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Mathematical Modeling State Analysis of Multifunctional Energy Converters with a Solid Rotor

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Abstract
Multifunctional energy converters (MFEC) are induction motors with an external hollow solid rotor. Structurally, the MFEC is an electric machine in which the stator has the appearance of a conventional winding rotor and is located in a steel tube, which performs the functions of the rotor. In normal use for an electric motor, this design is inefficient due to significant losses in the solid rotor due to eddy currents. In the case of the MFEC, all losses go to the heating of the loose material that moves along the surface of the solid rotor, so the efficiency of the MFEC is very high. The non-standard design of the MFEC raises a number of questions regarding the calculation of such an electric machine and the mathematical modeling of transient modes: start-up in idle mode, start-up under load, operation during long-term parking under current, random load change during operation, etc. The complexity is caused by taking into account the given parameters of the solid rotor during the change of slip and currents. On the one hand, the currents in the rotor affect the parameters of the solid rotor, on the other hand, these currents cannot be calculated without determining the parameters of the rotor. In this regard, this paper aims to reveal problematic issues in mathematical modeling of transient modes of MFEC with a solid rotor and create a basis for further research in this direction.

INTRODUCTION

In the modern theory of electromechanical energy converters, the tasks of composing equations are set, which make it possible not only to explain the work of energy converters [1–3], which is complicated by the principle of operation from the point of view of classical theory, but also to find ways to create new electric machines [4]. The tasks facing the researcher are the optimization of the electric machine; obtaining static and dynamic characteristics; choosing the optimal design; taking into account the restrictions imposed on the electric machine; drawing up the experiment planning methodology. In connection with the lack of complex mathematical models of induction machines with a solid rotor, and even more so of multifunctional electromechanical energy converters (MFEC) operating in the environment of loose or viscous materials, there is a logical need to create a general approach to the development of mathematical models and methods calculation of induction machines mainly with an inverted solid rotor [5–8]. 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: they have, along with mechanical and thermal dependences, the heating of the MFEC nodes and the environment [8].

MFEC refers to complex energy converters, in which the electromechanical conversion of energy is accompanied by the conversion of electrical P_{el} or mechanical energy P_{meh} into thermal P_t. In its general form, the EMF can be imagined as a six-pole with an internal resistance Z_{ep} and two electrical terminals characterized by voltage U and frequency f with two mechanical terminals determined by torque M and frequency of rotation n, as well as a thermal circuit characterized by the amount of heat Q and temperature [9–11].

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Traditionally, in MFEC, the energy that is converted into heat is attributed to losses, and the efficiency ratio 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 of technological processes in which thermal energy is used along with mechanical energy. For such a class of MFEC, the issues of optimal design and areas of effective use require their own solution. Solving these problems will contribute to the creation of energy-resource-saving technologies [12, 13]. MFEC operating in a closed environment, the working body (fluid or low-melting materials) is a kind of cooler, which during its melting absorbs residual heat 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 the MFEC and the heating of the substance violates the consideration of thermal processes; from the second, the environment acts as a load on the rotor of the MFEC [5, 6]. 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.

For a complete analysis of the work of the MFEC, it is necessary to consider models that provide a complex connection between two interconnected objects: the MFEC – the environment (Fig. 1). It is proposed to consider the following direction of modeling of the closed system MFEC – environment: working environment – MFEC – internal thermal system of MFEC – complex environment-heater model.

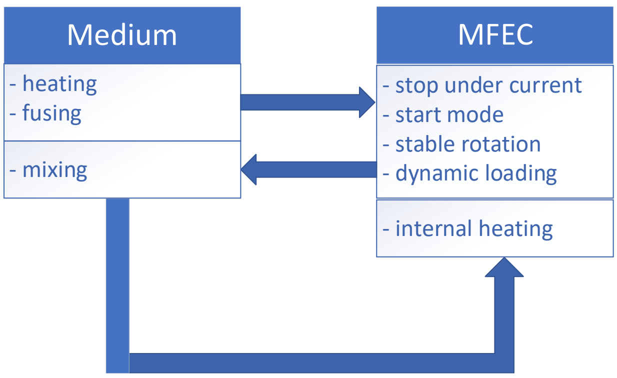

Figure 1. Connection of processes in the environment with the modes of the MFEC operation

The given scheme is explained simply – to reach the required design power of the MFEC, which ensures heating and melting of the given volume of material in the allotted time, as well as its mixing, it is necessary to know the amount of thermal, mechanical and electrical energy for the described processes. Therefore, one of the first models is the compilation of the model of the distribution of the thermal field of the MFEC [14–16]. Such a model as a secondary problem solves the issue of calculating the melting time of the calculation point of the medium, as well as the optimal choice of the trajectory of the movement of the material on the surface of the MFEC in order to ensure the minimum time of processing the material [17–20].

