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Khaustov Oleksandr, Postgraduate student of the Department of Electric Transport and Diesel Locomotive Engineering, +38(097)834-03-77, hausz91@gmail.com, ORCID ID: 0009-0001-0363-6173

National Technical University "Kharkiv Polytechnic Institute".
2, St. Kirpychova, Kharkiv, Ukraine, 61002

Liubarskyi Borys, Doctor of Science, Professor, Head of the Department of Electric Transport and Diesel Locomotive Engineering, lboris1911@ukr.net, ORCID ID: 0000-0002-2985-7345

National Technical University "Kharkiv Polytechnic Institute".
2, St. Kirpychova, Kharkiv, Ukraine, 61002

OPTIMIZATION OF QUASI-STEADY-STATE OPERATING MODES OF SYNCHRONOUS JET MOTORS WITH PERMANENT MAGNETS FOR ELECTRIC BUSES

Abstract. *The work created an algorithm for determining the optimal control parameters of a traction synchronous jet motor with permanent magnets based on the specified power supply conditions and rotation frequency. The dependences of the drive efficiency, the traction motor efficiency, the load angle and the modulation coefficient for their optimal combination were analyzed. These dependences show similar trends for different temperatures of the stator winding, which reflects the consistent operating behavior of the traction system. It was determined that at a rotation frequency above 0.68 relative units and a torque above 0.6 relative units. A current limitation zone is observed, where the efficiency drops to zero both in the traction mode and in the braking mode.*

Keywords: *traction drive, synchronous jet motor, permanent magnets, electric transport, motor losses.*

Хаустов Олександр Едуардович, аспірант кафедри електричного транспорту та тепловозобудування, +38(097)834-03-77, hausz91@gmail.com, ORCID ID: 0009-0001-0363-6173.

Національний технічний університет «Харківський політехнічний інститут»
вул. Кирпичова, 2, Харків, Україна, 61002

Любарський Борис Григорович, д.т.н., проф., завідувач кафедрою електричного транспорту та тепловозобудування, lboris1911@ukr.net, ORCID ID: 0000-0002-2985-7345.

Національний технічний університет «Харківський політехнічний інститут»
вул. Кирпичова, 2, м. Харків, Україна, 61002

ОПТИМІЗАЦІЇ КВАЗІСТАЦІОНАРНИХ РЕЖИМІВ РОБОТИ СИНХРОННИХ РЕАКТИВНИХ ДВИГУНІВ З ПОСТІЙНИМИ МАГНІТАМИ ДЛЯ ЕЛЕКТРОБУСУ

Анотація. *В роботі створено алгоритм визначення оптимальних параметрів керування тяговим синхронним реактивним двигуном з постійними магнітами на основі заданих умов живлення та частоти* *обертання. Проаналізовано залежності ККД приводу, ККД тягового двигуна, кута навантаження та коефіцієнта модуляції для їх оптимального поєднання. Ці залежності показують подібні тенденції для різних температур обмотки статора, що відображає послідовну робочу поведінку тягової системи. Визначено , що при частоті обертання вище 0,68 в.о. і крутному моменті вище 0,6 в.о. спостерігається зона обмеження струму, де ефективність падає до нуля як в режимі тяги, так і в режимі гальмування.*

Ключові слова: *тяговий привод, синхронний реактивний двигун, постійні магніти, електротранспорт, втрати двигуна*

Introduction. Permanent magnet synchronous reluctance motors (PMASR) are considered to be one of the most energy-efficient electric motors used in vehicles. Their high efficiency allows to reduce energy consumption and increase the distance that the vehicle can travel on a single charge. Compared with other types of electric motors, PMASR have significant advantages, such as consistently high efficiency in different operating modes, simplified design and lower weight. [1-3]

Analysis of previous research. In PMASR, a significant portion of the torque is generated through the interaction between the magnetic field produced by the permanent magnets and the field created by the stator. However, another key element influencing torque production in PMASR is the asymmetry in the motor's design. This asymmetry can arise from factors such as the uneven arrangement of rotor components, like rotor ribs, or from an irregular distribution of the permanent magnets. The interplay of these factors enables the motor to generate high torque and maintain efficient performance.

