

Analytical transformations software for stationary modes of induction motors and electric drives

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ABSTRACT

A program was developed in the package of symbolic transformations Maple. It provides automatic analytical transformation and derivation of formulas and plotting of the main characteristics of induction motors (IM) in a convenient form for an electrical engineer and student: torque= $f(\text{slip})$ $T=f(s)$, angular speed= $f(\text{Torque})$ $\omega=f(T)$, angular speed= $f(\text{Current})$ $\omega=f(I)$, current= $f(\text{slip})$ $I=f(s)$; $\cos(\varphi)$ and phase angle (φ) for stator currents and rotor currents, and magnetizing circuit, machine efficiency $\eta=f(s)$ and a number of other characteristics. The calculation is based on the equivalent circuit of IM motors in its different variants: with one cage in the rotor, with two or more cages in the rotor, taking into account the skin effect in the rotor rods and without it. The user can build up the equivalent circuit to the desired configuration. The algorithm of further transformations is based on analytical obtaining of amplitude/frequency and phase/frequency characteristics in the nodes of the equivalent circuits with further calculation by power and slip. Online animation of the graphs with alternate variations of all resistances R and inductances L values of the model is provided. The article contains screenshots of important parts of the programs and illustrates the complete set of graphs.

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1. INTRODUCTION

In this article we will consider questions that engineers and researchers have when choosing or creating software to perform calculations of stationary modes of induction motor and electric drive. These questions are common for engineers who design electric machines, and for engineers who choose and adapt electric machines to the tasks of various machines and mechanisms, that is, electric drive engineers. For example, it is important for the first to create an induction motor (IM) with sufficient starting torque or $\cos(\varphi)$, and the second should choose an IM that is guaranteed to start the projected electric drive of the installation. Therefore, the material of the article is focused on engineers of both specialties, which is reflected in the title. A variety of mathematical models of induction motor, its modern designs and technical

characteristics, characteristics of modern construction materials, software packages, in which dynamic models of IM are implemented, as well as tasks of design engineers and researchers require systematization and optimization of the accumulated material and, often, development of their programs, taking into account new statements of problems and opportunities, for example wind power plant [1]. Let us dwell on the issue of development of calculation programs.

We will take the IM as an object of consideration. The tasks to be solved are the construction of its typical characteristics. This is $T=f(s)$, $\omega=f(T)$, $\omega=f(I)$, $I=f(s)$; $\cos(\varphi)$ and φ for stator currents, rotor currents, magnetizing circuit; machine efficiency $\eta=f(s)$ and several other characteristics, including the animation version of characteristics visualization.

The aim of the work is to develop a software tool for plotting these graphs in one package in one run with the possibility of animating the obtained graphs and issuing a report document, and for different IMs with different (freely extendable) equivalent circuits, that is, taking into account different known physical effects in motors and their peculiarities from different authors. We see quite a lot of such circuits in scientific literature [2]–[20], moreover, for IM, its magnetic part or with consideration of mechanical load, and the probability of their wide application and comparison depends on the ease of use. In this case, it is desirable to obtain an analytical solution, so as not to worry about the magnitude of the error from the application of numerical methods for quite complex circuits, and the causes of the error are attributed to the imprecisely set values of the object parameters. Application of package of analytical transformations in development of the mentioned program will provide novelty, practical usefulness and innovativeness of the problem being solved. Let's consider the state of the question on the specified aspects of the statement of the general problem.

Fragmentary solutions of the above problems already exist for ten years. However, the Kloss formula [21], [22] for calculating the curve $\omega=f(T)$ or $s=f(T)$ does not allow plotting this graph for deep-slot IMs or machines with a double squirrel cage. The known solution for calculation of $T=f(s)$ of these machines [21], [22] requires knowledge of data of structural elements of IMs, and these values most often cannot be found, especially for old machines to be replaced and for new series there are no catalogs, and the developers have no desire to publish this intellectual property. Any other effect, for example, skin effect in deep-slot rotor, requires consideration of a complicated equivalent circuit, and there are different approaches to the degree of detailing of the circuit itself, as different approaches have been proposed: physical descriptions and approximation/optimization procedures [17], [21]–[26]. Excessive approximation increase in the number of branches in the rotor leads to very cumbersome transformations in the field of complex numbers, and the obtained formula becomes of great value. At the same time, due to the frequent lack of necessary data, and accurate data-even more so, there is no confidence that the obtained solution can claim an engineering accuracy of 2% to 3%. Such situation leads to search of approximation solutions not within the limits of physical effects [21], [25], [26], but to use of numerical optimization procedures [27], "fitting" the curve $\omega=f(T)$ to motor data from a nameplate (shield) and from catalogs (rated, or nominal data, and critical and starting torque). At the same time, according to the information from the developer of the quite successful program [27], the convergence of the optimization procedure was not ensured for every sixth engine (out of 300 double-cage machines processed). It is clear, that the "behavior" of the curve graph in the interval between the set points turned out to be smooth, as the additional data were not entered into the program, and the purpose of calculations was not to obtain the "true" curve $\omega=f(T)$ throughout its unstable (non-working) section. In addition, only the author himself can upgrade the program.

In the present article we used this algorithm for comparison with our own development, since in a significant number of engineering and student problems the task is to simulate the start of IM from the mains without taking into account the secondary effects of its importance, but with an acceptable estimate of the start-up time in terms of accuracy. At the same time, simulation of start not from the mains, through SoftStarter requires a more detailed consideration of processes in the speed section below the speed of maximum torque. For SoftStarters developers, especially with a closed-loop control system that maintains a constant starting current or starting torque, a more accurate description of IM operation in the unstable section would probably help to improve the dynamic qualities of their system with a strongly pulsating phase voltage of the IM.

It is still not clear how widely can enter the mass practice of engineering calculations such "inconvenient features" of IM, for example, higher spatial harmonics, various parasitic torques, and how complex the equivalent circuit can turn out when taking them into account separately and/or in aggregate. Therefore, the possibility to transfer the procedure of obtaining the curve $\omega=f(T)$ and other curves to a qualitative and sufficiently fast software tool of analytical transformations seems to be relevant. Certainly, an alternative to such an approach is the finite element method (FEM) together with its known advantages and disadvantages: the necessity to have a complete drawing of IM, to know properties of structural materials, to create long and very long time to calculate the model and thus without more or less successful analytical approximation-to have no second, quickly calculated variant, for comparison of results. But in case of

modeling or design/restoration of quite structurally unusual machine, getting its analytical description can take much more time than using FEM method, especially at one-time development.

Figures 1-12 show typical and some special equivalent circuits of induction motors. These equivalent circuits of induction machines are described in detail in these references to sources. Therefore, it is impractical to give their full descriptions here, since these descriptions will be repeated. The designations of resistors and inductors can differ only in indices, which is of little importance for specialists in electrical machines and electric drive. The main meaning and features of the drawings are presented in the captions. However, mutual transitions between them will require attention. Therefore, it is better to have them all together in one program.

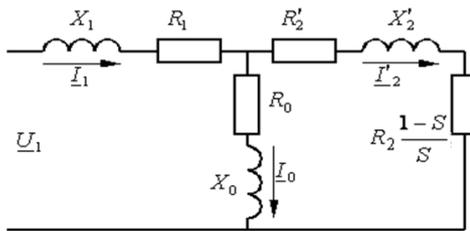


Figure 1. T-circuit of IM with one branch of short-circuit rotor with series resistors R0 [5]

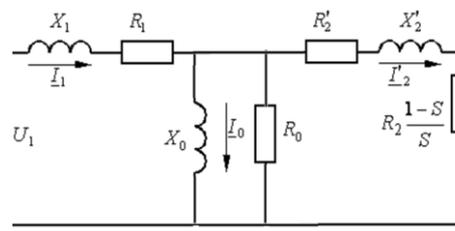


Figure 2. T-circuit of IM with one branch of short-circuit rotor with parallel resistors R0 [5]

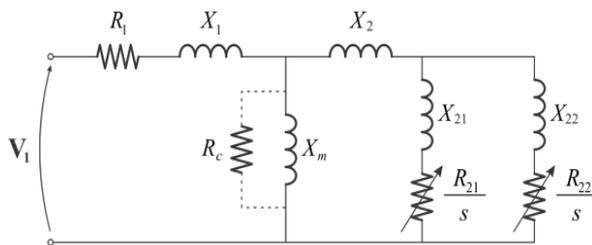


Figure 3. T-circuits of a double-cage IM with a short-circuit-rotor [11]

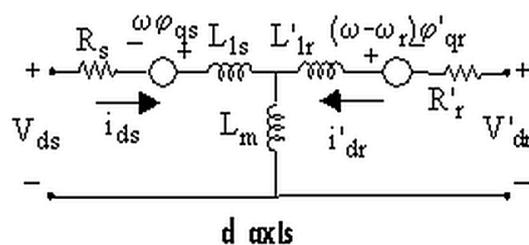


Figure 4. T-circuits of a double-cage IM with a short-circuit-rotor from MATLAB [11]

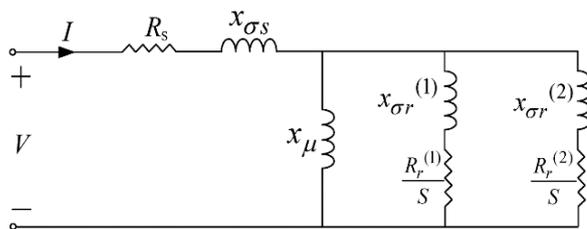


Figure 5. Equivalent circuits of IM with one branch on the rotor and the steel loss circuit [12]