Another no less important task, which is a kind of connection between the environment and the heater, is the mathematical modeling of the hydrodynamic processes of the vane swirler in a viscous melt [17]. The obtained dependences of the resistance moment of the medium on the rotation speed of the MFEC rotor provide the necessary equations for modeling electromechanical processes in the MFEC, as well as the amount of power spent to overcome the resistance of the viscous medium.

The simulation results of the two previous models lead to mathematical models of the processes that occur in the MFEC itself. These are mathematical models of transient processes during the start-up of the MFEC [21, 22], a model of rotation in a steady state, a model of random load [23, 24], as well as a model of the internal thermal field of the MFEC in stationary and regular hydrodynamic loads [25, 26] and thermal modes [27–29].

Completion of the mathematical description of the MFEC is the compilation of a general model that combines the considered models of thermal, hydrodynamic, electromagnetic and thermal processes of the MFEC occurring in a closed medium-heater system. Such a model makes it possible to obtain a calculation of the main components of the object under consideration given the given initial conditions and initial parameters.

The aim of this paper is to analyze the construction of mathematical models of electromechanical transient processes of induction machines with a solid rotor in the context of thermal and hydrodynamic loads, which are inherent in the functional features of MFEC. Solving the set tasks is the basis for further analytical research of solid rotary machines for technological purposes and the creation of their digital twins.

ELECTROMECHANICAL ENERGY CONVERTERS MATHEMATICAL MODELING

MFEC, which refers to electric machines connected to the technological process, is a new type of electric machine. A complete picture of the operation of such an electric machine can only be given by a complex calculation, which consists in considering the external environment of the closed system heater - environment and the transition to the internal system of the MFEC.

In [1–5], currently relevant research problems of electromechanical energy converters are formed:

- improvement of mathematical models of electric machines, combining field theory and circuit theory;
- determination of dynamic efficiency and power factor, active, reactive and exchanged power;
- creation of new electric machines;
- solving the fundamental problems of electromechanical energy conversion.

Mathematical modeling of electric machines is closely related and determined by the development of the theory of the electromechanical converter (EMF) in stable and dynamic modes of operation. The genesis of mathematical models is described in detail in [4].

The processes of energy conversion in electric machines in stable modes are described by complex equations. For induction machines with a short-circuited rotor at a sinusoidal voltage, they have the following form [5]:

$$\left.\begin{aligned} &\dot{U}_1 = -\dot{E}_0 + \dot{I}_1 z_1; \\ &0 = \dot{E}_0 - \dot{I}_2' z_2' - \dot{I}_2' r_2' (1-s)/s; \\ &\dot{I}_0 = \dot{I}_1 + \dot{I}_2' \end{aligned}\right\},$$

where $\dot{U}_1$, $\dot{I}_1$, $\dot{I}_2'$ are the voltage and currents of the stator and rotor phases, respectively; $\dot{I}_0$, $\dot{E}_0$ are the current and EMF idling; z_1 and z_2' are the full resistance of stator and rotor windings; *s* is the relative rotation frequency (slip); $\dot{I}_2' r_2' (1-s)/s$ are the losses equivalent to useful power on the shaft.

Vector diagrams and substitution schemes are the geometric representation of the given equations. With constant parameters – active and inductive resistances or coefficients in front of dependent variables, circular diagrams have found quite wide use in the theory of electric machines. In dynamic modes, electric machines are described by differential equations. The geometric view of the MFEC of energy is a model, for example, for the simplest electric machine, shown in Fig. 2.

A mathematical model based on differential equations is much richer than substitution schemes and vector diagrams and has a deeper physical meaning and adequately reflects the processes of electromechanical energy conversion. As one can see, the classification of MFEC modeling schemes is quite simple. The classification of methods used for solving models of electric machines is much expanded (Fig. 3). Abbreviations used in the Fig. 3: GEM is generalized electric machine; GEMC is generalized electromechanical converter; IEM is an ideal electric machine; IZEM is an idealized electric machine.

