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IMPROVEMENT OF THE METHOD OF CALCULATION OF MECHANICAL CHARACTERISTICS OF A TRACTION MOTOR OF DIRECT CURRENT WITH COMBINED EXCITATION

Об'єктом дослідження є процес виникнення електромагнітного моменту у тягових двигунах комбінованого збудження тролейбусу при одночасному включенні обох складових системи збудження. Цей процес формально представлено у вигляді механічних характеристик – залежності електромагнітного моменту двигуна від струмів збудження.

Одним з найбільш проблемних місць є визначення впливу струмів збудження послідовної та незалежної обмотки на електромагнітний момент двигуна у вигляді неперервної залежності, яка дозволяє створити систему управління тяговим приводом з DC-DC перетворювачем збудження. А також враховує особливості магнітної системи двигуна.

В ході дослідження використовувався метод кінцевих елементів в плоско-паралельній постановці задачі обчислення моментів за результатами розрахунку магнітного поля та наступним регресійним аналізом результатів цифрових експериментів за допомогою поліномів Чебишева на множині рівновіддалених точок.

Отримано неперервна залежність електромагнітного моменту від струмів збудження у вигляді поліному, який можливо використовувати як при створенні систем керування DC-DC перетворювачем збудження, так і при моделюванні режимів роботи тягового приводу в цілому. Це пов'язано з тим, що запропонований вид поліному має неперервний вигляд залежності та її похідних при усіх можливих значеннях струмів при роботі приводу. За результатами регресійного аналізу максимальне відхилення розрахованих залежностей не перевищує 0,052, а середньоквадратичне відхилення не більш 0,041. Це підтверджує адекватність отриманих залежностей результатам цифрового експерименту по визначенню електромагнітного моменту.

Завдяки цьому забезпечується можливість моделювання режимів роботи тягового приводу на основі двигуна з комбінованим збудженням та DC-DC перетворювачем. Отримані за результатами моделювання параметри системи керування дозволять підвищити енергетичні характеристики тролейбусів. У порівнянні з аналогічними відомими системами це забезпечує більш раціональне використання електричної енергії на тягу електрорухомого складу.

Ключові слова: механічні характеристики, тяговий привод, комбіноване збудження, метод кінцевих елементів.

1. Introduction

The development of modern infrastructure of Ukrainian cities cannot be imagined without creation of the energy-saving urban electric transport, which component is trolleybus routes. The main component that conditions the energy saving of a trolleybus is a traction drive [1]. Contactless traction drives, based on asynchronous traction motors, remarkable for the high security, are widespread in modern trolleybuses. But the widespread traction drive, based on traction motors of the direct current with combined excitation, is continuously modernized in Ukraine [2].

That is why it is urgent to study directions of increasing the effectiveness of traction drives of trolleybuses. One of such directions is creation of the traction drive based on the motor with combined excitation and DC-DC transformer for feeding the winding of separate excitation.

2. The object of research and its technological audit

The research object is a process of appearing of an electromagnetic moment in traction motors at synchronous

inclusion of both components of the excitation system. This process is formally presented as mechanical characteristics – dependence of an electromagnetic moment of the motor from excitation currents.

One of most problem points is to determine the influence of excitation currents of series and separate winding on an electromagnetic moment of a motor as a continuous dependence that allows to create a system of managing the traction drive with DC-DC excitation transformer. Peculiarities of the motor magnetic system are also taken into account.

3. The aim and objectives of research

The aim of the work – to create the method of calculating mechanical characteristics of the traction motor with combined excitation, based on the method of finite elements.

The following research tasks were set for attaining this aim:

1. To calculate the magnetic field of the traction motor of combined excitation in the two-measured target setting.

2. To realize the complex of digital experiments on determining dependencies of an electromagnetic moment on currents in motor windings.

3. To establish the continuous dependency of an electromagnetic moment by the results of the regression analysis.

4. Research of existing solutions of the problem

Among main directions of solving the problem of raising the effectiveness is the use of DC-DC transformer for feeding the separate excitation winding [3], but this work doesn't consider the use of the transformer for the traction drive of just a trolleybus. The authors concentrated attention on the autonomous electric transport.