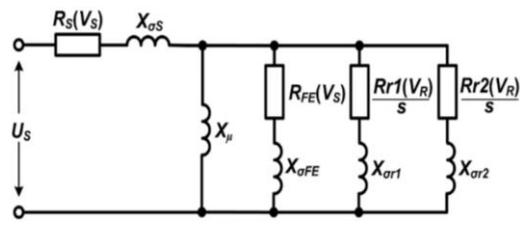


Figure 6. Equivalent circuits of IM with two branches on the rotor and the steel loss circuit [22]

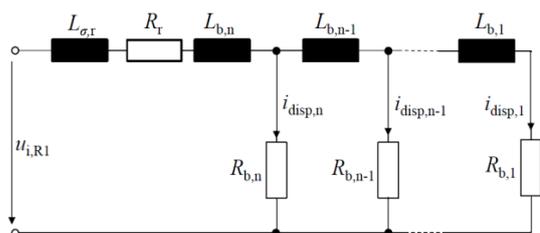


Figure 7. Equivalent circuit for modeling of the current displacement effect in the rotor bars [25], [26]

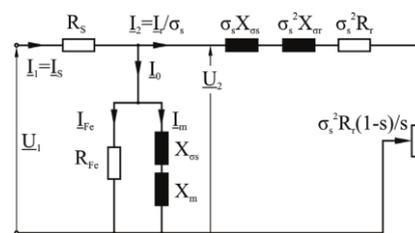


Figure 8. IM, Γ-circuit with equivalent iron loss resistor [15]

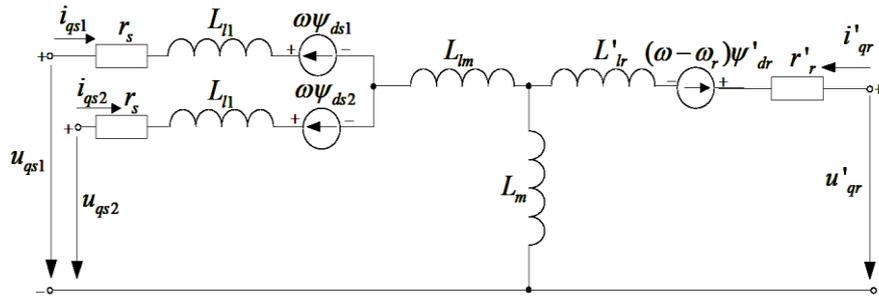


Figure 9. Dynamic equivalent per phase circuits of six-phase IM [1]

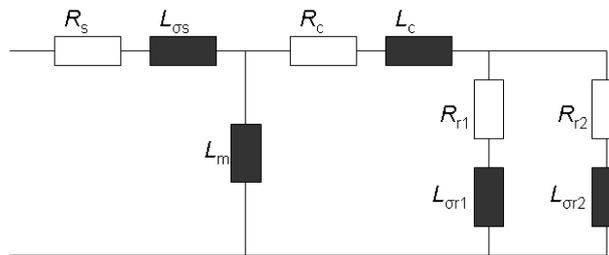


Figure 10. A double-cage circuit model for induction machines [2]

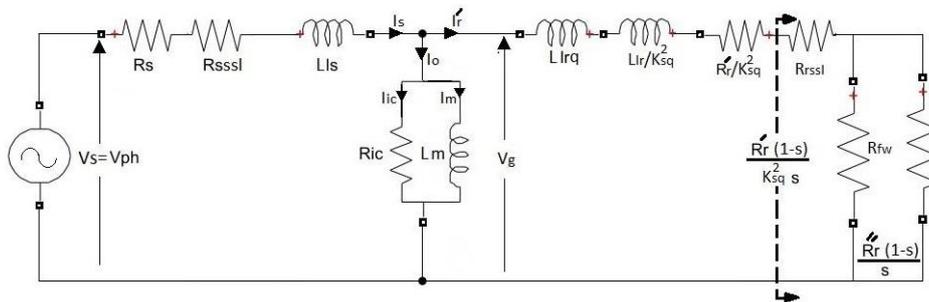


Figure 11. The proposed equivalent circuit of the IM with the skew effect, stray load loss, iron core loss, and mechanical losses [6]

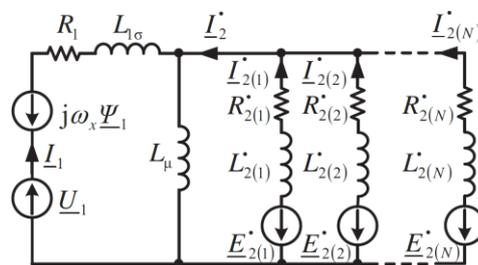


Figure 12. The induction machine RML-EC [7]

Figures 13-19 show the curves $\omega=f(T)$, which show the experimentally obtained curves $\omega=f(T)$ in stationary mode. They illustrate the curves $\omega=f(T)$ for various asynchronous motors. These IM have different design features. Hence, the curves $\omega=f(T)$ is also very different. Figure 13(a) show IM KMR 100L4 and Figure 13(b) show IM Pn=60 kW. These curves were taken by Prof. Akimov L.V. and then published for the first time with his consent, although without his participation by the authors [28]. Therefore, we set ourselves the task: to develop our own program for analytical derivation of formulas and plotting of these and a number

of other curves according to the principle here and now. We planned it to be enough for the user to select the equivalent scheme of his IM and enter the values of its parameters. This is necessary in order for the program to calculate all the characteristics under consideration. We have organized the article in such a way as to show the main fragments of the program listing in the Maple package; then, as an example of calculation, to show the full set of calculation curves, as example, for an AMA-500L2L type IM with two cages in the rotor; and then to show the torque=f(Speed) and stator current=f(Speed) curves for this IM from the MATLAB package to check their overlap or error.

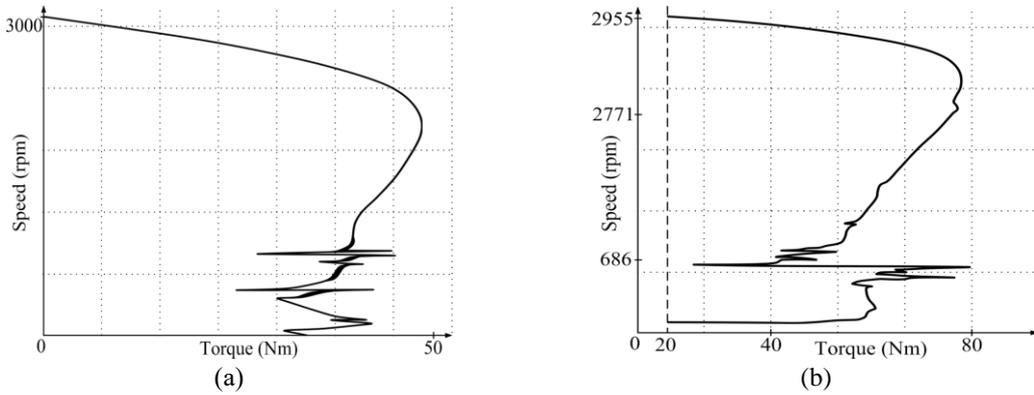


Figure 13. $\omega=f(T)$ (a) IM KMR I00L4 and (b) IM Pn=60 kW [28]

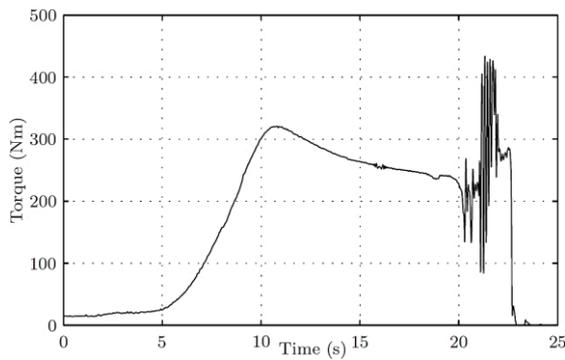


Figure 14. $T=f(t)$ curve of IM without skew [29]

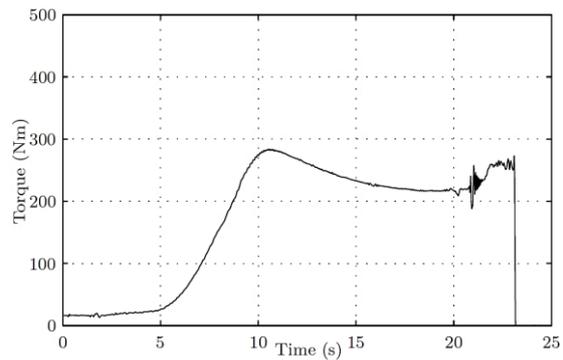


Figure 15. $T=f(t)$ curve of IM with skew [29]