The rotor design plays a critical role in the motor's operation. One of the simplest rotor designs involves a rotor with salient poles (Fig. 1a), where the permanent magnets are positioned on the rotor's surface, extending beyond the stator [4-12].

A more advanced design is the axially laminated anisotropy (ALA) rotor, which consists of thin sheets with magnetic orientation along the rotor axis (Fig. 1b). This configuration results in a high magnetic flux density on the rotor surface, which boosts torque and minimizes energy losses due to magnetization reversal. Siemens has utilized this technology in a traction motor, as illustrated in Fig. 1c [4-12].

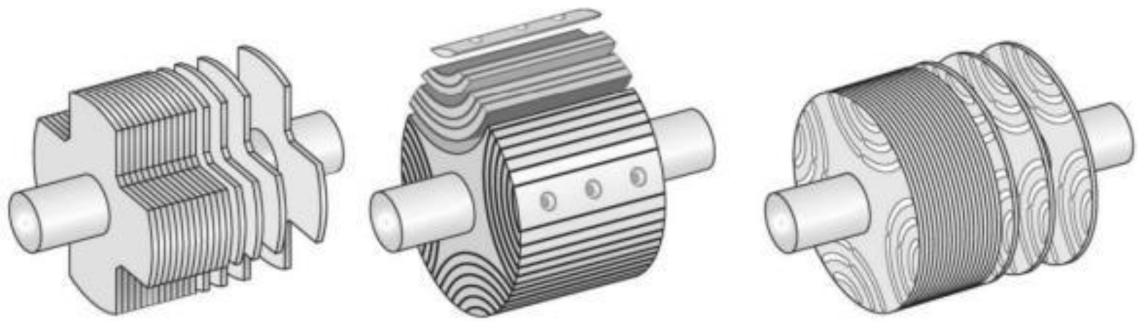

Fig.1 − Types of rotor designs for synchronous jet motors:
a) single-pole rotor; b) axial-layered anisotropy (ALA) rotor; c) transverse-layered anisotropy (TLA) rotor.

A rotor with transverse layered anisotropy (TLA) is composed of multiple layers of steel sheets, each oriented at varying angles with respect to magnetic conductivity (Fig. 1.2c). This configuration enhances magnetic flux density on the rotor surface, facilitating the generation of substantial torque and minimizing energy losses due to magnetic hysteresis.

In PMASR, the rotor typically features surface-mounted permanent magnets. Depending on the design, it may incorporate either axial laminated anisotropy (ALA) or transverse layered anisotropy (TLA) structures. Both configurations contribute to higher magnetic flux at the rotor surface and help mitigate magnetization losses.

Among these, the TLA rotor design is particularly prevalent in PMASR. This type involves steel laminations positioned at various angles in relation to the embedded permanent magnets, enabling more efficient energy conversion and reducing loss. Furthermore, TLA rotors exhibit high mechanical strength relative to their mass, allowing them to operate at elevated speeds while maintaining low levels of vibration and noise. These characteristics make TLA rotors especially well-suited for electric transportation applications, where reliability and smooth operation are essential.

The key distinction between internal permanent magnet synchronous motors (IPMSMs) and PMASR lies in how torque is produced. In PMASR, reactive torque – resulting from the interaction between the stator’s magnetic field and the rotor geometry containing magnets – plays a dominant role. This type of torque generation requires dynamic control to maintain stable operation. In contrast, IPMSMs generate the majority of their torque directly from the stator's magnetic field, leading to a more constant and efficient torque output, while reducing reliance on reactive torque.

Given that modern traction drives in electric rolling stock typically use a DC link, it is practical to assess their performance based on the maximum efficiency criterion, provided that operational constraints are observed. Notably, mechanical losses in the drive system remain unaffected by control parameters. Therefore, enhancing the overall efficiency of a traction drive primarily involves optimizing the efficiency function of its electromechanical subsystem, which includes both the traction motor and the semiconductor power converter.

$$\eta = f\left(M_z, n_z, t_z\right)_{var\begin{bmatrix} K_m \\ \theta \end{bmatrix}} \rightarrow max \quad , \qquad (1)$$

where η – efficiency of the electromechanical part of the drive, M_z, n_z, t_z – torque on the shaft, rotor speed and stator winding temperature of the traction motor that set its operating mode, K_m, θ – parameters of the control mode of the traction synchronous motor – modulation coefficient and load angle, which vary.