Work [1] is devoted to main directions of increasing the effectiveness of traction drives of the electric transport but the very little attention in it is paid just to traction motors with combined excitation.

The authors of work [2] note the prospects of using traction motors of direct current at modernizing the traction drive of just the urban electric transport, but the greatest attention is paid to the collector unit.

The alternative variant of solving this problem is presented in work [4], where the authors concentrated on the possibility of using the winding of separate excitation with DC-DC transformer for thrust. But the authors of work [5] offer the more rational approach – to use combined excitation that gives a possibility to essentially decrease losses and capacity in DC-DC transformer. The authors of work [6] present the improved method of regulating operation modes of the combined excitation motor, but its use for establishing parameters of managing systems is not considered. For determining these parameters, it is necessary to determine magnetic characteristics of the motor that work [7] is devoted to and mechanical characteristics [2]. But the essential shortcoming of method [7] is the absence of taking into account the mutual influence of winding fields and local saturation of elements of the magnetic drive of the motor. Just to solve it, the author of thesis [8] offers to use the method of finite elements in the two-measured target setting for combined excitation of welding generators. [9] considers the modern program complex FEMM (Finite Element Method Magnetics) for carrying out the finite element analysis using LUA special language [10] on the example of solving the problem for the inductor motor. The essential shortcoming of this approach is the discrete outlook of the mechanical characteristic of the electric machine. For getting the continuous dependence of an electromagnetic moment from currents, the author of work [11] offered to approximate it by polynomials, which most type is presented in work [12]. Work [13] offers to use Chebyshev polynomials on the set of equidistant points for the regression analysis.

Thus, the results of the analysis allow to make a conclusion that:

- for attaining the set aim, it is necessary to use finite elements method for calculating the magnetic field;
- the calculation of electromagnetic moments must be realized by the results of calculating the magnetic field;
- the regression analysis of the results of the digital experiments must be carried out using Chebyshev polynomials on the set of equidistant points.

5. Methods of research

Main statements of finite elements method. The method of finite elements of the two-measured calculating model and orthogonal coordinates system for the stationary magnetic field is in minimization of the non-linear energetic functional [5, 6, 10]:

$$F = \int_S \left(\int_0^{B_x} \frac{1}{\mu} B_x dB_x + \int_0^{B_y} \frac{1}{\mu} B_y dB_y \right) dS - \int_S \vec{A} \cdot \vec{\delta} dS,$$

where S – area of calculation of the magnetic field; B_x, B_y – components of the vector of magnetic induction by directions of the orthogonal system of coordinates x and y ; μ – magnetic permeability; $\vec{\delta}$ – current density; \vec{A} – vector magnetic potential, determined by the ratio:

$$\vec{B} = \text{rot } \vec{A}.$$

For the orthogonal coordinates system, accepted for calculations, the components of the vectors of magnetic induction are determined by formulas, derived from the solution of the equation:

$$B_x = \frac{\partial A}{\partial y}, \quad B_y = -\frac{\partial A}{\partial x}.$$

Calculation of the magnetic field of the motor. The traction motor ED 139A, produced by the State enterprise «Electrotyagmach «plant» (Ukraine), which main parameters are presented in Table 1, was chosen as a base construction for further studies.

Table 1

Main technical characteristics of traction motor ED 139A

Parameter	Value
Nominal strain	550 W
Rotor nominal strain	280 A
Rotation nominal frequency	1650 turn/min
Efficiency in nominal mode	91 %
Moment of a shaft in the nominal mode	810 Nm
Poles number	4
Grooves number	45
Rotor internal diameter	79 mm
Rotor external diameter	294 mm
Air gap under the head pole	2/3.5 mm
Rotor winding type	wave

For solving the set task, there is used the software complex FEMM (Finite Element Method Magnetics) that includes:

1) a preprocessor that allows to set limit conditions, properties of materials of calculating areas and triangulation program;

2) a program of calculating the magnetic field that sets and solves the system of non-linear equations by the method of Newton-Raphson;

3) a postprocessor that allows to reflect the calculation picture of the magnetic field and also makes the following calculations:

- surface integrals of different kind;
- integrals by the given contour;

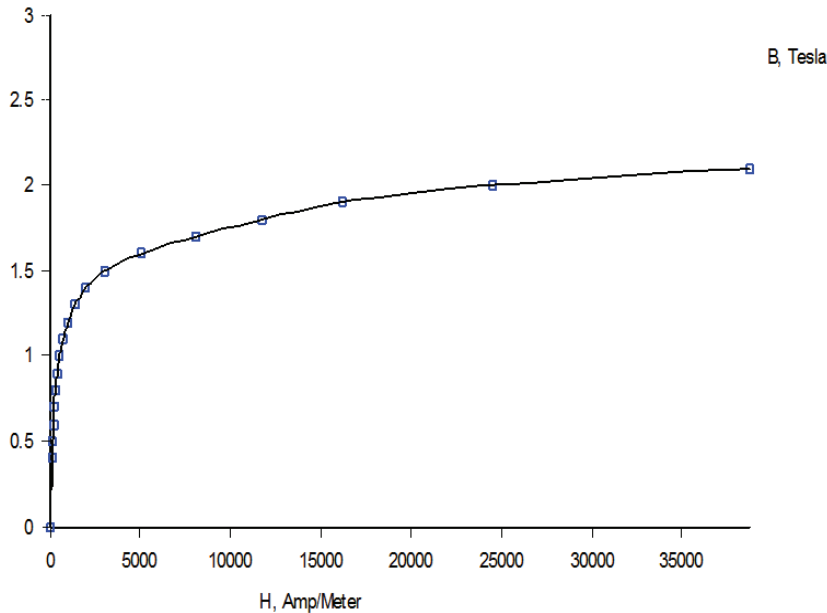


Fig. 3. Curve of magnetization of St3 steel in additional poles

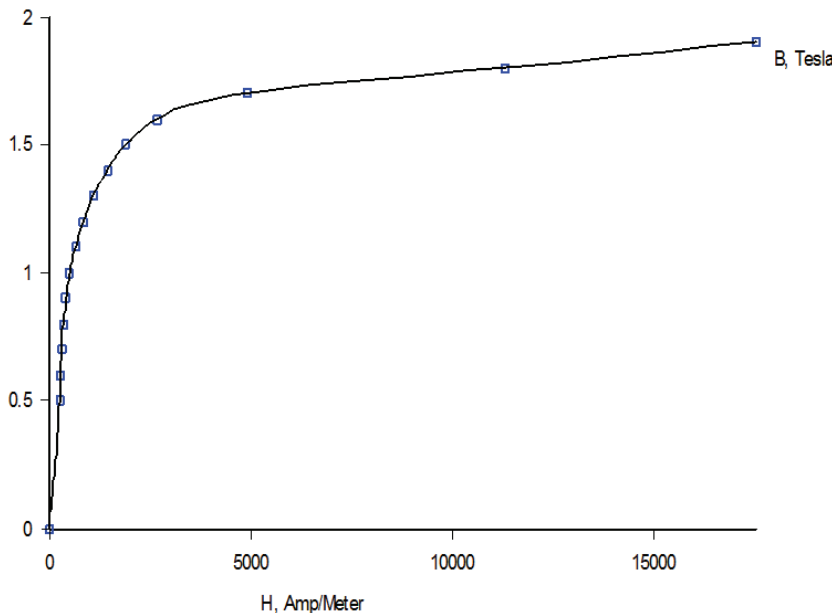


Fig. 4. Curve of magnetization of 2212 steel in rotor core

As it is seen from Fig. 5–7 the types of the magnetic fields are familiar. There is observed the unessential demagnetization of the magnetic system of the motor, caused by the effect of the cross stream of the rotor reaction. The pictures of the magnetic field demonstrate rather essential and uneven saturation of magnetic drive elements. Such processes condition the non-linearity of magnetic characteristics of the motor and their dependence on both excitation currents.

