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STUDY OF QUASI-STATIONARY OPERATING MODES OF A TRACTION DRIVE BASED ON A SYNCHRONOUS-REACTIVE MOTOR WITH PERMANENT MAGNETS

The paper analyzes quasi-stationary processes in traction electric drives of subway cars using mathematical models of synchronous jet motors with permanent magnets. These models were adapted for modeling in MATLAB SIMULINK in accordance with general methodologies. This approach simplifies the modeling process by using proven mathematical representations of semiconductor components available as standard library blocks in the modeling environment. The development of a simulation model for determining the operating parameters of the traction drive of subway cars from a synchronous jet motor with sectioned and non-sectioned permanent magnets is considered, which allows determining the level of higher harmonics of the phase current of the motor, as well as the parameters that determine the operation of semiconductor keys in the inverter: current, average and maximum values of the current flowing through the insulated-gate bipolar transistor, as well as the maximum value of the voltage on the insulated-gate bipolar transistor in different operating modes. It is proposed to present the results in relative units for comparative analysis of the research results. The nominal value of the phase current was used as the base current, and the base voltage was the linear voltage of the traction motor stator. It was established that at a pulse-width modulation frequency of more than 1200 Hz, the amplitudes of higher harmonics, both in traction and braking modes, do not exceed 10 % of the effective value of the phase current for a motor with a sectioned rotor and 12 % for a motor with a non-sectioned rotor. The use of modern insulated-gate bipolar transistor transistors, which allow the implementation of pulse-width modulation at frequencies up to 1500 Hz, makes the impact of higher harmonics on the operation of the motor minimal, since their value can be compared with the accuracy of engineering calculations. However, when using low-frequency insulated-gate bipolar transistor transistors with a pulse-width modulation frequency of up to 1000 Hz, it is necessary to take into account the influence of higher harmonic currents. These patterns should be taken into account to optimize the operation of the traction drive of subway cars.

Keywords: subway cars; traction drive; synchronous-reactive motor with permanent magnets; higher harmonics of the motor phase current; IGBT transistor; influence of higher harmonics.

Introduction. Currently, global practice widely adopts traction electric drives with asynchronous motors for railway rolling stock, as well as for industrial and urban transport systems. In Ukraine, high-power asynchronous electric drives are implemented in both urban electric transport and mainline railways [1].

Traction asynchronous electric drives offer numerous advantages, including high energy efficiency, favorable weight and size parameters, reliability, structural simplicity, and extended service life. Nonetheless, the ongoing demand for reduced energy consumption and prolonged rolling stock lifespan presents new challenges for the scientific and engineering community – namely the need for further enhancement of asynchronous traction drives and exploration of alternative electric drive technologies [2]. One such alternative involves synchronous motors with permanent magnet excitation [3]. However, the substantial weight and high cost of high-coercivity magnets significantly increase the production cost of these motors. One of the promising directions in developing energy-efficient technologies for metro rolling stock is the implementation of traction drives utilizing synchronous traction motors. These motors offer high efficiency, particularly under partial load conditions, and ensure rapid acceleration and deceleration of trains [4].

To explore this further, we examine the fundamental principles behind developing the core component of a traction drive's mathematical model – the synchronous motor. Since the high energy performance of synchronous motors is largely attributed to their magnetic systems with complex flux distribution, the mathematical model must account for the geometric characteristics of both the rotor and the stator [5]. This model is constructed based on a generalized mathematical representation. The basics of this mathematical model are given in [6].

Quasi-stationary processes in traction electric drives of metro cars are analyzed using mathematical models of synchronous reluctance motors with permanent magnets, as presented in [6]. These models have been adapted for simulation in MATLAB SIMULINK, following the general methodologies outlined in [7, 8, 9]. This approach streamlines the modeling process by utilizing validated mathematical representations of semiconductor components, which are available as standard library blocks within the simulation environment.

Purpose of the article. The developed simulation model was used to determine the operating parameters of the traction drive of subway cars from a synchronous jet motor with sectioned and non-sectioned permanent magnets to determine the influence of pulse-width modulation (PWM) frequencies on the characteristics of the inverter semiconductor devices and the level of higher harmonic currents of the motor.

Research results. The simulation model for modeling quasi-stationary modes of operation of a traction drive based on a synchronous jet motor with permanent magnets is presented in Fig. 1 and 2. The general structure of the simulation model is presented in Fig. 1.

It consists of the following main subsystems, MOTOR, AIN, SV_PWM. The MOTOR subsystem (Fig. 2) is designed to simulate a traction motor, the AIN subsystem simulates an autonomous three-phase autonomous voltage inverter based on insulated-gate bipolar transistor (IGBT) key models, SV_PWM is a control system for an autonomous voltage inverter that implements the law of space-vector pulse-width control [10] of the engine.

 Conflict of interest: The author has declared no conflict of interest.