Let us determine the efficiency of the drive depending on the operating modes, taking into account that only the individual drive of the wheel pairs is considered (each traction motor is powered by one inverter)

$$\eta = \left(\frac{P_2}{P_d}\right)^{sign(P_d - P_2)} , \qquad (2)$$

where P_2 –power on the shaft of the traction motor, P_d – power coming from the DC link.

The power passing between the DC link and the inverter can be determined

$$P_d = U_d I_d . \qquad (3)$$

The power on the shaft of the traction motor differs from the power on the DC link by the total amount of drive losses.

$$P_2 = P_d - sign(\ P_d - P_2\ )\sum p\ , \tag{4}$$

where $\sum p$ – total losses in the drive.

Let's consider the structure of losses in the drive

$$\sum p = p_{si} + p_{tm}\ , \tag{5}$$

where p_{si} – losses in the converter, p_{tm} – losses in the motor.

The torque on the motor shaft is determined by the expression

$$M_2 = 9{,}55\frac{P_2}{n}\ . \tag{6}$$

Losses in the traction semiconductor converter and traction motor depend on both the parameters of the traction drive operating mode and the control parameters – modulation coefficient and load angle.

Therefore, this section has the following tasks:

For a traction drive based on a synchronous reactive traction motor, formulate an analysis task that adequately reflects the relationship between the efficiency of the electrical part of the drive and the parameters of the operating modes and control parameters.

Choose a method for solving the efficiency maximization problem and determine for the system under consideration the parameters that ensure the maximum efficiency of electromechanical energy conversion in different operating modes of the electric drive of the electric rolling stock.

Problem statement. The purpose of the work is To formulate an analysis task for a traction drive based on a synchronous reactive traction motor that adequately reflects the relationship between the efficiency of the electrical part of the drive and the parameters of the operating modes and control parameters.

Research results. The main element of the solution to the analysis problem represented by expression (2) is the determination of losses in the electrical part of the traction drive. Losses consist of losses in the semiconductor converter and losses in the traction motor.

Let us consider the components of losses. Losses in the semiconductor converter.

The most common circuit solution of semiconductor converters for synchronous traction motors with permanent magnets is an autonomous voltage inverter. It is used in the drives under consideration, in most designs built according to the bridge two-level three-phase circuit. [13] is considered by us further. Other solutions are also possible, for example, based on three or more level inverters [14], the approaches to calculating losses in which will be similar. In this case, the motors are powered both using three-phase PWM (at low speeds) and in single-pulse mode.

In the works [15, 16] a power supply circuit of a three-phase ATD based on a two-level bridge inverter is presented.

As power switches, IGBT transistors are currently the most widespread, which we will consider further.

$$p_{si} = N_{kl}\,(P_{IGBT} + P_{VD}) + P_{sn} + P_{upr} + P_{oh}, \tag{7}$$

where P_{IGBT} – losses in the IGBT transistor, P_{VD} – losses in the diode, N_{kl} – determines the number of keys in the converter, for a three-phase two-level bridge inverter N_{kl} = 6, P_{sn} – losses in the snubber circuits, P_{upr} – losses in the control circuits, P_{oh} – cooling losses.

Traction motor losses.

Total losses

$$p_{tm} = P_{1T} + P_f + P_{dod} + P_a + P_z + P_{meh}, \tag{8}$$

where $P_{1T}, P_f, P_{dod}, P_a, P_z, P_{meh}$ – main and additional losses in the stator winding, additional losses, losses in the stator core and teeth, and mechanical losses in the drive, respectively.

The components of the engine losses can be determined by the method [15] and improved in [16]. The efficiency of the traction engine can be determined by expression (2). The basis for finding the costs in a synchronous traction engine with excitation from permanent magnets. We adapt the considered method to the engine design under consideration.

We find the losses based on the identification of the value of the electromagnetic power by determining the electromagnetic torque, no-load EMF, magnetic flux, inductive resistances of the engine, as well as the stator current and power factor.

We consider the calculation of losses in the most common design of a synchronous traction engine – PMASR. The configuration of the PMASR with sectioned magnets is shown in Fig. 2. Distributed stator windings are used in this engine.

