculation of the entire machine, but in the context of these studies, a compatible calculation with ANSYS RMxprt is assumed. In this case, the uncertainty or lack of accuracy in parameter determination is corrected in the parameterization and optimization processes, as well as further refinement in field calculations in 2D and 3D settings. The main thing for ANSYS RMxprt is the task of close to a reasonable correspondence of geometric dimensions and power, in the future automatic adjustment of parameters is performed.

The procedure for calculating MFEC after assigning input data is given below. It is based on the generalization of calculation formulas given in [19–26]. The coefficients and reference data are taken from the induction motor design handbook [27].

Synchronous rotation speed, rev/min

$$n_1 = 2\pi f.$$

Synchronous angular speed, rad/s

$$\Omega = \pi n_1/30.$$

Calculated power, W

$$P' = P_2 \frac{k_e}{\eta \cdot \cos\varphi}.$$

Polar division, m

$$\tau = \pi D/2p.$$

The length of the stator core, m

$$L_\delta = \frac{P\prime}{1.11 D^2 \Omega k_w A B_\delta}.$$

Further, the recommended minimum t_{min} and maximum t_{max} values of the stator tooth pitch are determined according to the reference [27], m. The minimum and maximum value of the number of stator teeth:

$$Z_{min} = \frac{\pi D}{t_{max}}; Z_{max} = \frac{\pi D}{t_{min}}.$$

In the specified range of teeth, the number of stator teeth Z is selected according to the recommendations for three-phase machines. The tooth pitch is calculated, m:

$$t = \frac{\pi D}{Z}.$$

The number of slots per pole and phase is determined:

$$q = \frac{Z}{2p \cdot m},$$

where m is the number of phases.

Rated current of the stator winding, A:

$$I_{1n} = \frac{P_2}{m U_n \cos\varphi \eta}.$$

The number of effective conductors per slot

$$U_p = \frac{\pi D \cdot A}{I_{1n} Z}.$$

The number of parallel branches a is accepted. For the first approximation, one can take a = 1, then follow the recommendations in accordance with the type of winding and motor power.

The number of turns of the stator winding:

$$W = \frac{U_p Z}{2a \cdot m}.$$

Specific electric loading, A/m

$$A = \frac{2m I_{1n} W}{\pi D}.$$

Magnetic flux in the air gap, Wb

$$\Phi_\delta = \frac{k_E U_n}{4.44 W \cdot k_w \cdot f}.$$

Magnetic flux density in the air gap, Tl

$$B_\delta = \frac{p \Phi_\delta}{D \cdot L_\delta}.$$

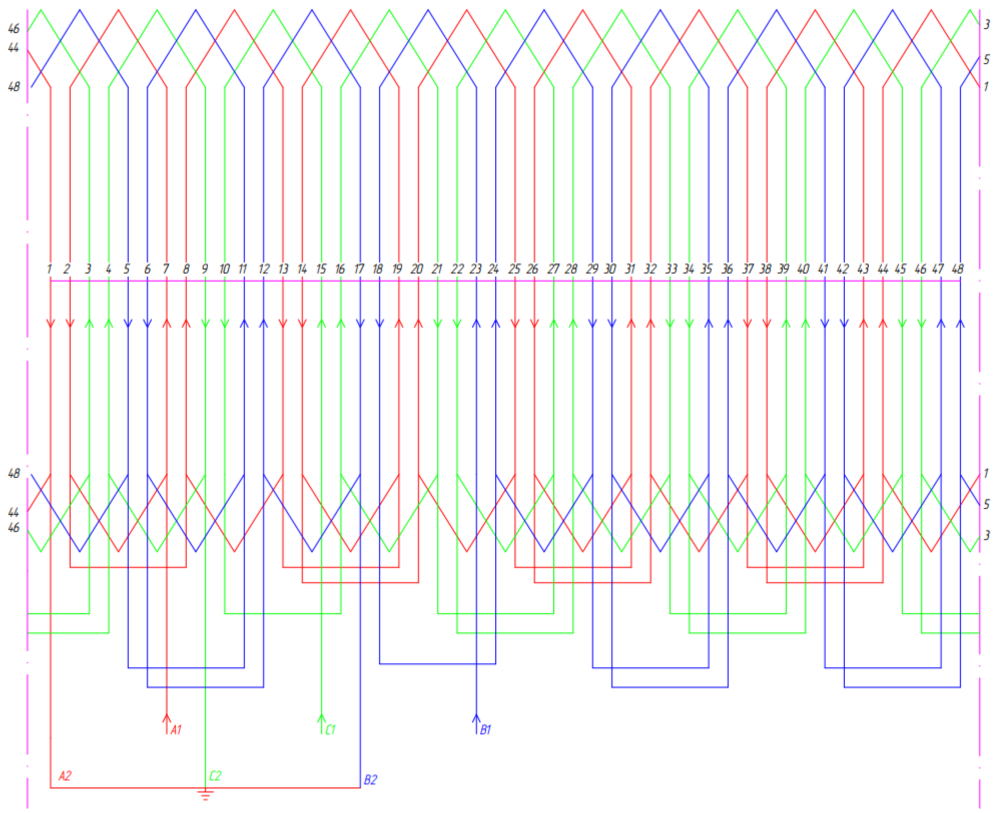

Figure 4. Scheme of the whole-coiled winding of the MFEC

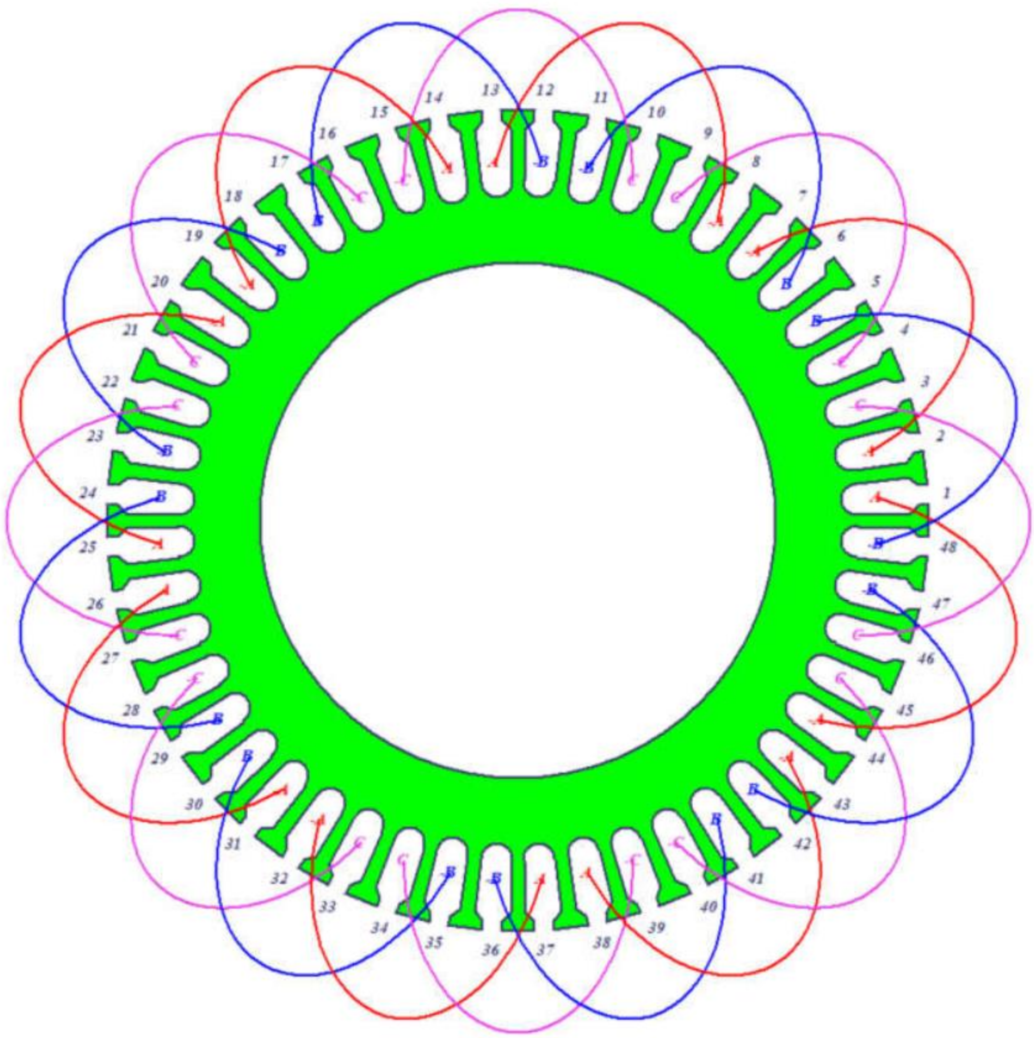

Figure 5. Sketch of the cross-section of the MFEC with winding in ANSYS RMxprt

If the obtained values of the linear specific electric loading *A* and the magnetic flux density in the air gap B_δ differ significantly from those taken at the beginning of the calculation (Table 1), then the calculation of the number of conductors in the slot, the number of parallel branches and other parameters that affect the determination must be revised electromagnetic loads. In case of significant discrepancies, the main geometric dimensions are adjusted - the outer diameter of the stator *D* and the length of the stator core L_δ. At this stage, it is possible to choose the type of winding, calculate the steps of laying conductors, determine the phase connection scheme. The scheme of a simple wave winding of the MFEC is shown in Fig. 4, 5.

Cross-section of the effective conductor, m^2

$$q_{ef} = \frac{I_{1n}}{a \cdot J}.$$

Taking into account the type of winding, the way it is inserted into the slots of the stator, the winding wire is selected according to the guide from the standard line (cross-section q_e, diameter of the bare wire d_e, diameter of the insulated wire d_i), the number of strands n_e is determined.

The final value of the cross-section of the effective conductor, m^2, is determined:

$$q_{ef} = n_e \cdot q_e.$$