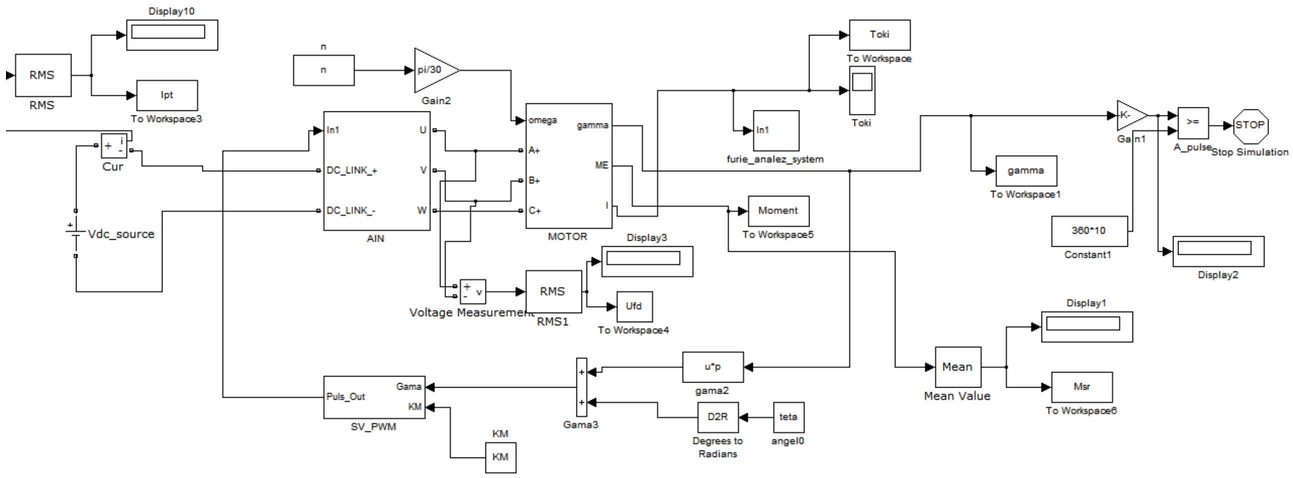


Figure 1 – Simulation model for modeling quasi-stationary modes of operation of a traction drive based on a synchronous jet motor with permanent magnets

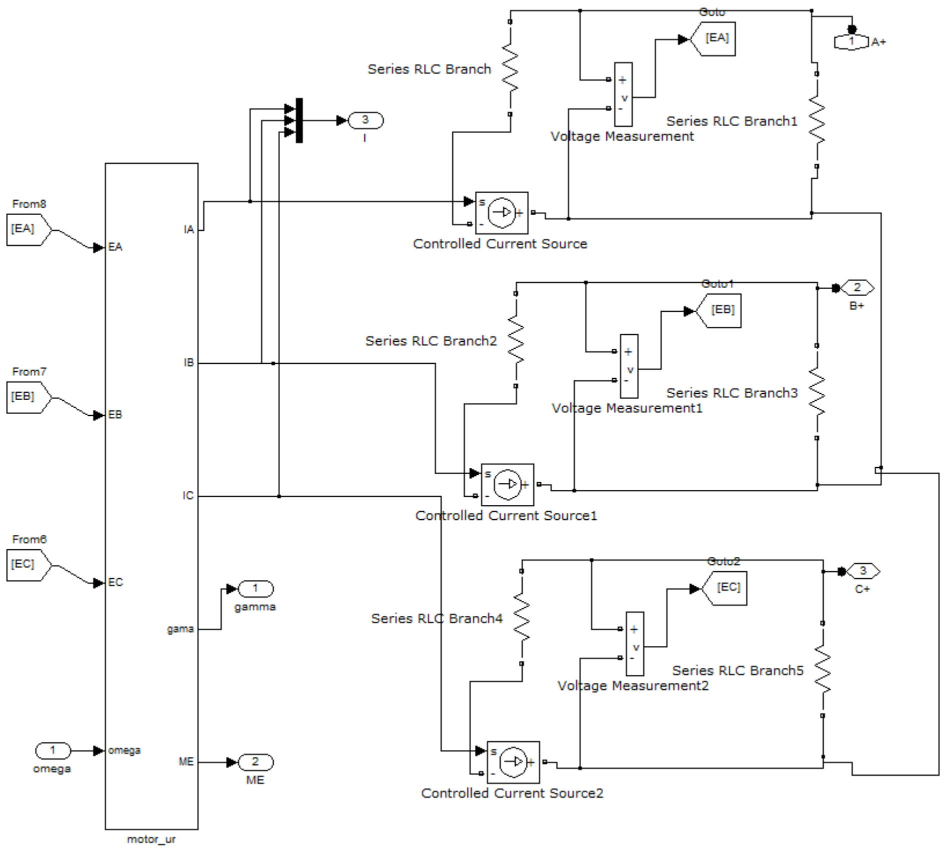


Figure 2 – MOTOR subsystem

The subsystem “furie_analez_system” is intended for spectral analysis of the stator phase current (determination of the maximum values of the harmonic components of the current $I_{f\,max\,15}$, $I_{f\,max\,17}$, $I_{f\,max\,111}$, $I_{f\,max\,113}$) and determination of the effective value.

The subsystem “MOTOR” (Fig. 2) provides a simulation model of a synchronous-reactive motor with permanent magnets. This model includes the subsystem “motor_ur”, where the mathematical model of the motor is implemented, as well as the blocks “Controlled Current Source”, “Controlled Current Source1” and “Controlled Current Source2”, which provide the ability to coordinate the blocks of s-models and sps-models by including controlled current sources. The voltmeter blocks “Voltage Measurement”, “Voltage Measurement3” and “Voltage Measurement5” are used to monitor the phase voltage. The subsystem “motor_ur” contains the blocks “Interpreted MATLAB Function", “Interpreted MATLAB Function1” and “Interpreted MATLAB Function2”, which implement the right-hand sides of the differential equations describing the derivatives of the stator currents according to the mathematical model [10]. The blocks “Interpreted MATLAB Function3” are intended for calculating the level of the electromagnetic torque of the motor.

