Оптимізовано режими роботи тягового асинхронного приводу тепловоза за критерієм ефективності. Ідентифіковано оптимальні режими керування автономного інвертору напруги при різних температурах обмоток тягових двигунів. Проаналізовано оптимальні режими роботи тягового приводу тепловоза та трамваю, що дозволило встановити відмінності розташування точки переходу з просторово-векторної до однократної ШІМ від температури двигуна

Ключові слова: тяговий асинхронний двигун, ідентифікація оптимальних режимів роботи, ефективність тягового приводу

Оптимизированы режимы работы тягового асинхронного привода тепловоза по критерию эффективности. Идентифицированы оптимальные режимы управления автономного инвертора напряжения при различных температурах обмоток тяговых двигателей. Проанализированы оптимальные режимы работы тягового привода тепловоза и трамвая, что позволило установить различия расположения точки перехода с пространственно-векторной к однократной ШИМ от температуры двигателя

Ключевые слова: тяговый асинхронный двигатель, идентификация оптимальных режимов работы, эффективность тягового привода

UDC 629.429.3:621.313
DOI: 10.15587/1729-4061.2017.109179

ANALYSIS OF OPTIMAL OPERATING MODES OF THE INDUCTION TRACTION DRIVES FOR ESTABLISHING A CONTROL ALGORITHM OVER A SEMICONDUCTOR TRANSDUCER

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1. Introduction

Worldwide trend of energy saving is implemented through the improvement of performance efficiency [1]. The rising cost of energy resources and competition between manufacturers requires constant work in order to increase efficiency factor of electrical equipment in different spheres of application [2]. Special attention is paid to electric drives of general designation [3], as well to the traction ones [4], which are designed to drive electric transport [5]. This is understandable as the former are the most common, and thus consume a significant amount of electricity, while the latter form a basis for the creation of environment-friendly "green" transport.

As noted in [6], traction drive of electric rolling stock can operate under the following modes:

– maximum thrust or braking – regime of maximum torque of the traction motor;

– maintaining the preset motion speed – regime of the maximum performance efficiency of the traction motor;

– overshooting or mechanical braking is the regime of traction motor without power supply; the rotor is rotating by inertia; energy not consumed – performance efficiency is predetermined by mechanical and ventilation losses only.

Under the mode of maximum thrust or braking, the main (basic) is a criterion for providing the maximum torque of the traction motor. Because it allows for the fulfillment of requirements in terms of acceleration of the rolling stock during acceleration and braking, on the one hand. On the other hand, to maintain a preset traffic schedule. Under the mode of keeping the assigned motion speed, the main criterion is the maximum efficiency.

The effectiveness of traction drive under a certain regime of its work can be evaluated by the criterion of its maximum performance efficiency [7, 8] provided the requirements imposed by the modes of operation are met. That is, the task to ensure effectiveness of the traction drive comes down to determining the maximum of a performance efficiency function of the drive in each of its operating modes.

Traction drive based on the induction traction motor (ITM) can operate at one and the same point of the traction characteristic. Each point of the traction characteristic corresponds to a certain frequency of rotation and torque on the shaft of the motor. However, the level of losses in the elements of the drive for these points will be different.

That is why the task of determining optimal modes in the traction drive operation can be reduced to defining optimal operation regimes of the link ITM – AVI. In this case, it is necessary to take into account those constraints that are set on the work of mechanical part of the traction drive (constraints on clutch and speed).

At the same time, when powering ITM from AVI, two basic control varieties can be applied. The first is based on using a spatial-vector pulse-width modulation (PWM) of ITM employing the algorithms of vector control [9], or direct control over the moment.

The second mode is the regime of one-time PWM. In it, the motor voltage is set at the highest possible level that allows reduction of the major losses. However, the step shape of voltage creates a spectrum of voltage higher harmonics, causing additional losses in ITM.

An important element in the control system of the traction drive with ITM is to determine transition points of the traction drive from a regime of spatial-vector to the one-time PWM, which can vary depending on the parameters of ITM and which determines the working algorithm of a semiconductor transducer.

Thus, determining optimal operating modes of the induction traction drive in order to enable its maximum performance efficiency is one of the relevant scientific and technical tasks of electric transport.

2. Literature review and problem statement

The task of improving performance efficiency of the induction traction drive is solved in two ways: by increasing the efficiency of ITM, and through the optimization of its control mode, that is, determining optimal parameters of AVI operation, which makes it possible to reduce losses both in the motor itself and in the semiconductor transducer [10]. But the larger effect is achieved only employing a comprehensive study into the entire drive as a whole, therefore, such studies are most common. Thus, in article [11], authors developed a computer model for ITM control, which allows defining power parameters of AVI. Authors of paper [12] focus their attention on improving efficiency of the drive under the mode of acceleration of electric rolling stock. In article [13], authors conducted a comprehensive optimization of various physical parameters of ITM. In order to determine energy indicators of traction motors, authors of paper [14] constructed a virtual model of ITM. Determining operational effectiveness of the traction drive of rolling stock in general is addressed in article [15].