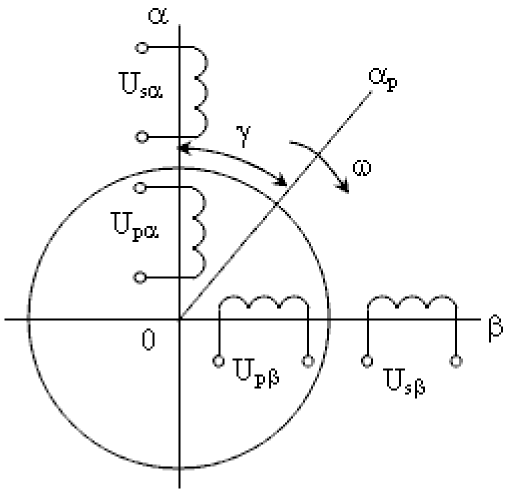

Figure 2. Model of the simplest MFCE

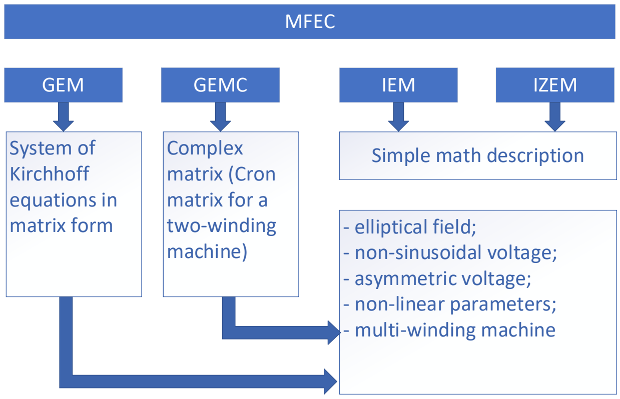

Figure 3. Classification of MFEC modeling methods

Among the methods most commonly used in the calculation of periodic processes and the electromagnetic field are the following:

- finite-difference grid method;
- models based on substitution schemes with distributed parameters;
- models based on substitution schemes with concentrated parameters;
- method of analog modeling of multilayer structures (two-dimensional theory);
- methods of orthotropic modeling;
- grid harmonic model (differential and harmonic method);
- propagation models of plane electromagnetic waves;
- the method of expanded magnetic and electrical schemes of substitution;
- method of conductance of toothed contours;
- method of instantaneous values;
- numerical analysis of the field and parameters of a solid rotor.

ANALYTICAL METHODS FOR HYDRODYNAMIC PROCESS CALCULATION

Analytical methods are distinguished by the commonality and transparency of the obtained solutions, which is undoubtedly their great advantage. However, when using these methods to solve the equation of the electromagnetic field in a multidimensional nonlinear environment, which is a solid ferromagnetic rotor, it is necessary to make significant assumptions that in some cases may affect the reliability of the obtained results.

The use of numerical methods significantly expands the possibilities of researching processes in the solid ferromagnetic rotor of the MFEC, allows to take into account the nonlinearity of the medium by applying the known dependence $B = f(H)$ and thus increase the accuracy of the calculation.

Among the existing methods of numerical analysis, the finite difference method received the greatest development. The finite element method is widely used to calculate the electromagnetic field.

The history of the development of electric machines testifies to the presence of two extreme approaches in the EMF theory of energy: based on field theory and circle theory. Field theory is developed based on Maxwell's equations, and circuit theory is based on Kirchhoff's equations. The third approach to the analysis of the processes of electromechanical energy conversion is the combinational approach, which is combined with field and circuit theories. In it, based on the picture of the field in the air gap of the electric machine, the voltage equations are written, and the equations of the electromagnetic moment are expressed through currents or flux coupling.

Many papers are devoted to the analysis of induction machines with a solid ferromagnetic rotor, which is a MFEC. All of them describe electromagnetic processes in a ferromagnetic rotor array and obtaining the input (wave) equivalent resistance of a solid rotor.

The analysis of the electromagnetic field in a smooth ferromagnetic rotor of an electric machine at a constant value of magnetic permeability $\mu = const$ was carried out by many domestic and foreign authors in different settings (using both rectangular and cylindrical coordinate systems), under different assumptions.

After the release of the classic work of Neumann [30] on the solution of the one-dimensional problem of the propagation of a plane electromagnetic wave in a ferromagnetic half-space taking into account the variable value μ and hysteresis, in a number of works [31, 32] there were recommendations regarding the use of the so-called "Neumann coefficients", which take into account the above factors, to clarify the equivalent parameters of the solid rotor, which were obtained under the condition $\mu = const$. The use of these coefficients turned out to be quite successful. They are still used to calculate the characteristics of a solid ferromagnetic rotor [6]. However, the task of refining the analysis of the two-dimensional electromagnetic field in the array of a smooth rotor at $\mu = const$ is still relevant.