Since during the simulation modeling the rotation frequency is constant, which is provided by the conditions of the quasi-stationary approach to considering the engine operating modes, the model [10] takes into account only the equations describing the electrical coordinates. The integration of these differential equations is implemented in the blocks “Integrator6”, “Integrator2” and “Integrator3”.

The subsystem “AIN” (Fig. 3) implements a model of a three-phase bridge inverter assembled on IGBT transistors using elements of the “SimPowerSystem” library. “RMS” and “Mean Value” determine the actual and average current of the IGBT transistor. The “To Workspace3”, “To Workspace4” blocks are designed to transfer the current value of the currents and voltages on the IGBT transistor to the workspace. Using the analysis of the results of these currents based on the results of the simulation model during the time period of the main harmonic of the current, the maximum current ($I_{max\,VT}$) and $U_{max\,VT}$ voltage on the IGBT transistors are determined. In the “SV_PWM” subsystem, the “Pulse Generator” block sets the PWM frequency (f_{PWM}).

To conduct a comparative analysis of the research results, it is rational to present the results in relative units. So, for the base current we will take the nominal value of the phase current I_{f1}, the base voltage is the linear voltage U_{l1} of the traction motor stator.

Thus, we determine the amplitude values of the traction motor currents for the l = 5th, 7th, 11th and 13th harmonics by the expressions

$$I_{f\,max\,l\,ru} = I_{f\,max\,l}/I_{f1}. \qquad (1)$$

For the effective value of the current flowing through the IGBT transistor, in relative units, the expression is proposed

$$I_{CRMSru} = I_{CRMS}/I_{f1}. \qquad (2)$$

The average value of the current flowing through the IGBT transistor, in relative units

The maximum value of the current flowing through the IGBT transistor, in relative units:

$$I_{max\,VToe} = I_{max\,VT}/I_{f1}. \qquad (3)$$

Maximum voltage value on the IGBT transistor in relative units

$$U_{max\,VToe} = U_{max\,VT}/U_{l1} = U_{max\,VT}\frac{K_m}{2U_d}. \qquad (4)$$

The results of the numerical simulation are shown in Fig. 4–15. Their analysis showed the following.

The dependences of the maximum value of the higher harmonic currents in the nominal operating mode are shown in Fig. 4–7, which show that at a PWM frequency of more than 1000 Hz it does not exceed 15 % of the effective value of the phase current for a synchronous reactive motor with sectioned permanent magnets in the braking mode , and when using a non-sectioned rotor, the higher harmonic currents are larger and do not exceed 15 % of the effective value of the phase current at a PWM frequency of more than 1000 Hz.