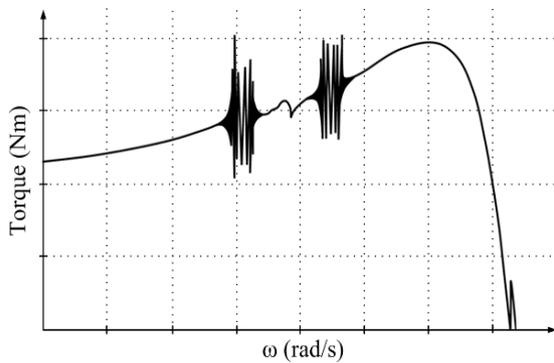


Figure 16. Averaging through the elimination of the higher harmonics-harmonics up to 220 rad/s were retained [29]

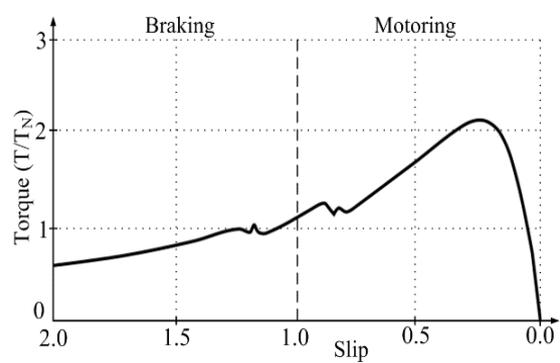


Figure 17. Simulated (average) torque and (rms) current-slip curves for the IM motor assuming non-sinusoidally distributed windings and no skin effect [17]

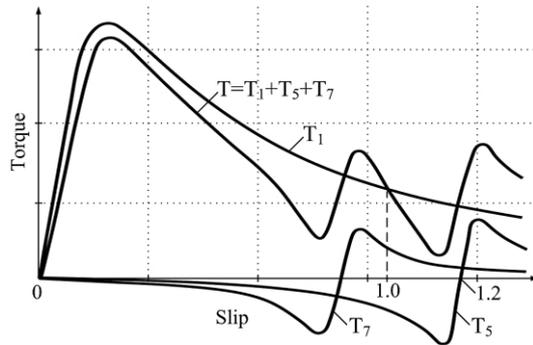


Figure 18. Asynchronous torques due to 1, 5 and 7 harmonics of the magnetic field [22]

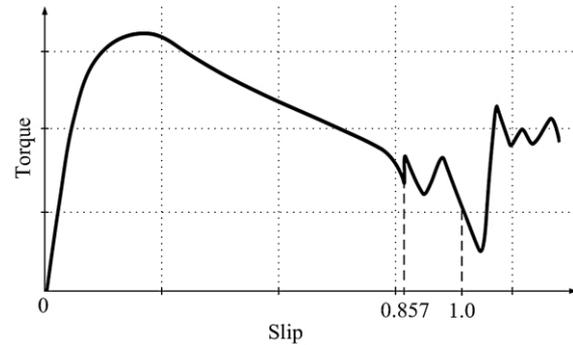


Figure 19. Superimposition of synchronous torque on asynchronous torque, $p=2$, $Z1=24$, $Z2=28$ [30]

The monograph [22] deeply and broadly presents various theoretical aspects of IM, summarizes the study of IM over many years with many references to various sources. However, the authors did not find in this monograph a concentrated compact approach to noninteractively constructing families of basic IM features, as they are presented for example in our paper. For example, chapter 9, “Skin and on-load saturation effects” proposes an iterative algorithm to calculate IM performance and parameters as influenced by skin and on-load saturation effects, but it calculates only part of IM parameters ($I(S)$, $I'(S)$, (S) , $\cos(S)$, $T(S)$, $I(S)$, $L(S)$, $L'(S)$, $R'(S)$), and further in this section there are no such graphs, which we gave in our article. That is, our proposed single-executable non-iterative calculation of the family of IM characteristics and the compact representation of the graphs allow us to perform their effective comparison and obtain generalizable conclusions about the features of the IMs under study. There is no suggestion in the paper [22] to use amplitude/frequency and phase/frequency characteristics (from automatic control theory) to construct a family of IM characteristics, despite the extensive review of sources in this monograph.

Any engineer can build such characteristic of IM as torque= $f(\text{slip})$ by Kloss formula. But for IM, for example, with two-cage rotor, or with account of skin effect or with account of other features and nonlinearities of IM, the engineer cannot do it without preliminary and long theoretical research. Moreover, it will not be possible to obtain an extensive family of different IM characteristics by a non-iterative algorithm in a single program pass. The literature review presents a variety of only one type of characteristics (Torque= $f(\text{slip})$) considered in the references. The other characteristics were not considered in these articles.

Our paper proposes an algorithm for obtaining many important IM characteristics simultaneously. It illustrates it by the example of a two-cage motor. At the same time, fragments of the developed program, which best comment the order of the algorithm, are given.

We used multiple citations in the article solely to show the relevance of the task of obtaining a family of IM characteristics based on the variety of their substitution schemes. These schemes were presented in the cited articles and were subjected to scientific analysis in them. The variety of equivalent circuits leads to a variety of forms of Torque= $f(\text{slip})$ characteristics, which is also confirmed by their citation. Naturally, all other characteristics are also very different, which is confirmed by the cited papers with experimental oscillograms. However, the cited papers did not discuss, set and solve the problem of calculating the whole family of characteristics for different IMs, as it was done in our paper. Thus, the papers [2]–[7], [8]–[13], [14]–[20] only show the existence and reality of the problem of obtaining an extensive family of IM characteristics, based on the variety of their equivalent circuits.

2. MATERIALS AND METHODS

The purpose of this paper is to develop the program of automatic analytical transformation and derivation of formulas and plotting of the main characteristics of Induction motors in a convenient form for an electrical engineer and student: torque= $f(\text{slip})$, angular speed= $f(\text{torque})$, angular speed= $f(\text{current})$, current= $f(\text{slip})$; $\cos(\varphi)$ and phase angle (φ) for stator currents and rotor currents, and magnetizing circuit, machine efficiency $\eta=f(s)$ and a number of other characteristics. The theoretical part of the proposed method is based on basic concepts and knowledges from university courses as theoretical foundations of electrical engineering and the theory of automatic control, for example, Ohm’s law, Kirchhoff’s rule, transfer function and Laplace time function images. The main idea of the work is to use a package of symbolic transformations (in particular, maple) to perform analytical transformations in the user’s equivalent circuit of an induction machine according to the following algorithm:

- Choose a graphical representation of the circuit with the “letter” designations of its parameters R and L, phase voltage V1 and slip s; in all further transformations these values will be included in the letter form up to the stage of graphing;
- Denote the complex resistances of the circuit branches as standard: Z1 for the stator, Z2 for the magnetization circuit, Z3, and Z4. for the rotor circuits;
- Transform the circuit to determine the total complex resistance Z_{orig} ;
- We find the complex stator phase current according to Ohm’s law $I(p)=V1(p)/Z_{orig}(p)$;
- Continue transformations, using Ohm’s law and Kirchoff’s rule or the graph method or another method to find complex currents of all circuit branches and, if necessary, nodes voltage;
- Write the transfer functions W(p) of the objects from the input phase voltage V1 to the currents of all circuit branches;
- We obtain the frequency transfer functions W(j ω) by appropriate substitution of j ω instead of the Laplace operator in W(p);
- We isolate the real Re and imaginary Im parts of all obtained W(j ω);
- According to the found real and imaginary parts of the frequency transfer functions we obtain the amplitude values of branch currents A(ω), “phase” $\Delta\phi$ relative to the phase of voltages V1 and V0 (induction electric and magnetic fields (EMF) E1), $\cos(\Delta\phi)$, and the found “amplitudes” correspond to the automatic control theory terminology and simultaneously to the RMS values of currents (if a RMS value was taken as V1);
- Using all obtained currents, with known V1, Ri, Li we find the input active power, then we get all the power losses and, subtracting the losses, we find the mechanical power on the shaft;
- Knowing the power on the shaft, we determine the electromagnetic torque as $T=P/\omega$; all obtained formulas are written in alphabetic form, which allows us to graph any of the values s, V1, Ri, Li as an independent variable and to study the sensitivity of the motor model to variation of a given parameter, that is, its robustness; formulas are cumbersome, but quick;
- After the stage of analytical transformations we set rated (nominal) values of motor parameters and values of parameters of its equivalent circuit and obtain a complete set of graphs; all this work can be done in automatic transformation mode in a few seconds or line by line in the program text when it is necessary to make changes, adjustments or debugging, and also in animation mode with variation of numerical values of rated (nominal) machine parameters and R, L equivalent circuit in a given range. To correct the phases of the rotor currents, based on the known ratio for the EMF of the IM $E1=-E2$ in vector diagram, it is sufficient to subtract pi from the obtained formulas for the arguments of the rotor currents I3, I4.

3. RESULTS AND DISCUSSION

It should be noted that the developed program is not presented in the article as its scientific result. The program is only a proof and illustration of the performance and effectiveness of our proposed idea and algorithm for calculating a whole family of the most relevant characteristics on the example of one arbitrarily selected IM. It really can be a tool for construction and visualization of characteristics, convenient for engineers. We emphasize this as a practical utility, but we also do not associate it with scientific novelty.

It is the idea outlined in the article and its embodiment into a linear algorithm as shown in section 2 that possesses scientific novelty from our point of view. This idea, in the order of its development, is applicable to the calculation of various IM circuits (for example, with three or more circuits in the rotor circuit of the equivalent circuit). There are no restrictions on the number of these circuits in theoretical terms, since there are no restrictions on the application of Ohm’s law and Kirchoff’s rule. Limitations may exist on the amount of RAM of the computer and on its speed. But these are engineering limitations.