Adjusted current density, m^2

$$J = \frac{I_{1n}}{a \cdot q_{ef}}.$$

The shape of the slot is taken and its dimensions are calculated. The calculation of the MFEC slot (Fig. 6) is given below.

Tooth width, m

$$b_z = \frac{B_\delta t}{B_z k_c}.$$

The height of the yoke, m

$$h_a = \frac{\Phi}{2 B_a L_\delta k_c}.$$

Full slot current, A

$$I_s = I_{1n} \cdot U_p.$$

The required area for placing conductors, m^2

$$q_{si} = \frac{I_s}{J}.$$

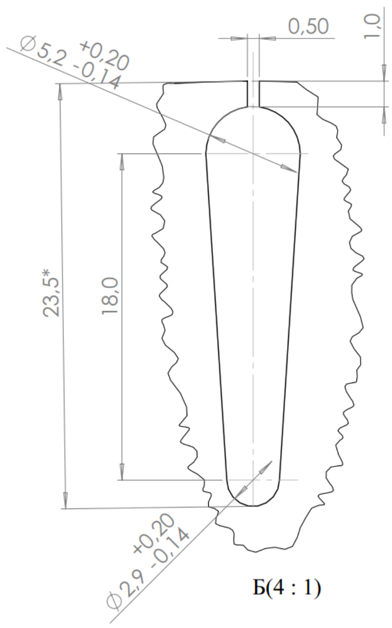

Figure 6. Sketch of the stator slot of the MFEC

The area of the slot for placing conductors, taking into account the slot filling factor k_z = 0.72, m²:

$$S_{pz} = \frac{d_i^2 U_p \cdot n_e}{k_z}.$$

The size of the larger diameter of the slot, m

$$b_1 = \frac{\pi(D-2h_{sl}) - Z \cdot b_z}{\pi + Z},$$

where h_{sl} is the height of the slot, m.

The size of the smaller diameter of the slot, m

$$b_2 = \sqrt{\frac{b_1^2 \cdot \left(\frac{Z}{\pi}+\frac{\pi}{2}\right) - 4S_{pz}}{\frac{Z}{\pi}-\frac{\pi}{2}}}.$$

The distance between the centers of the slot circles, m

$$h_1 = (b_1 - b_2) \cdot \frac{Z}{2\pi}.$$

Net area of the slot, m²

$$q_s = \frac{\pi}{8}(b_1^2 + b_2^2) + 0.5(b_1 + b_2) \cdot h_1.$$

The dimensions of the slot, considering the tolerance for the lamination, m

$$b_{11} = b_1 + \Delta b; b_{21} = b_2 + \Delta b;\ h_{11} = h_1 + \Delta b,$$

where Δb – lamination tolerance, m.

Slot area, taking into account lamination tolerance, m²

$$q_{s1} = \frac{\pi}{8}(b_{11}^2 + b_{21}^2) + 0.5(b_{11} + b_{21}) \cdot h_{11}.$$

Slot height, m

$$h_p = h_{sl} + 0.5 \cdot (b_1 + b_2) + h_1.$$

Area of slot insulation, m²

$$S_{iz} = b_{iz} \cdot (2h_p + b_1 + b_2),$$

where b_{iz} is the double-sided thickness of slot insulation, m.