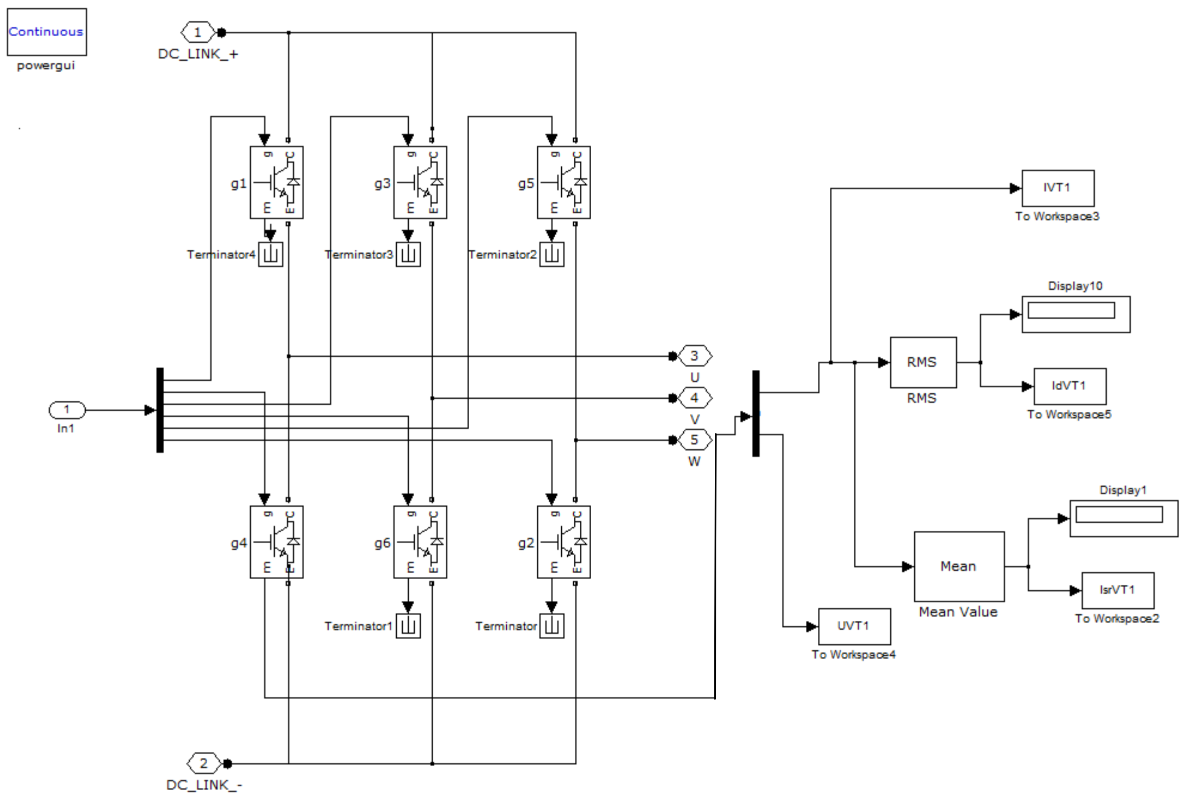


Figure 3 – AIN subsystem

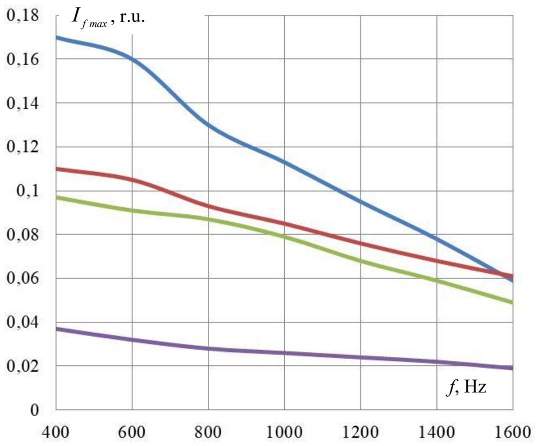


Figure 4 – Dependence of the amplitudes of phase harmonic currents on the PWM frequency of a synchronous jet motor with sectioned permanent magnets in traction mode:
blue line – $I_{f\,max15ru}$; red line – $I_{f\,max17ru}$; green line – $I_{f\,max111ru}$; purple line – $I_{f\,max113ru}$

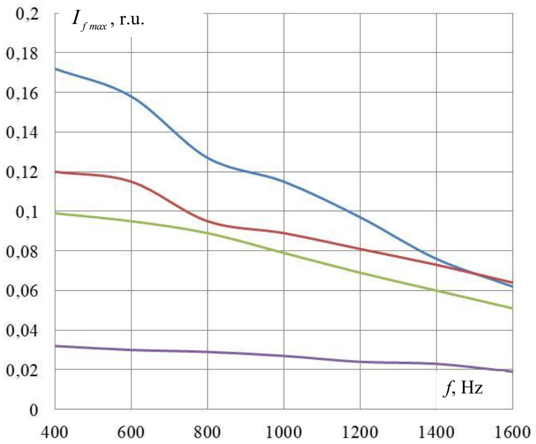


Figure 5 – Dependence of the amplitudes of phase harmonic currents on the PWM frequency of a synchronous reactive motor with sectioned permanent magnets in braking mode:
blue line – $I_{f\,max15ru}$; red line – $I_{f\,max17ru}$; green line – $I_{f\,max111ru}$; purple line – $I_{f\,max113ru}$

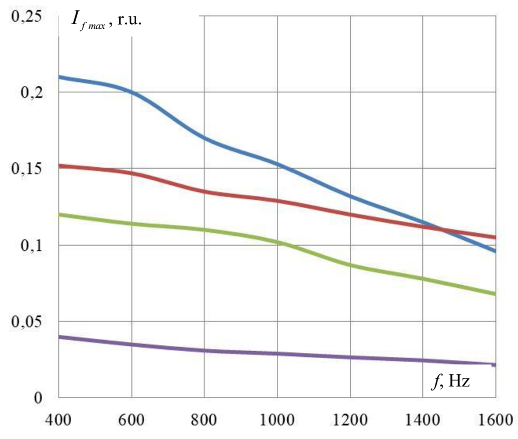


Figure 6– Dependence of the amplitudes of phase harmonic currents on the PWM frequency of a synchronous jet motor with non-sectioned permanent magnets in traction mode:
blue line – $I_{f\,max15ru}$; red line – $I_{f\,max17ru}$; green line – $I_{f\,max111ru}$; purple line – $I_{f\,max113ru}$

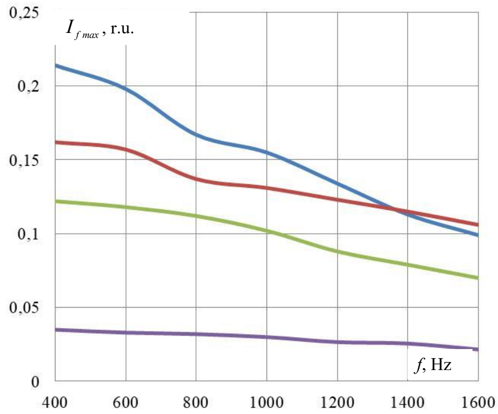


Figure 7 – Dependence of the amplitudes of phase harmonic currents on the PWM frequency of a synchronous jet motor with non-sectioned permanent magnets in braking mode:
blue line – $I_{f\,max15ru}$; red line – $I_{f\,max17ru}$; green line – $I_{f\,max111ru}$; purple line – $I_{f\,max113ru}$

When using modern IGBT transistors, which allow PWM at frequencies up to 1200 Hz, the influence of higher harmonics on the operation of a synchronous reactive motor with permanent magnets is insignificant, as the magnitudes of the higher harmonic currents can be compared with the accuracy of engineering calculations. However, when using low-frequency IGBT transistors with a PWM frequency of up to 1000 Hz, it is necessary to take into account the higher harmonic currents.