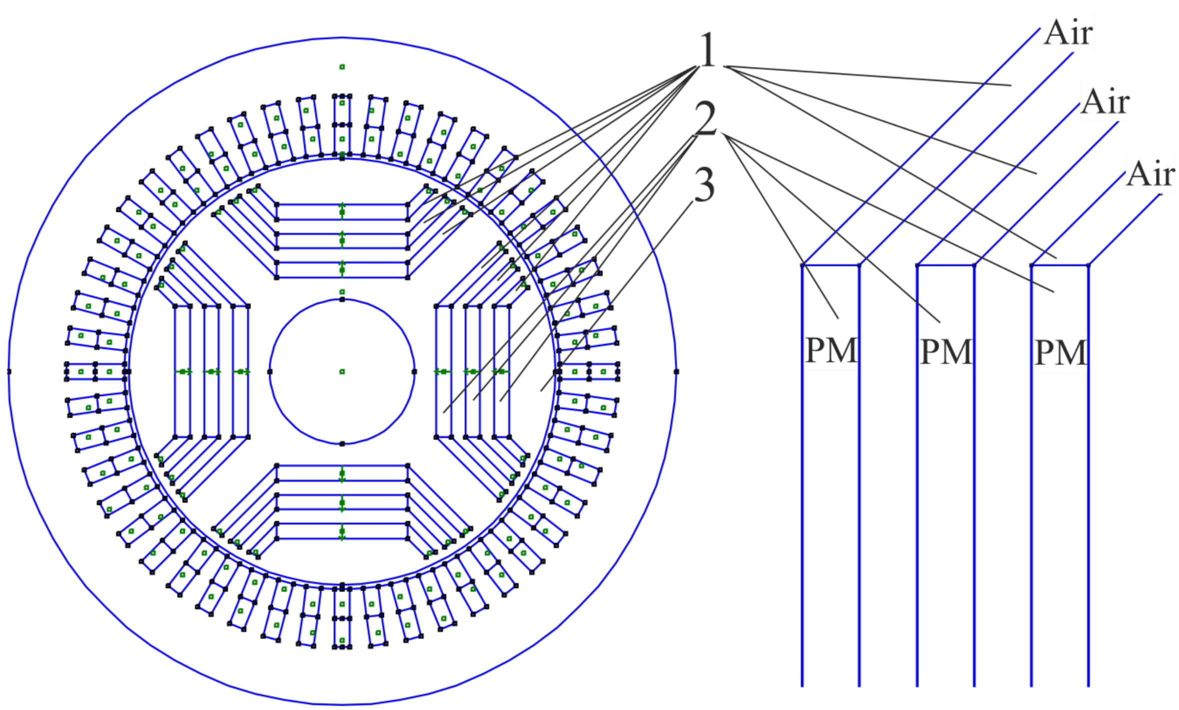

Fig. 2 – Geometry of a synchronous jet engine with sectioned permanent magnets:
1 – cutouts in the rotor core; 2 – permanent magnets; 3 – rotor core

The algorithm for solving the problem of synthesizing optimal engine control parameters in quasi-steady-state operating modes and K_m and θ using the criterion for determining the drive efficiency has the following form.

Step 1: Input the specified motor shaft speed, rotor speed, K_m ,θ and stator winding temperature.

Step 2: Calculate the motor phase voltage and the corresponding supply frequency.

Step 3: Determine the main magnetic flux by analyzing the magnetic circuit of the motor. The calculation is performed along the q-axis, which aligns with the magnetic flux direction of the permanent magnets.

Step 4: Calculate the motor's no-load electromotive force

Step 5: Calculate the synchronous inductive reactances along the d-axis (longitudinal) and q-axis (transverse).

Step 6: Determine the critical load angle, which defines the level of motor loading.

Step 7: Compute the electromagnetic power generated by the motor.

Step 8: Determine the motor current using the "Pascal's snail" graphical method applicable for PMASR.

Step 9: Based on the graphical analysis, calculate the motor's power factor.

Step 10: Evaluate the individual loss components within the traction motor.

Step 11: Calculate the mechanical power delivered at the motor shaft.

Step 12: Compute the torque produced at the motor shaft.

Step 13: Assess the component losses in the traction converter (inverter).

Step 14: Sum the losses from the motor and converter to determine the total losses in the traction drive system.

Step 15: Calculate the total electrical power delivered through the DC link.