We find the electromagnetic moment value by the results of the calculation of the magnetic field by the finite elements method. Integration by the surface is replaced by integration by the contour of the external rotor. The expression for determining the electromagnetic moment for this task is transformed into:

$$\vec{M} = \frac{1}{2} \int_{l_r} \left((\vec{H} \cdot (\vec{B} \cdot \vec{n}) + \vec{B} \cdot (\vec{H} \cdot \vec{n})) \cdot \vec{r} \right) dr,$$

where l_r – integration contour – circle with the center that coincides with the center of the rotor shaft with the diameter, equal to the rotor external diameter plus air gap length.

Having replaced integration operations by summarizing, we get the calculation expression:

$$\vec{M} = \frac{1}{2} \sum_l \left((\vec{H} \cdot (\vec{B} \cdot \vec{n}) + \vec{B} \cdot (\vec{H} \cdot \vec{n})) \cdot \vec{r} \right).$$

Thus, the expressions represent the electromagnetic moment as a function of three variables:

- rotor current coefficient;
- current coefficient of the main (series) excitation winding;
- current coefficient of the separate excitation winding (k_a, k_{v1}, k_{v2}), that can be determined by calculating the magnetic field of the machine.

For identifying the dependencies of the electromagnetic moment, let's make the complex of digital experiments for their calculation according to the results of the calculation of the magnetic field of the motor in FEMM environment [9]. For automation of the processes, there was developed a macro in LUA [9].

Analogously with the currents for the convenience of identifying operation modes of the motor, let's introduce relative values of the electromagnetic moment:

$$M_d^* = \frac{M_d}{M_{dn}},$$

where M_d, M_{dn} – electromagnetic moment in the calculation and nominal modes.

The results of digital experiments are the discrete space that doesn't give a possibility of using this model for studying operation properties of the traction drive in whole.

The regression analysis of the dependency of electromagnetic moment on the currents coefficients of the motor.

For creating the continuous mathematical model of mechanical characteristics of the traction motor ED 139A, let's carry out the regression analysis by the methods, presented and probated in [2, 11–13] based on the method of Chebyshev polynomials on the set of equidistant points.

At that approximation of the electromagnetic moment in relative values looks as:

$$M_d^* = \sum_{i=0}^{I_{fm}} \sum_{j=0}^{J_{fm}} \sum_{k=0}^{K_{fm}} \left(m_{ijk} \cdot (M_a \cdot k_a + Z_a)^i (M_{v1} \cdot k_{v1} + Z_{v1})^j \times \right. \quad (1)$$

$$\left. \times (M_{v2} \cdot k_{v2} + Z_{v2})^k \right)$$

where m_{ijk} – regression coefficient of the polynomial, approximating the electromagnetic volume; I_{fm}, J_{fm}, K_{fm} – degrees of the approximating polynomial of the electromagnetic moment by coefficients of rotor currents and excitations – respectively.