Further studies of the influence of the operating modes of the traction drive were carried out for an engine with sectioned permanent magnets, as a more promising design. Fig. 8–11 at a frequency of 1400 Hz presents the dependences of the relative values of the amplitudes of the higher harmonic currents 5, 7, 11 and 13 harmonics of phase currents. The dependences have a sharply variable nature.

When analyzing the graphs, two components of the harmonic amplitude changes depending on the rotation frequency are traced: the first harmonic amplitudes increase with increasing rotation frequency, the second is periodic, which lies in the range from 0.3…0.5 r.u.

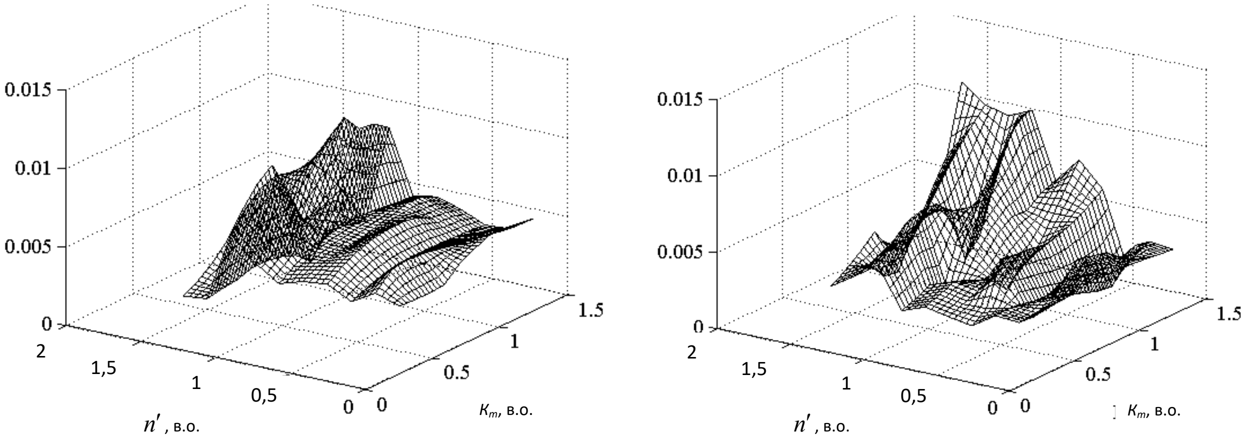
The amplitude of harmonics also increases. This is due to the decrease in the number of PWM pulses per period of the 1st harmonic of the current and the discreteness of their change. The amplitudes of harmonics are in the range from 0.01 to 0.05 r.u.

The maximum influence of the 11th harmonic is at a rotation frequency of 1.25 rpm and a modulation factor of 1.

The effective value of the current flowing through the IGBT transistor (Fig. 12 and 13) lies in the range from 0.7 to 0.9 of the phase current of the traction motor.

Larger values correspond to higher rotational speeds and lower modulation coefficient values.

The average value of currents in the traction mode lies in the range from 0.1 to 0.55 of the phase current, and in the braking mode from –0.1 to –0.42. The dependence is close to “smooth”. The maximum value in the traction mode is reached at the nominal speed and the modulation factor is equal to 1, the minimum in the braking mode at the same values.



a *b*

Figure 8 – Dependence of the relative value of the 5th harmonic phase current of a synchronous jet motor sectioned permanent magnets ($I_{f\,max15ru}$): *a*) in traction mode; *b*) in braking mode

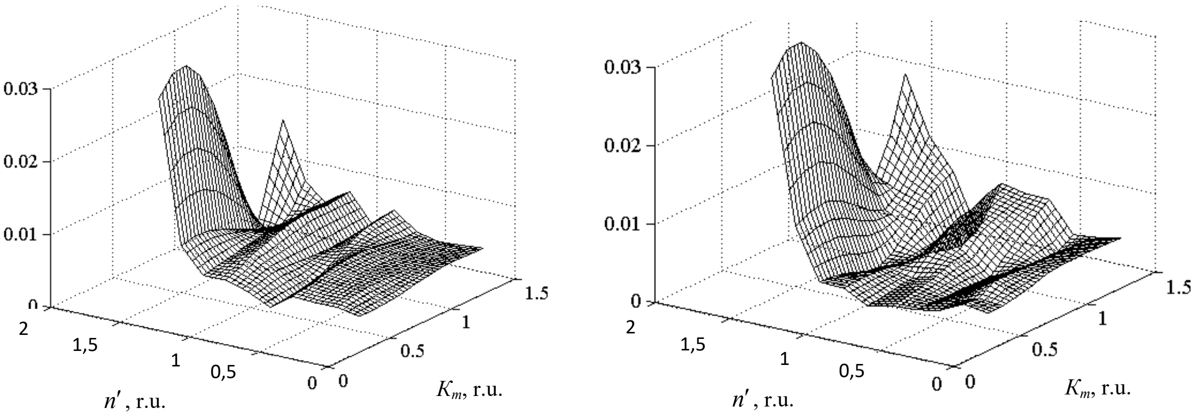


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Figure 9 – Dependence of the relative value of the 7th harmonic phase current of a synchronous jet motor sectioned permanent magnets ($I_{f\,max17ru}$): *a*) in traction mode; *b*) in braking mode