An algorithm has been developed to determine the optimal control parameters for a traction PMASR motor, depending on the specified power supply and rotor speed conditions.

Optimization Results for the PMASR Operating Modes in a electric buses Application. To evaluate and optimize the quasi-steady-state operating modes of an PMASR used in a electric buses, a promising traction drive system designed for electric buses was selected based on prior research into the performance and quality of baseline designs. The core specifications of the motor under study are detailed in [14], with additional technical characteristics summarized in Tables 1 and 2. The motor features a sectioned permanent magnet configuration, which is a distinctive design applied in synchronous-reluctance motors with embedded permanent magnets.

Table 1 – Design data of the electric buses traction motor

Name	Value
Motor power, kW	180
Maximum electromagnetic torque, Nm (M_e)	970
Maximum rotation speed, rpm (n_{max})	4000
Maximum linear voltage, V	560
Armature current at maximum torque, A	350
Number of slots	48
Number of effective conductors in a slot	6
Number of parallel branches	1
Pitch reduction factor	0,778
Number of elementary conductors in an effective(in height)	3
Designed outer stator diameter, m	0,46
Bore diameter, m	0,3
Axial length of the magnetic core, m	0,15
One-sided air gap, m	0,003

The motor rotor employs a design featuring sectioned permanent magnets positioned within dedicated slots in the rotor core. Prismatic-shaped magnets are embedded in the rotor cavities, while air gaps are used as magnetic flux guides to channel the magnetic field within the rotor structure. The fundamental geometry of the motor is illustrated in Fig. 2.

Table 2 – Parameters of permanent magnets

Name	Value
Number of magnets per pole	1
Total magnet thickness, m	0,03

End of table 2

Number of sectioning layers	3
Magnet width, m	0,09
Magnet material	Nd-Fe-B
Residual magnetic induction, T	1,0
Coercive force on magnetization, A/m	850 000

To evaluate the operating modes, it is recommended to utilize relative values for engine torque and speed, which numerically correspond to the relative values of the traction force and the speed of the electric vehicle in standardized units.

Let's take the basic values of the torque and engine speed which are equal to the maximum value of the electromagnetic torque and the maximum speed:

$$M_b = M_e, \quad (11)$$

$$n_b = n_{max}. \quad (12)$$

The torque and engine speed in relative units are determined by the expressions:

$$M = \frac{M_e}{M_b}, \quad (13)$$

$$n = \frac{n_{dv}}{n_b}. \quad (14)$$

To solve the optimization problem of the above-considered PMASR, the optlab package for MATLAB, developed at NTU "KhPI" [15-18], was used. Based on the capabilities of the complex, a method for solving the problem was chosen. The best results in terms of time and number of iterations when solving the problem of synthesis of operating modes were shown by the method of cyclic coordinate descent.

The dependences of the efficiency of the drive, traction motor, load angle and modulation coefficient were determined at the optimal combination of the load angle and modulation coefficient on the values of the winding temperature from 40°C to 180°C. The nature of the dependencies has a similar appearance at different winding temperatures, which is due to the same nature of the traction drive operation processes; only the resistance of the stator winding and losses in it differ, but the nature of the physical processes remains.

The results of the calculations are shown in Fig. 3-6.