It is worth noting that these limitations may hinder new knowledge about IM just as much as unacceptably cumbersome manual conversions with complex numbers on the methods of the theoretical foundations of electrical engineering. Therefore, we believe that the main scientific conclusion of the paper is to fix the possibility of constructing a family of IM characteristics with equivalent circuits of various levels of complexity if a package of symbolic transformations using known methods of automatic control theory is applied instead of working with manual transformations of complex resistances using the methods of theoretical foundations of electrical engineering.

The authors did not find such a conclusion in the reviewed sources, including various textbooks on electric machines, starting from the five-volume edition of Prof. Rudolf Richter, that is for the last 97 years. That is, the article answers the question: can we build a family of the considered IM characteristics for a model with a complex equivalent circuit or will it really fail? The development of the program as an engineering tool of course is not a scientific result, but is used only to illustrate and clarify the essence and

outcome of the proposed approach to constructing a family of IM characteristics with equivalent circuits of various levels of complexity. The most concise and convincing explanation of the problem of the article can be considered the proposal to build such a family of characteristics, for example, for IM with the skin effect in the rotor or even more complex description of IM. The main question for the specialist engineer here will be: how to do it?

The description of the proposed research method 2.1-2.12 is at the same time a linear algorithm for the program of analytical transformation of formulas, calculation of numerical values and graphical constructions of IM characteristics. The algorithm is truly linear. It does not have loops and more complex commands and other features of algorithms for only numerical data processing. This is provided by the powerful mathematical apparatus of analytical transformations of the maple package. All functions described in clauses 2.1-2.12 are performed by the instructions of the Maple package. Therefore, the program algorithm can be represented as a sequence of items 2.1-2.12 from section 2, as shown in Figure 20.

Let's show the main fragments of the developed program. The first part of the program is the built-in IM equivalent circuits shown in Figure 21. So, in the diagram in Figure 21(a), losses in steel are modeled by a series R_f resistor, and in the diagram in Figure 21(b), they are modeled by a parallel R_f resistor. The second part of the program is all formulas of symbolic transformations shown in Table 1. It also shows one of the important results of the transformations: the formula for calculating electromagnetic torque is obtained completely in symbolic form as a function of slip and all parameters of the equivalent circuit as well as other values of the machine and its equivalent circuit branches (powers, currents, angles, angular cosines, angular speed, efficiency). The third part of the program is the constructed graphs in Figures 22-29. Their calculations are performed for one of the substitutions of numerical values of IM parameters. A 1.8 MW motor by ABB type AMA-500L2L was used as IM. As its rated (nominal) data and values of parameters of the equivalent circuit the results of optimization procedure according to the algorithm [27] were taken.

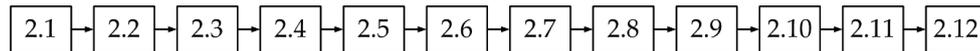


Figure 20. Linear algorithm of the program for calculating and plotting the characteristics of IM in the Maple package, where 2.1-2.12 are the paragraphs of section 2

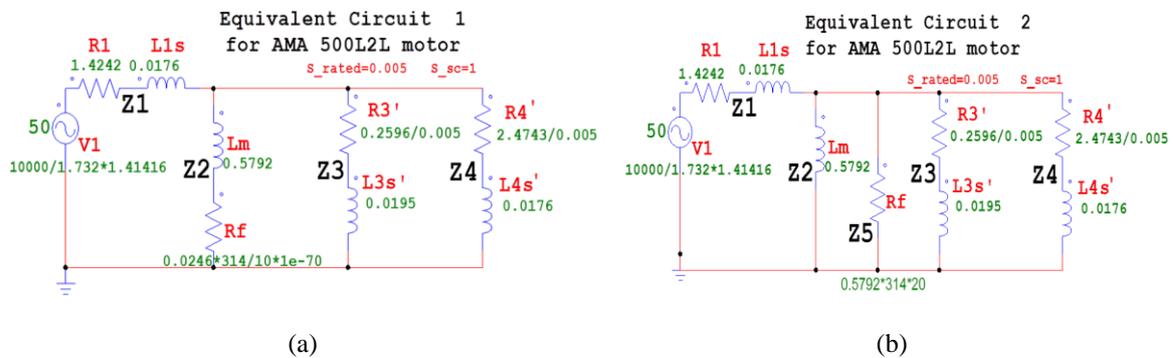


Figure 21. Equivalent circuits for induction motor (a) with double-cages rotor or and (b) approximation of skin effect

3.1. Main fragments of the developed program

The main fragments of the listing of the developed program, corresponding to the research method. Table 1 show the main fragments of the listing of the developed program, corresponding to the research method. They contain sets of operators from the Maple package. These operators sequentially solve tasks in accordance with the algorithm shown in Figure 21.

The resulting compact formula for $T = f(s)$ is obtained from Maple with one last command $Torque = M_s := sort(simplify(Torque_orig), s)$. Here, as an example, the formula for the electromagnetic torque of an induction motor, obtained in the Maple package, is given. This is its compact transformed form after all the described analytical transformations. The rest of the engine formulas are also very large. But errors in transformations, firstly, the maple package does not allow, and, secondly, the calculation of graphs of dynamic processes in the MATLAB package using the simulation of the IM in the SimPower-MATLAB package did not reveal any errors.

Table 1. The main fragments of the listing of the developed program, corresponding to the research method

I. Complex impedances of the equivalent circuit	
1. These operators define in symbols with the Laplace operator p the complex impedances of the equivalent circuit branches with serial link Rf and parallel link Rf:	2. These operators derivate the complex impedances of a complete equivalent circuit with Rf in series and parallel Rf connection by Ohm law for first or second scheme on user interest:
<pre>>if eq_cir=1 then >Z1:=R1+L1s*p;Z2:=Lm*p+Rf; >Z3:=R3/s+L3s*p;Z4:=R4/s+L4s*p; >else >Z1:=R1+L1s*p;Z2:=Lm*p; >Z3:=R3/s+L3s*p;Z4:=R4/s+L4s*p;Z5:=Rf; >end if;</pre>	<pre>>if eq_cir=1 then >Z_or:=Z1+1/(1/Z2+1/Z3+1/Z4); >Z_or:=collect(simplify(Z_or),p); >else >Z_or:=Z1+1/(1/Z2+1/Z3+1/Z4+1/Z5); >Z_or:=collect(simplify(Z_or),p); >end if;</pre>
II. Transformations in Laplace and frequency domains	
3. These operators find currents and voltages in the elements and nodes of equivalent circuit by Ohm law and find transfer functions on transfer functions (from control theory) rules:	4. These operators select variables to obtain frequency characteristics by replacing the Laplace operator p with jω, which provides a transition to the frequency domain:
<pre>>I1_or:=V1/Z_or; >Vo_or:=V1-I1_or*(Z1); >Imu_or:=Vo_or/(Z2); >I3_or:=Vo_or/(Z3); >I4_or:=Vo_or/(Z4); >I5_or:=Vo_or/(Z5); > >W_I1_V1_p_or:=1/Z_or; >W_Imu_V1_p_or:=simplify(Imu_or/V1); >W_I3_V1_p_or:=simplify(I3_or/V1); >W_I4_V1_p_or:=simplify(I4_or/V1); >W_I5_V1_p_or:=simplify(I5_or/V1);</pre>	<pre>>fr_resp_I1_V1_or:=subs(p=I*w,W_I1_V1_p_or); >fr_resp_I3_V1_or:=subs(p=I*w,W_I3_V1_p_or); >fr_resp_I4_V1_or:=subs(p=I*w,W_I4_V1_p_or); >fr_resp_Imu_V1_or:=subs(p=I*w,W_Imu_V1_p_or); >fr_resp_I5_V1_or:=subs(p=I*w,W_I5_V1_p_or);</pre>
5. Obtaining all frequency Transfer functions from the equivalent circuit	
<pre>>fr_resp_b_I1_V1_or:=evalc(fr_resp_I1_V1_or); >fr_resp_b_I3_V1_or:=evalc(fr_resp_I3_V1_or); >fr_resp_b_I4_V1_or:=evalc(fr_resp_I4_V1_or); >fr_resp_b_Imu_V1_or:=evalc(fr_resp_Imu_V1_or); >fr_resp_b_I5_V1_or:=evalc(fr_resp_I5_V1_or);</pre>	
III. The Currents, Powers and Motor Electromagnetic Torque	
5.1. These operators find the stator phase current I1 as the frequency response, find the phase of the stator current and then the power factor cos(φ) for the stator current:	5.2. These operators find the rotor phase currents of cage I3, I4 as the frequency responses, find the phases of the rotor currents and then the power factors cos(φ) for the rotor currents:
<pre>>Re_part_I1_V1_or:=Re(fr_resp_b_I1_V1_or); >Im_part_I1_V1_or:=Im(fr_resp_b_I1_V1_or); >A_I1_V1_or:=evalc(sqrt(Re_part_I1_V1_or^2+Im_part_I1_V1_or^2)); >A_f_I1_V1_or:=subs(w=2*pi*f,A_I1_V1_or); >phi_I1_V1_or:=evalc(arctan(Im_part_I1_V1_or,Re_part_I1_V1_or)); >phi_f_I1_V1_or:=subs(w=2*pi*f,phi_I1_V1_or); >cos_phi_I1_V1_or:=evalc(cos(phi_f_I1_V1_or)); >cos_phi_f_I1_V1_or:=evalc(cos(phi_f_I1_V1_or));</pre>	<pre>>Re_part_I3_V1_or:=Re(fr_resp_b_I3_V1_or); >Im_part_I3_V1_or:=Im(fr_resp_b_I3_V1_or); >A_I3_V1_or:=evalc(sqrt(Re_part_I3_V1_or^2+Im_part_I3_V1_or^2)); >A_f_I3_V1_or:=subs(w=2*pi*f,A_I3_V1_or); >phi_I3_V1_or:=evalc(arctan(Im_part_I3_V1_or,Re_part_I3_V1_or)); >phi_f_I3_V1_or:=subs(w=2*pi*f,phi_I3_V1_or); cos_phi_f_I3_V1_or:=evalc(cos(phi_f_I3_V1_or)); >Re_part_I4_V1_or:=Re(fr_resp_b_I4_V1_or); >Im_part_I4_V1_or:=Im(fr_resp_b_I4_V1_or); >A_I4_V1_or:=evalc(sqrt(Re_part_I4_V1_or^2+Im_part_I4_V1_or^2)); >A_f_I4_V1_or:=subs(w=2*pi*f,A_I4_V1_or); >phi_I4_V1_or:=evalc(arctan(Im_part_I4_V1_or,Re_part_I4_V1_or)); >phi_f_I4_V1_or:=subs(w=2*pi*f,phi_I4_V1_or); cos_phi_f_I4_V1_or:=evalc(cos(phi_f_I4_V1_or));</pre>
IV. Rated motor data and parameters of equivalent circuit. Motor AMA-500L2L characteristics curves	
6. These operators enter the numerical values of the rated motor data and the parameters of the equivalent circuit with an approximate skin effect:	7. These operators calculate and plot the engine performance curves for the AMA-500L2L:
<pre>>P_rated:=1.8e6;U_rated_phase:=10000/1.732; I_rated:=120.75;pair:=1; >Omega0_mec:=2*pi*50/pair; >T_rated:=5758; >ww:=2*pi*50; k_vit_R:=3*0; >k_vit_L:=0.3 >R1:=1.4242; L1s:=0.0176; R4:=2.4743; >R3:=0.2596*(1+k_vit_R*abs(s)); >L3s:=0.0195*(1-k_vit_L*abs(s)); L4s:=0.0176; >Lm:=0.5792;J_motor:=22.4; >if eq_cir=1 then Rf:=Lm*314.16/20; else Rf:=(Lm*314.16)*50 end if;</pre>	<pre>>readlib(unassign):with(plots):eq_cir; >assign(f=50):assign(V1=U_rated_phase); >tit:=title='Torque_Curve_for_T/Trated': lfont:=labelfont=[TIMES,ROMAN,14]:lab:=labels=[Slip,T]: >plot([Torque_or/T_rated],s=-0.5..1.5,color= >[red,green,blue],tit,lab,lfont,gridlines);</pre>