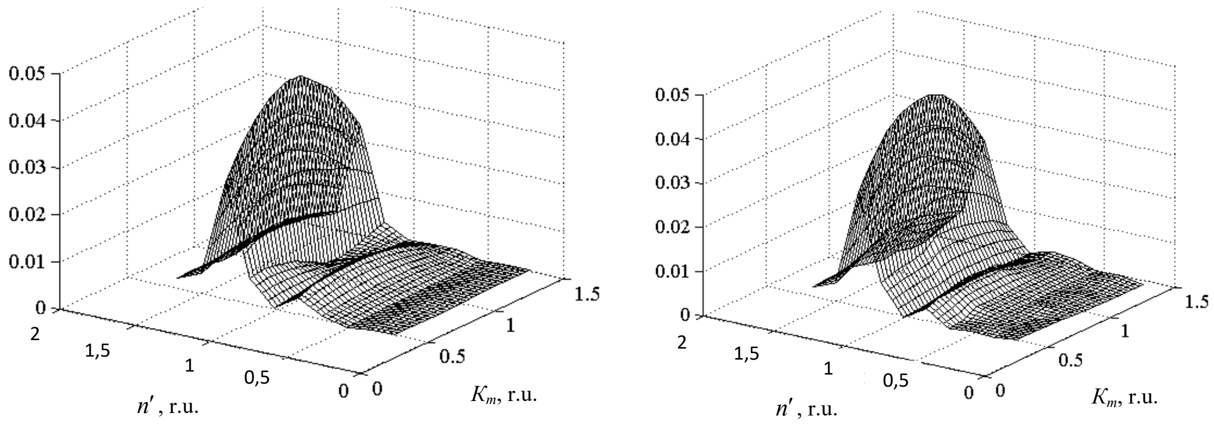

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Figure 10 – Dependence of the relative value of the 11th harmonic of the phase current of a synchronous jet motor sectioned permanent magnet ($I_{f\,max111ru}$): *a*) in traction mode; *b*) in braking mode

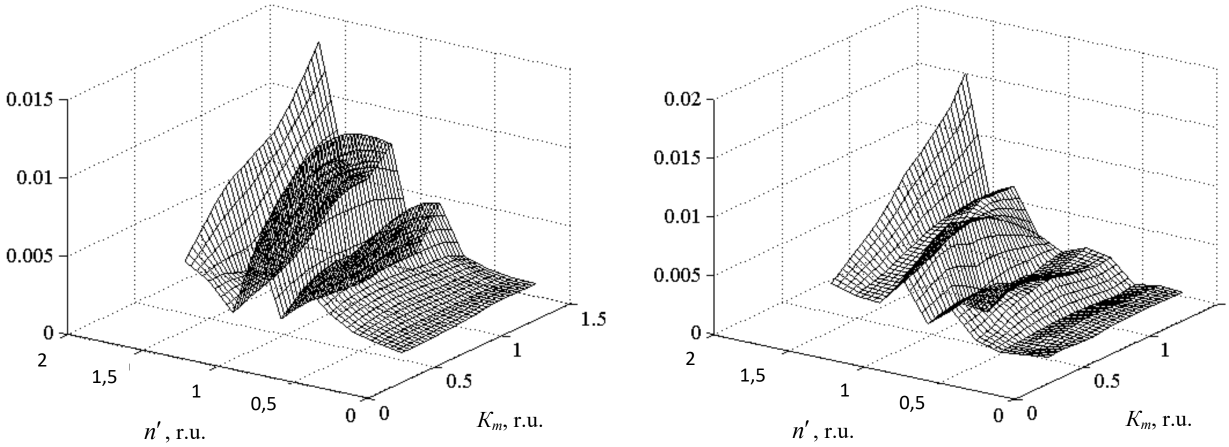

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Figure 11 – Dependence of the relative value of the 13th harmonic phase current of a synchronous jet motor sectioned permanent magnets ($I_{f\,max113ru}$): *a*) in traction mode; *b*) in braking mode