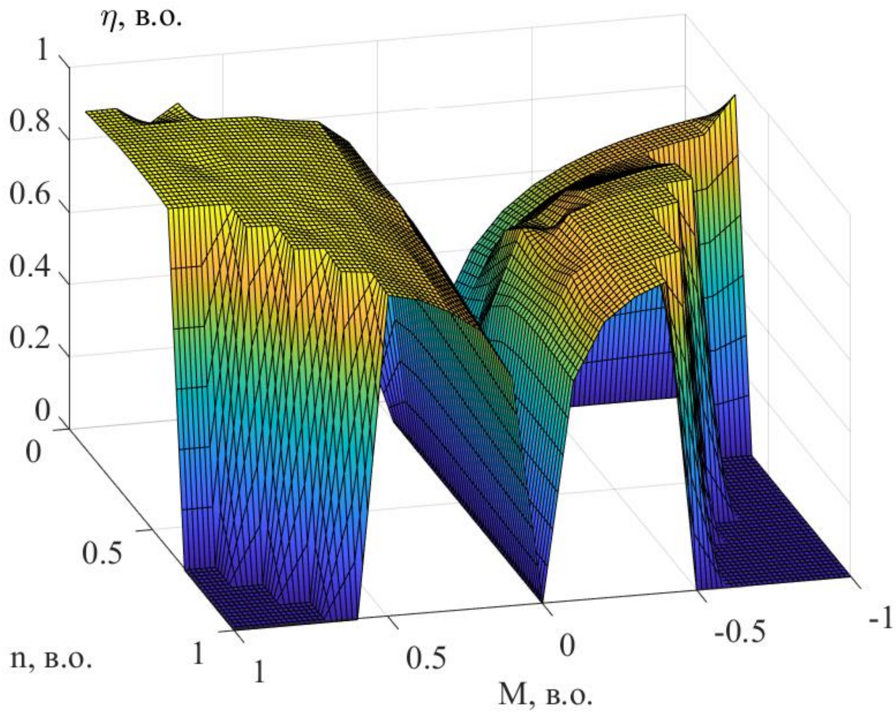

Fig. 3 – Optimal value of drive efficiency (η) at a winding temperature of 100°C

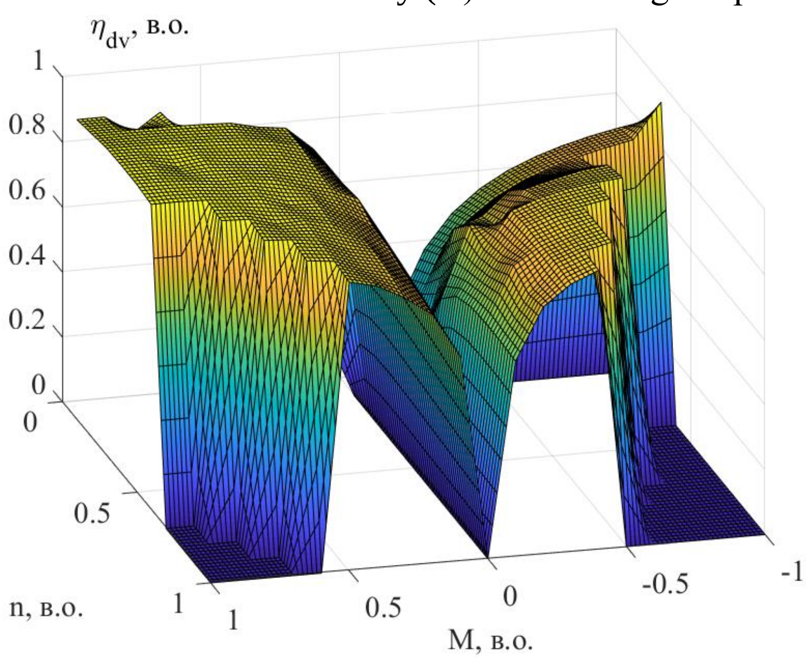

Fig. 4 – Optimal value of motor efficiency (η_{dv}) at a winding temperature of 100°C