The resulting formula (1) for calculating the electromagnetic torque is obtained completely in symbolic form as a function of slip and all parameters of the equivalent circuit from Figure 21, as well as other values of the machine and its equivalent circuit branches (powers, currents, angles, angle cosines, speed, and efficiency). This is what all other results of symbolic transformations of items I-III of the program from Table 1 look like. All together they occupy 278 pages of pdf-file. The program substitutes each of these

formulas into the next one and performs transformations “in letters”. This eliminates errors in conversions, further numerical calculations, and plotting, which ensures that reliable results are obtained quickly. This approach also does not require the introduction of additional simplifications (and hence errors) to obtain formulas for $T=f(s)$, as specialists in electrical machine theory have previously had to do during “manual” transformations in the complex variable domain. However, the formulas obtained in the program, in contrast to calculations [31]–[33], turned out to be so large that it is impossible to perform their parametric analysis.

$$\begin{aligned}
M_s := & (12V1^2 Lm^2 \pi^2 Rf^2 f^2 (4L3^2 \pi^2 R4f^2 s^2 + 4L4^2 \pi^2 R3f^2 s^2 + R3^2 R4 + R3 R4^2)s)/ \\
& (\text{Omega0_mex}(128L1 \pi^6 f^6 Lm^2 Rf^2 L3^2 L4s^4 + 16R1^2 Rf^2 L3^2 \pi^4 f^4 L4^2 s^4 \\
& + 16R1^2 Lm^2 \pi^4 f^4 Rf^2 L4^2 s^4 \\
& + 16R1^2 Lm^2 \pi^4 f^4 Rf^2 L3^2 s^4 + 32 R1^2 Lm^2 \pi^4 f^4 Rf^2 L4L3^2s^4 + 64L1^2\pi^6 f^6 Lm^2 Rf^2 L3^2 s^4 \\
& + 128L1^2 \pi^6 f^6 Rf^2 L3L4^2 Lm s^4 \\
& + 128L1^2 \pi^6 f^6 Rf^2 L3^2 L4 Lm s^4 + 64Lm^2 \pi^6 f^6 Rf^2 L3^2 L4^2 s^4 + 32 R1^2 Rf^2 L3 \pi^4 f^4 L4^2 Lm s^4 \\
& + 32R1^2 Rf^2 L3^2 \pi^4 f^4 L4 Lm s^4 \\
& + 128L1 \pi^6 f^6 Lm^2 Rf^2 L4^2 L3 s^4 + 64L1^2 \pi^6 f^6 Rf^2 L3^2 L4^2 s^4 + 64L1^2 \pi^6 f^6 Lm^2 Rf^2 L4^2 s^4 \\
& + 128R1 Lm^2 \pi^6 f^6 L3^2 L4^2 Rf s^4 \\
& + 64R1^2 Lm^2 \pi^6 f^6 L3^2 L4^2 s^4 + 256 L1^2 \pi^8 f^8 Lm^2 L3^2 L4^2 s^4 + 128L1 \pi^6 f^6 Rf^2 L3^2 L4^2 Lm s^4 \\
& + 128L1^2 \pi^6 f^6 Lm^2 Rf^2 L3L4 s^4 \\
& + 32R1Lm^2 \pi^4 f^4 Rf^2 L4^2 R3s^3 + 128L1^2 \pi^6 f^6 Lm^2 RfL3^2 R4 s^3 + 32R1 Lm^2 \pi^4 f^4 Rf^2 L3^2 R4s^3 \\
& + 128L1^2 \pi^6 f^6 Lm^2 RfL4^2 R3s^3 \\
& + 32R1^2 Lm^2 \pi^4 f^4 RfL3^2 R4 s^3 + 32 R1^2 Lm^2 \pi^4 f^4 RfL4^2 R3 s^3 + 8R1^2 Rf^2 L3 \pi^2 f^2 R4^2 Lm s^2 \\
& + 4R1^2 Rf^2 R3^2 L4^2 \pi^2 f^2 s^2 \\
& + 4R1^2 Lm^2 \pi^2 f^2 Rf^2 R3^2 s^2 + 16Lm^2 \pi^4 f^4 Rf^2 L3^2 R4^2 s^2 + 64L1^2 \pi^6 f^6 Lm^2 L3^2 R4^2 s^2 \\
& + 4R1^2 Lm^2 \pi^2 f^2 Rf^2 R4^2 s^2 \\
& + 32 L1^2 \pi^4 f^4 Lm^2 Rf^2 R4R3 s^2 + 64 L1^2 \pi^6 f^6 Lm^2 R3^2 L4^2 s^2 + 4R1^2 Rf^2 L3^2 \pi^2 f^2 R4^2 s^2 \\
& + 32L1^2 \pi^4 f^4 Rf^2 L3R4^2 Lm s^2 \\
& + 16 L1^2 \pi^4 f^4 Lm^2 Rf^2 R3^2 s^2 + 16 Lm^2 \pi^4 f^4 Rf^2 R3^2 L4^2 s^2 + 8R1^2 Lm^2 \pi^2 f^2 Rf^2 R4 R3 s^2 \\
& + 16L1^2 \pi^4 f^4 Rf^2 R3^2 L4^2 s^2 \\
& + 32 L1 \pi^4 f^4 Rf^2 L3^2 R4^2 Lm s^2 + 16 R1^2 Lm^2 \pi^4 f^4 R3^2 L4^2 s^2 + 16R1^2 Lm^2 \pi^4 f^4 L3^2 R4^2 s^2 \\
& + 32 R1 Lm^2 \pi^4 f^4 L3^2 R4^2 Rf s^2 \\
& + 16 L1^2 \pi^4 f^4 Rf^2 L3^2 R4^2 s^2 + 16 L1^2 \pi^4 f^4 Lm^2 Rf^2 R4^2 s^2 + 32R1Lm^2 \pi^4 f^4 R3^2 L4^2 Rf s^2 \\
& + 32L1^2 \pi^4 f^4 Rf^2 R3^2 L4Lm s^2 \\
& + 32 L1 \pi^4 f^4 Rf^2 R3^2 L4^2 Lm s^2 + 32L1 \pi^4 f^4 Lm^2 Rf^2 R4^2 L3 s^2 + 32L1 \pi^4 f^4 Lm^2 Rf^2 R3^2 L4 s^2 \\
& + 8R1^2 Rf^2 R3^2 L4 \pi^2 f^2 Lm s^2 \\
& + 8 R1Lm^2 \pi^2 f^2 Rf^2 R3^2 R4 s + 8R1^2 Lm^2 \pi^2 f^2 RfR4^2 R3 s + 32L1^2 \pi^4 f^4 Lm^2 Rf R3^2 R4 s \\
& + 32L1^2 \pi^4 f^4 Lm^2 Rf R4^2 R3 s \\
& + 8 R1Lm^2 \pi^2 f^2 Rf^2 R4^2 R3s + 8R1^2 Lm^2 \pi^2 f^2 RfR3^2 R4 s + R1^2 Rf^2 R3^2 R4^2 \\
& + 16L1^2\pi^4 f^4 Lm^2 R3^2 R4^2 + 4L1^2\pi^2 f^2 Rf^2 R3^2 R4^2 \\
& + 4 Lm^2 \pi^2 f^2 Rf^2 R3^2 R4^2 + 4R1^2 Lm^2 \pi^2 f^2 R3^2 R4^2 + 8R1 Lm^2 \pi^2 f^2 R3^2 R4^2 Rf \\
& + 8 L1 \pi^2 f^2 Rf^2 R3^2 R4^2 Lm))
\end{aligned} \tag{1}$$