Area for placement of conductors, m²

$$S_{p1} = q_{s1} - S_{iz}.$$

Slot fill factor

$$k_z = \frac{d_i^2 U_p n_e}{S_{p1}}.$$

If the value of the slot fill factor is outside the acceptable limits, the conductor sizes, the slot, the number of turns in a phase, electromagnetic loads and even the basic geometric dimensions are reviewed.

Shaft diameter, m

$$D_j = 2(0.5D - h_p - h_a).$$

Inner diameter of the rotor, m

$$D_{ri} = D + 2\partial.$$

Outer diameter of the rotor, m

$$D_{re} = D_{ri} + 2h_r.$$

Weight of the rotor, kg

$$m_r = \pi(D_{ri} \cdot h_r - h_r^2) \cdot L_\delta \cdot \rho_s,$$

where ρ_s is the density of steel, kg/m³.

Moment of inertia of the rotor, кг·м²

$$J_r = \frac{m_r}{8} \cdot (D_{ri}^2 + D_{re}^2).$$

The data found on this is quite sufficient to fill out the MFEC form in ANSYS RMxprt [25, 26] for further determination of device parameters and characteristics, as well as optimization.

CONCLUSIONS

In this paper, the methodology for the initial calculation of the main geometric dimensions, electromagnetic loads, and winding data of the screw-type MFEC is given. By its design, the MFEC is an atypical electric motor – it is a three-phase induction motor with an external hollow solid rotor. In this regard, the method of determining the parameters of MFEC differs from ordinary induction machines, which was disclosed in this paper. Attention should be paid to the new approach used in determining the dimensions of the slot zone of the stator. The paper proposes a preliminary determination of the required area of the slot before calculating the dimensions of the slot itself. In this case, the problem of determining the optimal value of the slot filling factor is eliminated. The design method of the MFEC presented in the work is limited to finding the main geometric dimensions, electromagnetic loads and winding data – this information itself is necessary and sufficient for the further analysis of the MFEC in the ANSYS RMxprt program, about which the authors have already made a series of publications.

Further research will be related to the refinement of the mathematical models of MFEC, considering the parameters that are determined in the methodology presented in this paper.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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Методика проектування гвинтового багатофункціонального перетворювача енергії

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Анотація. У даній роботі досліджено метод конструювання нестандартної електричної машини – трифазного асинхронного двигуна з порожнистим суцільним ротором, на поверхні якого розташовані витки гвинта. Така незвичайна конструкція дозволяє перетворити основний недолік асинхронних машин з суцільним ротором, а саме нагрівання ротора за рахунок дії вихрових струмів, на перевагу. Тепло від ротора передається сипучому матеріалу, який перемішується шнеком, для сушіння та зменшення вологості. При цьому для виконання трьох функцій - змішування, сушіння, транспортування сипучого матеріалу використовується лише один пристрій, який, завдяки зазначеним функціональним особливостям, отримав назву багатофункціональний перетворювач енергії (БФПЕ). Метод проектування БФПЕ відрізняється від звичайних машин тим, що враховує особливості визначення параметрів ряду типових методів: асинхронного двигуна з короткозамкненим ротором, асинхронного двигуна з суцільним внутрішнім ротором, індуктора. У попередніх публікаціях авторів комплексна методика проектування асинхронного двигуна із зовнішнім суцільним ротором була детально розглянута, однак, зважаючи на проведені додаткові теоретичні та експериментальні дослідження, вона потребує уточнення та коригування. Крім того, в даній роботі по-іншому виконано початок проектування, визначення вихідних даних і основних розмірів БФПЕ. Зокрема, габаритні розміри БФПЕ визначаються не сумою потужностей, витрачених на нагрівання і перемішування матеріалу, і внутрішніми втратами в індукційній машині (з урахуванням ККД і коефіцієнта потужності), а необхідною продуктивністю агрегату і граничні розміри зони установки. У роботі запропоновано новий підхід до визначення розмірів паза статора з урахуванням необхідної площі для розміщення провідників та густини струму в обмотці. Дана стаття є однією з кількох публікацій, які мають на меті розкрити особливості конструкції та математичного моделювання такого нетипового класу електричних машин, як асинхронний двигун із зовнішнім порожнистим суцільним ротором.

Ключові слова: асинхронний двигун, суцільний ротор, зовнішній ротор, порожнистий ротор, гвинт, параметри, проектування.

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