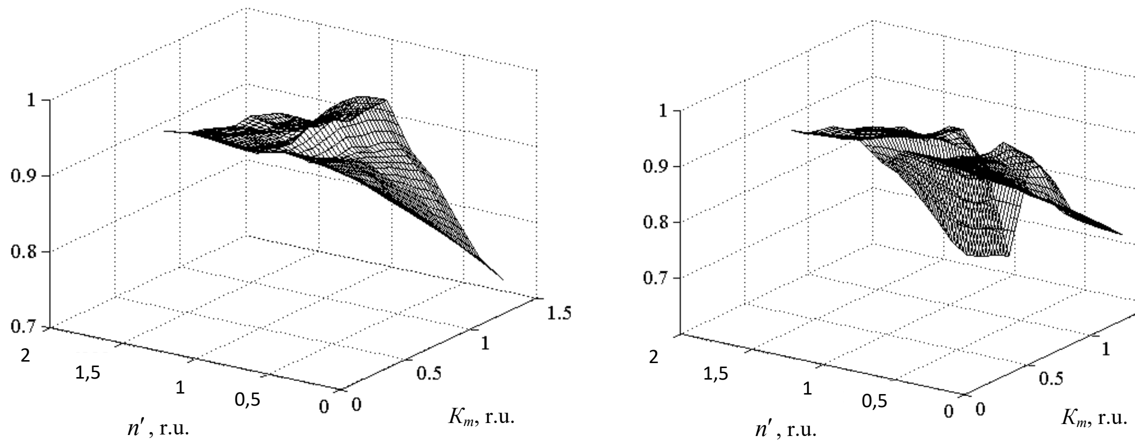

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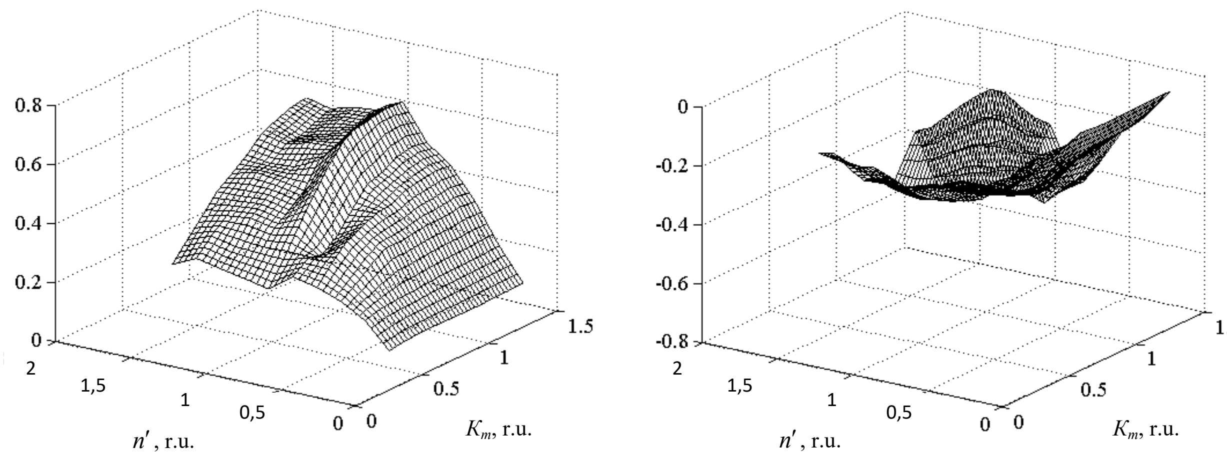
Figure 12 – Dependence of the relative value of the current flowing through the IGBT transistor (I_{CRMSoe}): *a*) in traction mod; *b*) in braking mode



a *b*

Figure 13 – Dependence of the relative average value of the current flowing through the IGBT transistor (I_{CAVoe}): *a*) in traction mode; *b*) in braking mode

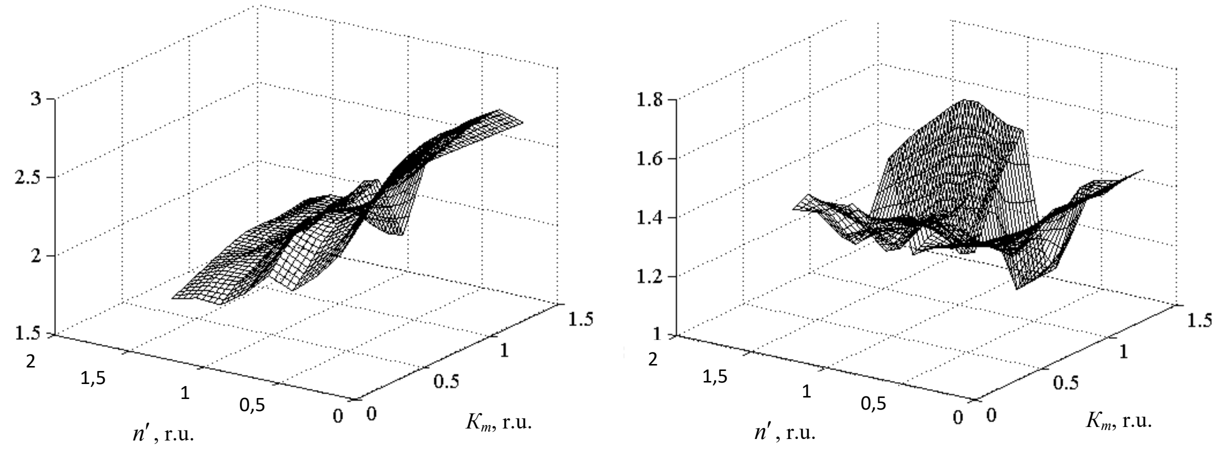


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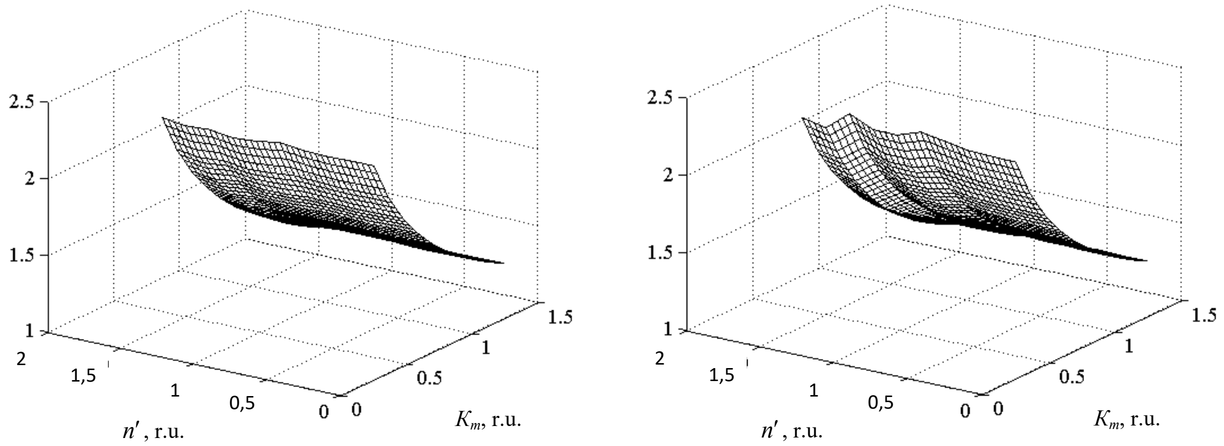
Figure 14 – Dependence of the relative maximum value of the current flowing through the IGBT transistor ($I_{max\,VToe}$): *a*) in traction mode; *b*) in braking mode