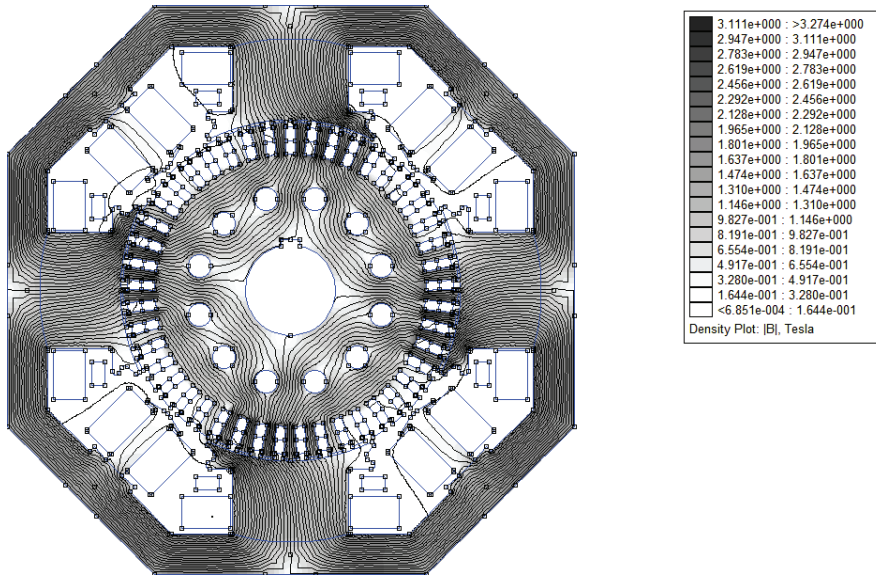


Fig. 5. Magnetic field in the mode: $k_a=1, k_{v1}=1, k_{v2}=0$

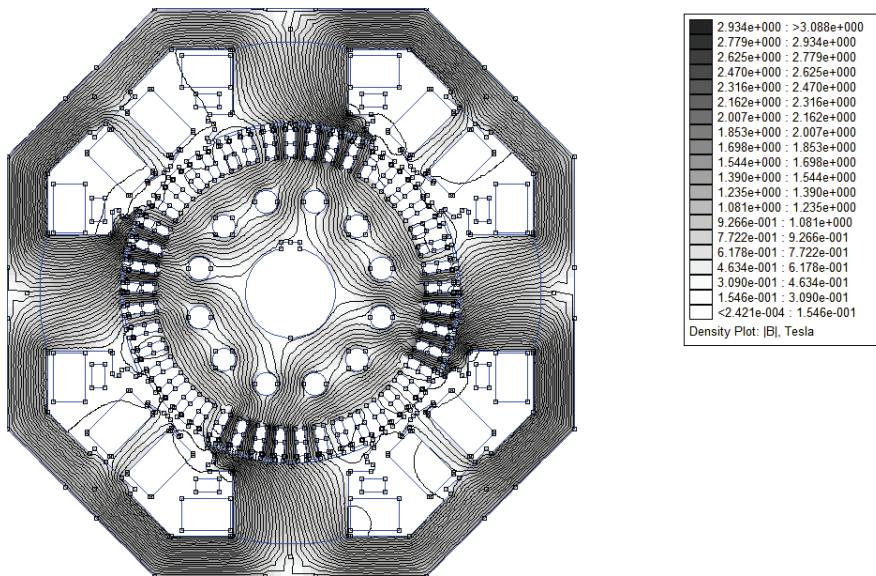


Fig. 6. Magnetic field in the mode: $k_a=1, k_{v1}=0.5, k_{v2}=0$

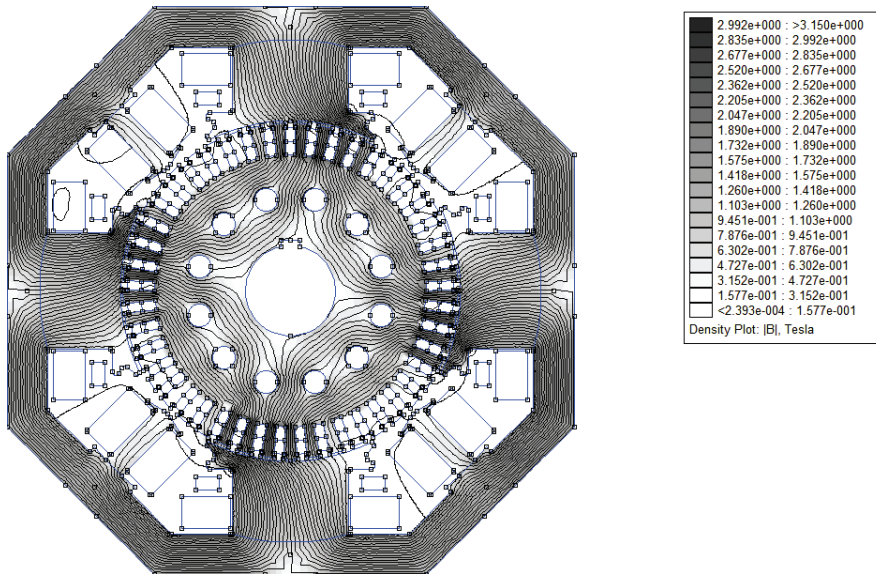


Fig. 7. Magnetic field in the mode: $k_a=1, k_{v1}=0.5, k_{v2}=1$

According to the results of the regression analysis, the maximal deviation of the calculated dependencies doesn't exceed 0.052, and mean squared one is no more 0.041.