3.2. Samples from the set of graphs built by the program

As an explanation of the program’s operation, Figures 22-29 show graphs of various IM characteristics. They were built by the authors in the maple package according to our program from Table 1. For the first time, such graphs were obtained during the development of the program and its testing. They are published in [28]. But it shows 24 graphs for various configurations of the rotor windings in order to study their effect on the engine. But for this article, 8 graphs have been selected: the most understandable version of the graph package (with two windings on the rotor, like the AMA-500L2L). To obtain Figures 22-29, a recalculation was carried out, the program was changed in part of the graph interface. In addition, the article describes the algorithm of the program, which was not in [28].

The developed program in 20 seconds calculates and plotting the set of typical IM characteristics described in the article, such as $T=f(s)$, $\omega=f(T)$, $\omega=f(I)$, $I=f(s)$; $\cos(\varphi)$ and phase angle (phi) φ for stator currents and rotor currents, and magnetizing circuit, machine efficiency $\eta=f(s)$ and a number of other characteristics. That is, this program solves the problems that many specialists in electrical machines and electric drives must solve in the course of evaluating the properties of the IM being designed or used. This determines its significance and field of application.

Figure 30 shows the animation window with the mechanical characteristic $T=f(s)$ of the left part. It is built by the same program. On the right side there are sliders indicating parameters of IM circuit $R1$, $L1$, k_{vi_R} , k_{vi_L} , h_{cm} , $R4$, $L4$, Lm , Rfe and parameters necessary to consider the skin effect, including the depth of the rotor slot. The range of parameter variation is set by the user in the range relevant to him. By moving the sliders with the mouse (one at a time, one at a time), he observes how the curve $T=f(s)$ deforms (changes) in real time. The changes occur without a lag. This allows the researcher to intuitively (quickly and

correctly) assess the sensitivity of the entire curve $T=f(s)$ at its various points to the variation of any machine parameter entered. In addition to $T=f(s)$, the left part of the window displays graphs similar to those shown in Figures 22-29. The animation is for a K22R 355bLY6 NS LL IL HW type with a different form of mechanical characteristic.

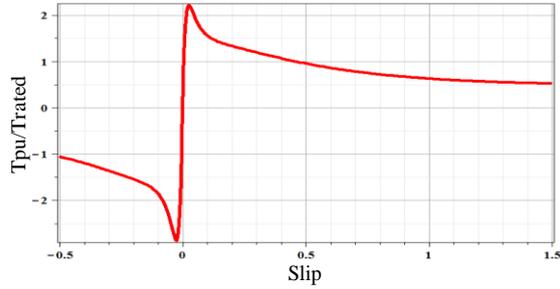


Figure 22. Torque vs slip

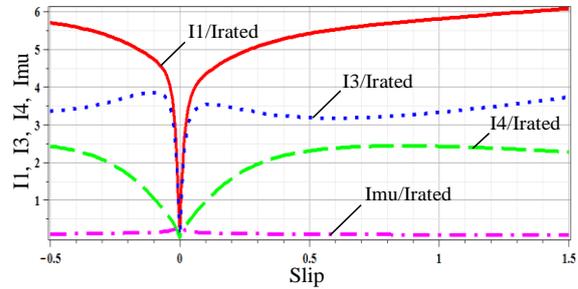


Figure 23. The currents I1, I3, I4, Imu vs slip

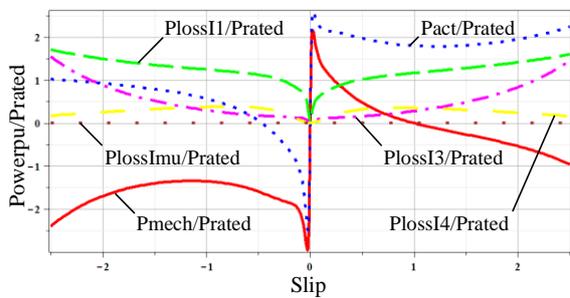


Figure 24. Loss powers P1, P3, P4, Pmu and active motor power vs slip

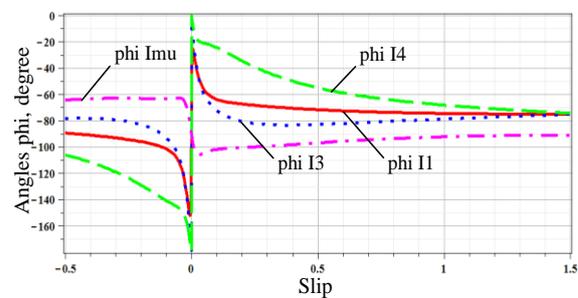


Figure 25. The angles ϕ of currents I1, I3, I4, Imu vs slip

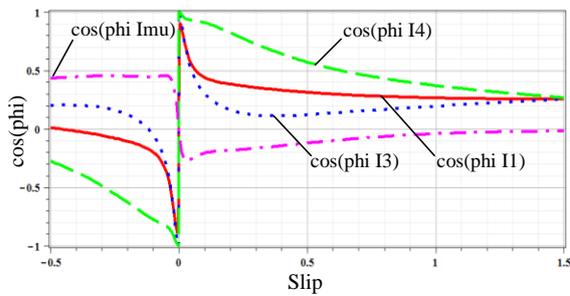


Figure 26. $\cos(\phi)$ of currents I1, I3, I4, Imu vs slip

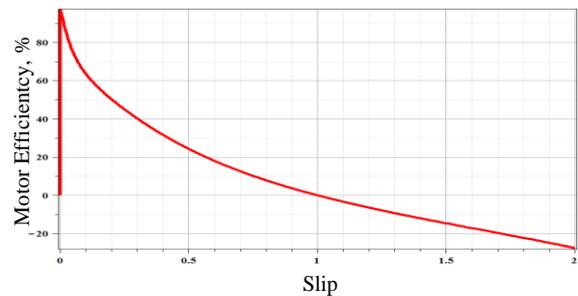


Figure 27. The motor efficiency vs slip

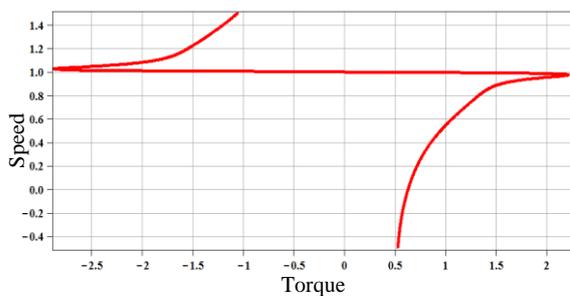


Figure 28. Speed-torque characteristic of the Motor, $\omega=f(T)$

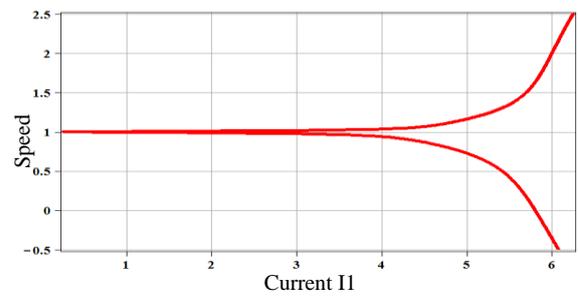


Figure 29. Speed-current characteristic of the Motor, $\omega=f(\text{abs}(I1))$

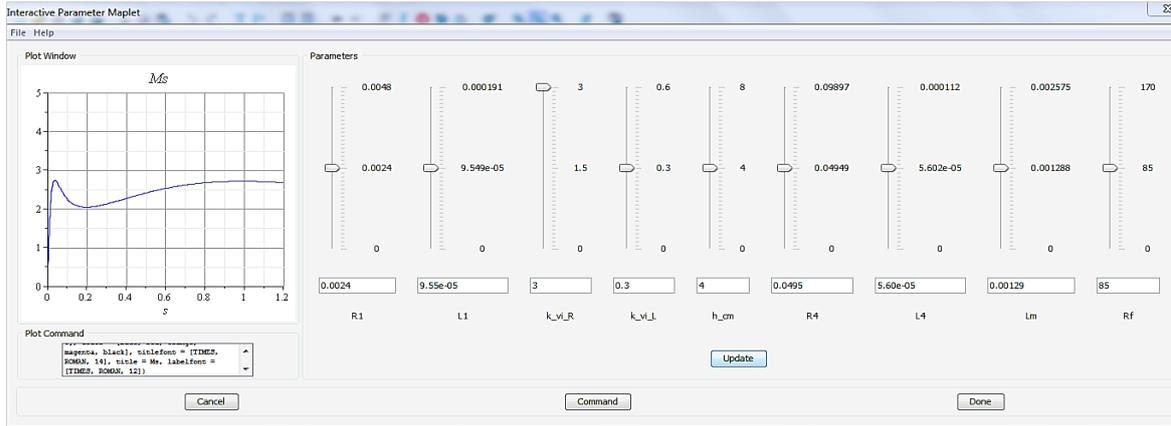


Figure 30. Animated graphics window for $\omega=f(T)$ of the K22R 355bLY6 NS LL IL HW motor