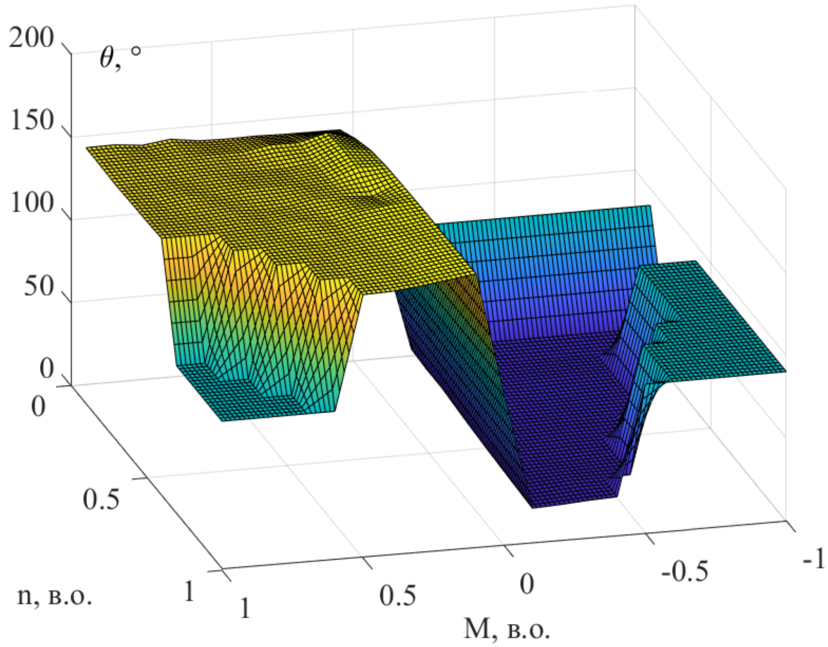

Fig. 5 – Optimal value of the load angle (θ) at a winding temperature of 100°C

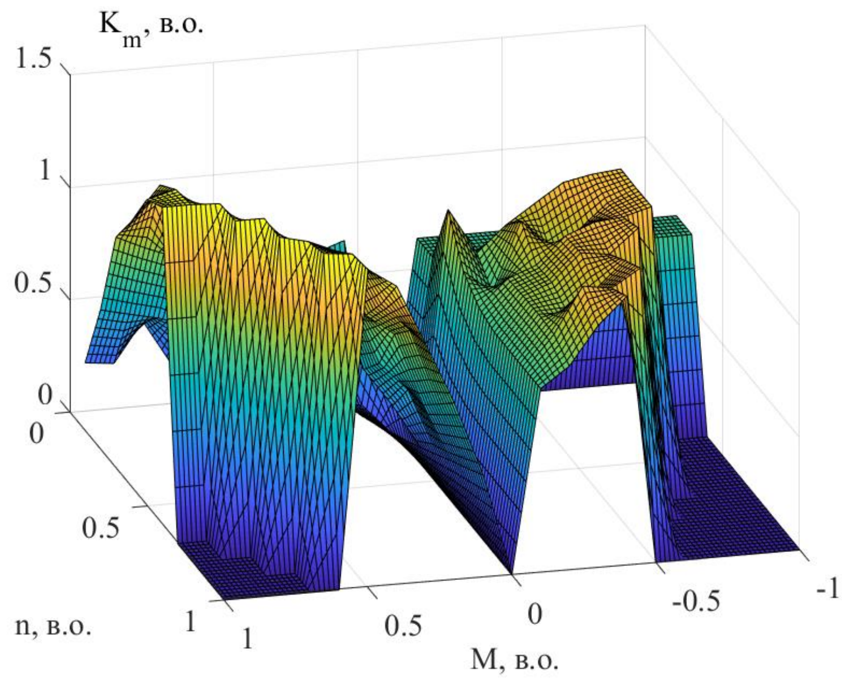

Fig. 6 – Optimal value of modulation coefficient (K_m) at winding temperature of 100°C

At rotation speeds exceeding 0,68 relative units and torques above 0.6 relative units, the system enters a current-limiting zone, where efficiency drops to zero in both traction and regenerative braking modes.

During control in most operating conditions, the load angle is maintained within 149–158° in traction mode and 15–22° in braking mode. At low speeds during braking, the load angle decreases sharply to ensure the desired braking torque is sustained.

Both the modulation coefficient and load angle exhibit constraints within the motor's operating region due to current limitations. The modulation coefficient increases gradually as power increases, in both traction and braking modes. Within this relationship, local fluctuations are observed, which are attributed to the need to compensate for increased losses caused by higher-order harmonic currents.

Conclusions. An algorithm has been developed to determine the quasi-steady-state operating modes optimal control parameters of a traction PMASR, based on given power supply conditions and rotational speed.

The dependencies of drive efficiency, traction motor efficiency, load angle, and modulation coefficient have been analyzed for their optimal combination. These dependencies show similar trends across various stator winding temperatures, reflecting consistent operational behavior of the traction system.

At rotational speeds above 0.68 relative units and torques above 0.6 relative units, a current-limiting zone is observed, where efficiency falls to zero in both traction and braking modes. During most operating conditions, the load angle is kept within the range of 149–158° in traction mode and 15–22° in braking mode, with a sharp drop at low speeds during braking to maintain the specified braking torque.

The modulation coefficient and load angle are restricted by the current limits in the motor's operational area. As power increases, the modulation coefficient also rises. However, local peaks occur in this relationship, driven by the need to offset increased losses caused by higher harmonic currents.

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