a *b*

Figure 15 – Dependence of the relative maximum value of the voltage applied to the IGBT transistor. ($U_{max\,VToe}$): *a*) in traction mode; *b*) in braking mode

The maximum value of the currents flowing through the IGBT transistor is in the range from 1.6 to 2.7 of the phase current of the synchronous jet motor permanent magnets, for traction mode and from 1.2 to 1.56 in braking mode. The maximum voltage applied to the transistor (Fig. 14 and 15) does not exceed twice the line voltage on the motor.

Conclusions. For the first time, a simulation model has been developed to determine the operating parameters of the traction drive of subway cars from a synchronous jet motor with sectioned and non-sectioned permanent magnets. The model allows you to determine the level of higher harmonics of the motor phase current, as well as the parameters that determine the operation of semiconductor switches in the inverter: current, average and maximum current values flowing through the IGBT transistor, as well as the maximum voltage value on the IGBT in different operating modes.

It was determined that at a PWM frequency of more than 1200 Hz, the amplitudes of higher harmonics, both in traction and braking modes, do not exceed 10 % of the effective value of the phase current for a motor with a sectioned rotor and 12 % for a motor with a non- sectioned rotor. The use of modern IGBT transistors, which allow implementing PWM at frequencies up to 1500 Hz, makes the impact of higher harmonics on the operation of the motor minimal, since their values can be compared with the accuracy of engineering calculations. However, when using low-frequency IGBT transistors with a PWM frequency of up to 1000 Hz, it is necessary to take into account the impact of higher harmonic currents. These patterns should be taken into account to optimize the operation of the traction drive of metro cars.

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ШТОМПЕЛЬ ОЛЕКСАНДР МИКОЛАЙОВИЧ ✉ – аспірант кафедри електричного транспорту, Харківський національний технічний університет міського господарства імені О М. Бекетова; м. Харків, Україна; ORCID: https://orcid.org/0009-0008-1757-2650; e-mail: shtompel100@gmail.com.

ДОСЛІДЖЕННЯ КВАЗІСТАЦІОНАРНИХ РЕЖИМІВ РОБОТИ ТЯГОВОГО ПРИВОДУ НА ОСНОВІ СИНХРОННО-РЕАКТИВНОГО ДВИГУНА З ПОСТІЙНИМИ МАГНІТАМИ

У роботі аналізуються квазистаціонарні процеси в тягових електроприводах вагонів метрополітену з використанням математичних моделей синхронних реактивних двигунів з постійними магнітами. Ці моделі були адаптовані для моделювання в MATLAB SIMULINK відповідно до загальних методологій. Такий підхід спрощує процес моделювання за рахунок використання перевірених математичних уявлень напівпровідникових компонентів, доступних у вигляді стандартних бібліотечних блоків у середовищі моделювання. Розглядається розробка імітаційної моделі для визначення робочих параметрів тягового приводу вагонів метрополітену від синхронно-реактивного двигуна з секціонованими та несекціонованими постійними магнітами, яка дозволяє визначити рівень вищих гармонік фазного струму двигуна, а також параметри, що визначають роботу напівпровідникових ключів в інверторі: струм, середнє та максимальне значення струму, що протікає через IGBT-транзистор, а також максимальне значення напруги на IGBT у різних режимах роботи. Запропоновано для проведення порівняльного аналізу результатів дослідження представити результати у відносних одиницях. У якості базового струму використано номінальне значення фазного струму , а базова напруга – лінійна напругу статора тягового двигуна. Встановлено, що при частоті широтно-імпульсної модуляції понад 1200 Гц амплітуди вищих гармонік, як у тяговому, так і в гальмівному режимах, не перевищують 10 % від ефективного значення фазного струму для двигуна з секціонованим ротором та 12 % для двигуна з несекціонованим ротором. Використання сучасних IGBT-транзисторів, які дозволяють реалізувати широтно-імпульсної модуляції на частотах до 1500 Гц, робить вплив вищих гармонік на роботу двигуна мінімальним, оскільки їх значення можна порівняти з точністю інженерних розрахунків. Однак, при використанні низькочастотних IGBT транзисторів з частотою широтно-імпульсної модуляції до 1000 Гц необхідно враховувати вплив струмів вищих гармонік. Ці закономірності слід враховувати для оптимізації роботи тягового приводу вагонів метрополітену.

Ключові слова: вагони метрополітену; тяговий привід; синхронно-реактивний двигун з постійними магнітами; вищі гармоніки фазного струму двигуна; IGBT-транзистор; вплив вищих гармонік.