3.3. On the technique of analytical building of IM characteristics, its results and analogues

The article reveals the algorithm, shows the developed program and the results of combining fully symbolic transformations, the apparatus of transfer functions, including frequency functions, with an array of tasks of plotting static characteristics of induction motors for different equivalent circuits of IM and a set of displayed functions derived from the equivalent circuits ($\omega=f(T)$, $\omega=f(I)$, $T=f(s)$, family of stator, rotor and magnetizing currents $I=f(s)$, powers of IM elements, efficiencies, angles and their cosines for branches of equivalent circuits between each current and stator voltage, between induced EMF and rotor currents). The problem is also solved for nonlinear nonlinearities if they are set analytically and included in the equivalent circuit of IM, for example, to take into account the skin effect in the rotor. At the same time in the program by means of maple package there was solved the task of animation of built above curves in real time by means of mouse for fast intuitive evaluation of sensitivity of IM characteristics to variation of feed voltage and frequency, parameters of IM systems $R1, L1, k_{vi_R}, k_{vi_L}, h_{cm}, R4, L4, Lm, Rfe$ and also parameters necessary for skin effect accounting, including depth of rotor slot. In this configuration, the problem statement seems to be relevant and original.

The authors compared the characteristics $T=f(\text{Speed})$ and $I1=f(\text{Speed})$ built in the developed program for the AMA-500L2L engine and the same graphs built in MATLAB for this machine after its optimization [27]. The results completely coincided, which follows from the comparison of Figures 28, 29, and 31. For example, we see that the ratio of the maximum torque to the starting torque in the first case (from Figure 27 when plotting in relative terms) is $2.5/0.6=4.166$, and in the second case (from Figure 30 when plotting in absolute terms) it is also $12500/3000.0=4.166$.

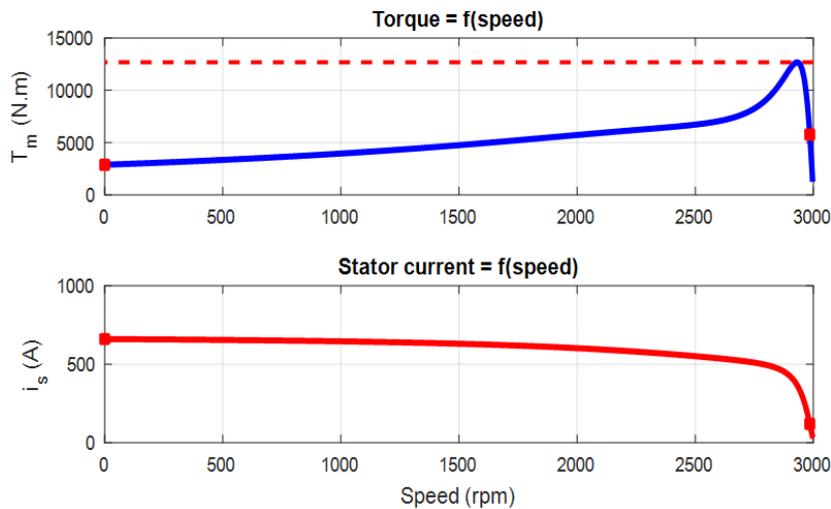


Figure 31. Calculation result [27]

4. DISCUSSION

Section 3 describes an approach to developing a program for constructing a family of basic IM characteristics. It based on the joint application of the following mathematical methods to an equivalent IM circuit with a deep-slot or double cage: a complex variable apparatus for electrical circuits; an apparatus of amplitude/phase/frequency characteristics (frequency transfer functions) and transfer functions from the control theory; a mathematical description of the skin effect for the parameters of the IM rotor. Such a combined application of various mathematical tools for the use of an equivalent IM circuits was not found in the literature reviewed by the authors.

Currently, it is easy to gain knowledge about the individual characteristics of a given serial IM using well-known formulas. These formulas are presented in well-known textbooks, for example [22]. At the same time, we see that IMs with improved equivalent circuits are appearing and will continue to appear, so users-engineers have to independently obtain formulas for plotting graphs, and this is a scientific task. In addition, obtaining a complete family of graphs presented in the article gives a complete picture of the properties of IM, but in papers and textbooks over the past years and decades they are either absent from such a set for a particular engine, or scattered in different sections and shown for different engines. That is, the user cannot find them ready and must independently make calculations in which he may make a mistake or spend too much time. Therefore, using the proposed algorithm of analytical formula generation to derive necessary or new IM formulas and build a complete family of graphs is a very productive approach for a quick and correct assessment of the main and additional IM characteristics at the same time.

The use of well-known theoretical methods in the proposed algorithm of the open-source program makes it possible to adapt the program text to the task of obtaining IM characteristics with various equivalent circuits, which are shown, for example, in Figures 1-12, without much effort. Therefore, the proposed algorithm, in which, instead of describing a machine based on complex variables, the basic concepts of the theory of automatic control are used to obtain a family of IM characteristic graphs, has, from our point of view, scientific novelty and originality, as well as great practical usefulness for specialist users, at least in electric drive. At the same time, all formulas generated by the program for IM with new equivalent circuits will have a formal scientific novelty, at least because it is almost impossible to obtain such cumbersome dependencies with manual transformations (and, as a result, they are not in the sources). Even for known equivalent circuits, obtaining without any simplifications such a formula for the electromagnetic moment, which is shown for example in Table 1, is a confirmation of scientific novelty. This is due to the fact that before the advent of reliably working analytical transformation packages, obtaining such formulas during manual transformations was a physically impossible task for a specialized engineer or scientist.

The proposed animation of graphs of calculated IM characteristics is also a well-known and very useful software solution for a design engineer and a student. However, it is not presented in the materials of textbooks and articles on IM. This allows us to talk about the originality of the approach specifically for tasks related to IM. The program implements animation of plotting the characteristics of $T=f(s)$, and it is established that this problem is successfully solved in real time, providing a quick intuitive assessment of the stability of IM characteristics to changes in the parameters of the equivalent circuit.

The program belongs to the category of free software and allows users to easily change the structure of an equivalent circuit (up to the introduction of capacitors and smoothing parametric nonlinearities, increasing the order of the circuit) to perform the calculations discussed above for the typical mechanical characteristics of new IM. The main advantage of the proposed algorithm and open-source program is the rapid and accurate construction of a large family of IM characteristics for machines with various equivalent circuits and the evaluation of their properties using graphical animation with changing parameters of equivalent circuits, such as active and reactive resistances. The examples of graphs constructed and shown in the article are only an illustration explaining the results of the program.

5. CONCLUSION

The paper proposes an idea and an algorithm for deriving analytical formulas for a number of the most important characteristics of IM using a package of analytical transformations. The algorithm is linear, non-iterative and consists of only 12 fragments. On the basis of this algorithm, a program was developed in a package of analytical transformations Maple for testing and further use.

With the help of the developed program, a complete analytical dependence was obtained and presented in the article for calculating the electromagnetic moment in the sliding function s and the parameters of equivalent circuits ($R1, Ls1, Lmu, Rmu, R3, Ls3, R4, Ls4, V1$, and f_{Hz}) for IM with a double cage/deep groove with a skin effect. Using the developed program, the calculation and plotting of dependencies such as $\omega=f(T)$, $\omega=f(I)$, $T=f(s)$, the family of stator, rotor (for both cages) and magnetization currents $I=f(s)$, powers of IM elements, motor efficiency, angles and their cosines for all branches of

equivalent circuits between each current and stator voltage, between induced electric and magnetic fields (EMF) and rotor currents is performed (8 different samples graphs are included in the article). Since the algorithm of the proposed program is linear and non-iterative, the program is executed in 20-30 seconds, depending on the type of IM (two-cell or deep-phase) and the value selected by the user of the tab slip sampling along the abscissa axis.

The developed program was tested on the example of an IM type AMA-500L2L. The authors compared the characteristics $T=f(\text{Speed})$ and $I_1=f(\text{Speed})$ built in the developed program for the AMA-500L2L engine and the same graphs built in MATLAB for this machine after its optimization, which shown in paragraph 3.3. The results completely coincided. This is a very good and important result, especially since up to nine methods of measuring the maximum IM moment are included in the standards of a number of states for IM, and an error of measuring T_{\max} up to 10% is allowed for IM industrial series.