Fig. 8 presents the dependency of the motor moments on the coefficients of rotor currents and excitation of the separate winding without weakening current.

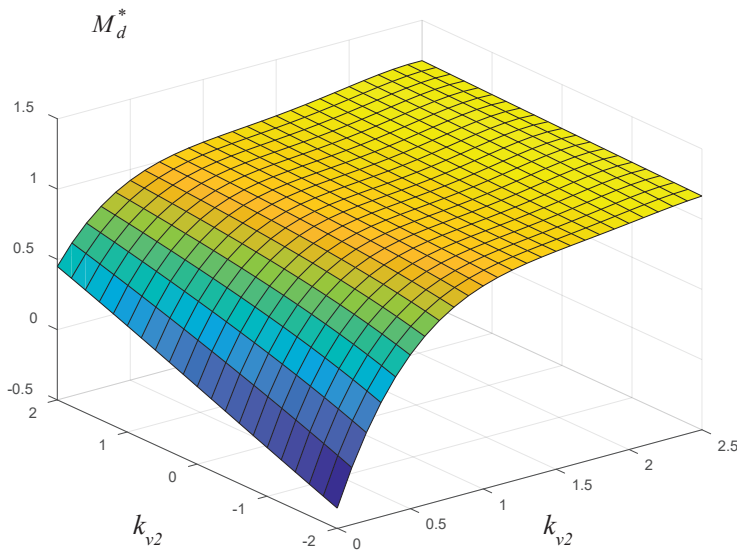


Fig. 8. Dependence $M_d^* = f(k_{v2}, k_{v1})$ in the loading mode

As it is seen on Fig. 8, inclusion of the separate winding gives a possibility to regulate the moment in the wide spectrum of rotation frequencies.

Thus, expression (1) is the continuous mathematical model of mechanical characteristics of the motor.

7. SWOT analysis of research results

Strengths. The offered method of determining the mechanical characteristic gives a possibility to get the continuous dependence of the mechanical characteristic that describes a rather complicated non-linear object – the process of appearing an electromagnetic moment in traction motors of combined excitation of trolleybuses at synchronous inclusion of both components of the excitation system. Parameters of the managing system of the traction drive of trolleybuses, received due to this model, allow to raise its efficiency in traction and brake operation modes.

Weaknesses. The offered methodology is accompanied by essential losses of the calculation time. At using a modern computer, based Intel Core I7 3770 processor, it is 243 min. But this time is completely compensated at the expanse of increasing efficiency of the traction drive of trolleybuses as exploitation.

Opportunities. The prospect of further studies is determination of continuous magnetic characteristics of the motor (dependency of magnetic streams in construction elements on currents in windings). And also development of the managing system of DC-DC excitation transformer that takes into account mechanical and magnetic characteristics of the traction motor, created by the determined characteristics.

The created method is a universal research instrument for traction motors with combined excitation of different producers – not only in Ukraine, but also abroad. It can

be used for any type of electric transport – urban and arterial.

Threats. An enterprise, that introduces the offered methodology, will face additional expenditures for using the modern computer equipment for providing it. The used program product FEMM [9] is free software. The original program in LUA [10] gives a possibility to investigate traction drives, with different parameters.

8. Conclusions

1. The calculations of the magnetic field of the traction motor of combined excitation ED 139A were carried out. Their peculiarity is taking into account the non-linearity of construction elements. The task is solved in the two-measured flat-parallel setting.

2. There was realized the complex of digital experiments on determining the dependency of an electromagnetic moment of the motor on excitation currents, which results are presented on Fig. 8. On the graph on Fig. 8 we can see that inclusion of the separate winding gives a possibility to regulate a moment in the wide spectrum of rotation frequencies. For carrying out the experiments, there was developed the program in LUA that automates the research process.

For establishing the continuous dependence of an electromagnetic moment on currents, there was conducted the regression analysis of the results of the digital experiment. The type of approximating polynomial was offered. According to the results of the regression analysis, the maximal deviation of the calculated dependencies doesn't exceed 0.052, and mean squared one is no more 0.041.

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