As is known, the results of such an analysis in a rectangular coordinate system led to the fact that the main field characteristics – the electric field strength along the rotor E_z and the tangential magnetic field strength H_x have an identical, exponential law of change along the y coordinate (depth of the array) with a complex wave propagation coefficient:

$$\dot{\beta} = \sqrt{(1+j)^2 k^2 + \alpha^2} \ ,$$

where $k = \sqrt{\omega_\mu \gamma / 2} = 1/\Delta$; $\alpha = \pi/\tau_2 = p/R_2$; $\omega_\mu = \omega_0 s$.

The analysis with $\mu = const$ in the cylindrical coordinate system gives approximately such data, but with some deviations from the specified law in the range of very low frequencies (at $s < 0.5\%$), when the penetration depth $\Delta \geq 0.2R_2$.

Comparison of these results with test data that were carried out in various works showed that the analysis of the field of a smooth solid ferromagnetic rotor under the condition $\mu = const$ does not give an accurate representation of the law of change of E_z and H_x along the depth of the array, overestimates the value of the module H_x (at a given E_z) on the surface of the solid rotor, distorts the phase H_x.

As a result, one of the most important parameters - the equivalent wave resistance of the active zone of a smooth solid ferromagnetic rotor is 15–20% lower than the test values, and its phase angle is greater than the experimental one and is always 45° (as a result of $\alpha \ll k$). Therefore, the calculation of the starting characteristics of torque $T = f(s)$ and current $I = f(s)$ of solid-rotor electric machines, performed on these bases, does not give the required accuracy (by 35–40% lower than the values from experimental tests).

CONCLUSIONS

This paper analyzes approaches to the construction of mathematical models of electromagnetic transients of solid-rotor electromechanical energy converters of technological purpose, which differ by taking into account the thermodynamic and hydraulic processes that accompany the mixing and heating of loose or fusible materials that move along the surface of the solid rotor and are mixed. A key factor in creating adequate models is taking into account the cyclic dependence: the current of the solid rotor on its parameters, parameters depending on the current and both of these values on slip. The conducted analysis raises several questions for further research:

- to develop a mathematical model of the distribution of the thermal field during the operation of MFEC in the medium of a low-melting substance;
- to carry out analytical studies of the process of spreading thermal energy in the medium of a low-melting substance;
- to develop a mathematical model of hydrodynamic processes during the rotation of the MFEC rotor in the environment of loose or easily melting materials;
- to investigate the mechanical characteristics of MFEC depending on the geometric dimensions, electrical parameters of the device and properties of the working environment;
- to develop mathematical models and investigate the MFEC in the main modes of operation, taking into account the influence of the working environment on thermal and mechanical characteristics.

DISCLOSURE STATEMENT

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

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Математичне моделювання аналізу стану багатофункціональних перетворювачів енергії з суцільним ротором

Микола Заблодський, Владислав Плюгін, Віталій Тетєрєв, Олег Синельников

Анотація. Багатофункціональні перетворювачі енергії (БФПЕ) являють собою асинхронні двигуни із зовнішнім порожнистим суцільним ротором. Конструктивно БФПЕ являє собою електричну машину, в якій статор має вигляд звичайної обмотки ротора і розташований в сталевій трубі, яка виконує функції ротора. При нормальному використанні електродвигуна ця конструкція неефективна через значні втрати в суцільному роторі через вихрові струми. У випадку БФПЕ всі втрати йдуть на нагрівання сипкого матеріалу, який рухається по поверхні суцільного ротора, тому ККД БФПЕ дуже високий. Нестандартність конструкції БФПЕ викликає низку питань щодо розрахунку такої електричної машини та математичного моделювання перехідних режимів: пуск в режимі холостого ходу, пуск під навантаженням, робота під час тривалої стоянки під струмом, випадкове змінення навантаження під час роботи та ін. Складність обумовлена врахуванням заданих параметрів суцільного ротора при зміненні ковзання і струмів. З одного боку, струми в роторі впливають на параметри суцільного ротора, з іншого боку, ці струми неможливо розрахувати без визначення параметрів ротора. У зв'язку з цим дана робота має на меті розкрити проблемні питання математичного моделювання перехідних режимів БФПЕ з суцільним ротором та створити основу для подальших досліджень у цьому напрямку.

Ключові слова: перетворювач енергії, асинхронний двигун, твердий ротор, вихрові струми, математична модель, перехідні режими.

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