REFERENCES

- [1] B. Kundrotas, S. Lisauskas, and R. Rinkeviciene, "Model of multiphase induction motor," *Elektronika ir Elektrotechnika*, vol. 111, no. 5, pp. 111–114, Jan. 1970, doi: 10.5755/j01.eee.111.5.369.
- [2] A. Arkkio, P. Rasilo, and A.-K. Repo, "Dynamic electromagnetic torque model and parameter estimation for a deep-bar induction machine," *IET Electric Power Applications*, vol. 2, no. 3, pp. 183–192, May 2008, doi: 10.1049/iet-epa:20070264.
- [3] L. C. Solar, A. A. C. Montiel, M. V. Llanes, V. S. Santos, and A. C. Colina, "A new exact equivalent circuit of the medium voltage three-phase induction motor," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 6, pp. 6164–6171, Dec. 2020, doi: 10.11591/ijece.v10i6.pp6164-6171.
- [4] L. Qaseer, F. De Leon, and S. Purushothaman, "Combined field and circuit theories in squirrel-cage induction motors based on Micro-T circuit model," *The Applied Computational Electromagnetics Society Journal (ACES)*, vol. 26, no. 7, pp. 551–560, Jul. 2011.
- [5] C. Gencer and M. Gedikpinar, "A computer-aided educational tool for induction motors," *Computer Applications in Engineering Education*, vol. 20, no. 3, pp. 503–509, Sep. 2012, doi: 10.1002/cae.20418.
- [6] B. Nasir, "An accurate determination of induction machine equivalent circuit components," *Proceedings of the Proceedings of the 1st International Multi-Disciplinary Conference Theme: Sustainable Development and Smart Planning, IMDC-SDSP 2020, Cyprus, 28-30 June 2020*, 2020, doi: 10.4108/eai.28-6-2020.2297941.
- [7] J. Rolek and G. Utrata, "An identification procedure of electromagnetic parameters for an induction motor equivalent circuit including rotor deep bar effect," *Archives of Electrical Engineering*, vol. 67, no. 2, pp. 279–291, 2018.
- [8] A. R. Helonde and M. M. Mankar, "Identifying three phase induction motor equivalent circuit parameters from nameplate data by different analytical methods," *International Journal of Trend in Scientific Research and Development*, vol. 3, no. 3, pp. 642–645, Apr. 2019, doi: 10.31142/ijtsrd22934.
- [9] A. Petrov, I. Plokhov, A. Rassolkin, T. Vaimann, A. Kallaste, and A. Belahcen, "Adjusted electrical equivalent circuit model of induction motor with broken rotor bars and eccentricity faults," in *2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, Aug. 2017, pp. 58–64, doi: 10.1109/DEMPED.2017.8062334.
- [10] H. A. Al-Isa, M. Qawaqzeh, A. Khasawneh, R. Buinyi, V. Bezruchko, and O. Miroshnyk, "Correct cross-section of cable screen in a medium voltage collector network with isolated neutral of a wind power plant," *Energies*, vol. 14, no. 11, May 2021, doi: 10.3390/en14113026.
- [11] C. A. C. Wengerkiewicz *et al.*, "Estimation of three-phase induction motor equivalent circuit parameters from manufacturer catalog data," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, vol. 16, no. 1, pp. 90–107, Mar. 2017, doi: 10.1590/2179-10742017v16i1873.
- [12] S. Al-Jufout, W. Al-rousan, and C. Wang, "Optimization of induction motor equivalent circuit parameter estimation based on manufacturer's data," *Energies*, vol. 11, no. 7, Jul. 2018, doi: 10.3390/en11071792.
- [13] H. Terzioğlu and M. Selek, "Determination of equivalent circuit parameters of induction motors by using heuristic algorithms," *Selcuk University Journal of Engineering, Science and Technology*, vol. 5, no. 2, pp. 170–182, Jun. 2017, doi: 10.15317/Scitech.2017.80.
- [14] M. M. Tezcan, A. G. Yetgin, A. I. Canakoglu, B. Cevher, M. Turan, and M. Ayaz, "Investigation of the effects of the equivalent circuit parameters on induction motor torque using three different equivalent circuit models," *Matec Web of Conferences*, vol. 157, Mar. 2018, doi: 10.1051/mateconf/201815701019.
- [15] M. Z. Qawaqzeh *et al.*, "Research of emergency modes of wind power plants using computer simulation," *Energies*, vol. 14, no. 16, Aug. 2021, doi: 10.3390/en14164780.
- [16] A. Diaz, R. Saltares, C. Rodriguez, R. F. Nunez, E. I. Ortiz-Rivera, and J. Gonzalez-Llorente, "Induction motor equivalent circuit for dynamic simulation," in *2009 IEEE International Electric Machines and Drives Conference*, May 2009, pp. 858–863, doi: 10.1109/IEMDC.2009.5075304.
- [17] L. Monjo, F. Córcoles, and J. Pedra, "Parameter estimation of squirrel-cage motors with parasitic torques in the torque-slip curve," *IET Electric Power Applications*, vol. 9, no. 5, pp. 377–387, May 2015, doi: 10.1049/iet-epa.2014.0208.
- [18] P. Komada, "The incentive scheme for maintaining or improving power supply quality," *Przeegląd Elektrotechniczny*, vol. 1, no. 5, pp. 81–84, May 2019, doi: 10.15199/48.2019.05.20.
- [19] S. Hesari, M. Noruziazghandi, A. A. Shojaei, and M. Neyestani, "Investigating the intelligent methods of loss minimization in induction motors," *Telecommunication Computing Electronics and Control (TELKOMNIKA)*, vol. 16, no. 3, pp. 1034–1053, Jun. 2018, doi: 10.12928/telekomnika.v16i3.8293.
- [20] A. Issa Ismael, L. E. Jumaa, and N. Khamas, "Design of H_{∞} for induction motor," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 11, no. 1, pp. 24–33, Mar. 2020, doi: 10.11591/ijpeds.v11.i1.pp24-33.
- [21] G. Müller and B. Ponick, *Calculation of electrical machines*, 6th ed. Weinheim: Wiley-VCH, 2012.
- [22] I. Boldea and S. A. Nasar, *The induction machines design handbook*. CRC Press, 2018., doi: 10.1201/9781315222592.
- [23] Z. Maddi and D. Aouzellag, "Dynamic modelling of induction motor squirrel cage for different shapes of rotor deep bars with estimation of the skin effect," *Progress In Electromagnetics Research M*, vol. 59, pp. 147–160, 2017, doi: 10.2528/PIERM17060508.

- [24] K. Oberretl, "Influence of skin effect on mutual inductance of double-cage induction motors," *Electrical Engineering*, vol. 87, no. 2, pp. 103–111, Feb. 2005, doi: 10.1007/s00202-004-0233-7.
- [25] O. Korolova, J. Torre Cubillo, and B. Ponick, "Transient modeling of ac machines considering second order effects," *Informatyka Automatyka Pomiary w Gospodarce i Ochronie Środowiska*, vol. 8, no. 2, pp. 4–8, May 2018, doi: 10.5604/01.3001.0012.0695.
- [26] M. Popp, W. Mathis, O. Korolova, and B. Ponick, "Modeling and simulation of electrical machines within a CCM framework," in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, May 2017, pp. 1–8., doi: 10.1109/IEMDC.2017.8002174.
- [27] J. Pedra, "On the determination of induction motor parameters from manufacturer data for electromagnetic transient programs," *IEEE Transactions on Power Systems*, vol. 23, no. 4, pp. 1709–1718, Nov. 2008, doi: 10.1109/TPWRS.2008.2002293.
- [28] A. Osichev, Y. Sharko, and A. Tkachenko, *Design and calculation method for high-voltage two-cage IM. Modeling an induction drive with current displacement (in Russian)*. LAMBERT Academic Publishing, 2018.
- [29] S. Tymchuk and O. Miroshnyk, "Assess electricity quality by means of fuzzy generalized index," *Eastern-European Journal of Enterprise Technologies*, vol. 3, no. 4 (75), Jun. 2015, doi: 10.15587/1729-4061.2015.42484.
- [30] A. Stening, "Analysis and reduction of parasitic effects in induction motors with die-cast rotors," KTH Royal Institute of Technology, 2013.
- [31] M. Calin, F. Rezmerita, C. Ileana, M. Iordache, and N. Galan, "Performance analysis of three phase squirrel cage induction motor with deep rotor bars in transient behavior," *Electrical and Electronic Engineering*, vol. 2, no. 2, pp. 11–17, Aug. 2012, doi: 10.5923/j.eee.20120202.03.
- [32] S. Tymchuk and O. Miroshnyk, "Calculation of energy losses in relation to its quality in fuzzy form in rural distribution networks," *Eastern-European Journal of Enterprise Technologies*, vol. 1, no. 8, pp. 4–10, Feb. 2015, doi: 10.15587/1729-4061.2015.36003.
- [33] O. Al-barbarawi and G. M. Qaryouti, "Implementation simulink modeling to analysis the transient cases and torque speed characteristic in a three phase induction motors," *Indonesian Journal of Electrical Engineering and Computer Science (IJECS)*, vol. 16, no. 3, pp. 1077–1087, Dec. 2019, doi: 10.11591/ijeecs.v16.i3.pp1077-1087.

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