Capabilities for increasing performance efficiency of existing ITM are limited [16], although studies in this direction are also conducted [17], moreover, ITM is calculated so that maximum efficiency for one working point is ensured. In the process of ITM operation on electric rolling stock, there are substantial changes in its speed and loading mode, that is, the operating mode, which significantly reduces the overall performance efficiency of the traction electric drive [8]. In addition, in order to provide for certain operation modes, it is necessary to switch AVI from a spatial-vector control to the one-time PWM.

Another factor that limits work of the drive is the thermal condition of ITM, that is, the temperature of heating its windings. It affects both the performance efficiency of ITM itself and the reliability of transport operation [18]. That is why, in some cases, a transition has to be applied from ventilation to cooling ITM with water [8, 19].

Complexity of the task to ensure effectiveness of the traction drive is in the existence of five modes of operation and difference in the performance criteria for each of these modes. In addition, it is necessary to take into account the thermal condition of ITM as a limiting factor. The transition to water cooling of ITM will complicate the design and cost of the drive itself. That is why most researchers try to optimize separate operational modes of the traction drive. Thus, article [20] considers a nominal mode of operation of the traction drive, paper [21] – a mode of braking. From the point of view of the authors of these works, ensuring maximum performance efficiency under nominal operating mode [20] is the most appropriate because the drive spends the largest share of the total operating time under this regime. Optimization of the braking mode [21] will make it possible, through recuperation, to save energy, that is, to reduce the overall cost. However, these studies were carried out by separate techniques with various parameters of the traction drive and by one criterion of effectiveness – performance efficiency. That is why applying these techniques jointly is impossible.

We believe that the most advisable is to determine optimum operating regimes of the entire traction drive as a whole, with unified parameters and criteria of efficiency [7, 8]. An analysis of this work for each of the modes of semiconductor transducer will make it possible to define the algorithm of its control. The algorithm is understood here as a point of transition in the operation of a semiconductor transducer from a spatial-vector PWM to the one-time.

3. The aim and objectives of the study

The aim of present work is to analyze optimum operating modes of the traction induction drives of varying capacity in order to identify a point of transition in the operation of a semiconductor transducer from a spatial-vector PWM mode to the one-time regime.

To achieve the set aim, the following tasks have been solved:

– optimization of operating modes of the induction traction drive of a tram and a diesel locomotive;

– determination of optimum AVI control modes depending on the ITM rotation frequency and the temperature of its windings;

– analysis of effect of temperature of the windings of the traction motor on operating modes of the traction drive of a tram and a diesel locomotive.

4. Technique for the optimization of operating modes of the induction traction drive

The research presented in the given article is a continuation of the studies reported in paper [8]. In order to solve the set task, it is necessary to create a technique for determining optimal operating modes of the induction traction drive, which was developed by the authors and described in detail in works [8, 22]. Employing the specified technique, in paper [8], the optimal modes were defined for ITM operation of the AD931 type, which is used to drive the tram, with the validity of the given technique proven. A further step in the research is to determine the optimal operating modes for the induction traction drive of a diesel locomotive and general (joint) analysis of these regimes, both for the tram and the diesel locomotive.

To determine effectiveness of the traction drive, we shall use a system of equations (1), which consists of separate systems of equations for each operating mode, which was proposed in articles [8, 22]:

$$\eta_1 = \left[\begin{array}{l} \left\{ \begin{array}{l} U_{op} = 1, \\ \eta_1 \to \max, \\ F_d \to \max, \\ |F_d| < |F_k'|, \\ \upsilon_{nc} < \upsilon_{\max}, \\ F_d > 0, \end{array} \right. \left\{ \begin{array}{l} U_{op} = 2, \\ \eta_1 \to \max, \\ |F_d| < |F_k'|, \\ \upsilon_{nc} < \upsilon_{\max}, \\ F_d > 0, \end{array} \right. \\ \left\{ \begin{array}{l} U_{op} = 3, \\ \eta_1 \to \max, \\ |F_d| < |F_k'|, \\ \upsilon_{nc} < \upsilon_{\max}, \\ F_d < 0, \end{array} \right. \left\{ \begin{array}{l} U_{op} = 5, \\ \eta_1 \to \max, \\ F_d \to \min, \\ |F_d| < |F_k'|, \\ \upsilon_{nc} < \upsilon_{\max}, \\ F_d < 0, \end{array} \right. \end{array} \right. \quad (1)$$

where η_1 is the performance efficiency of link ITM-AVI, U_{op} is the operating mode of the traction drive of a tram, F_d is the force of traction or braking, which a tram creates, F_k' is the limiting force by clutch of the contact wheel-rail, υ_{nc} is the speed of the rolling stock, $\upsilon_{\max}$ is the design motion speed. U_{op}=4 is the overshooting mode without load, which is why it is not considered when determining effectiveness of the drive.

We shall outline basic provisions of the technique that is applied to determine optimal operating modes. To determine the overall performance efficiency of the link ITM-AVI, it is required to solve four problems on the conditional optimization of operating parameters of the traction drive [8]. Under the modes: acceleration U_{op}=1, recuperative braking U_{op}=5, maintaining predetermined speed U_{op}=2, 3.

For each of these problems, two control modes are considered: one-time or spatial-vector PWM. The mode of acceleration and recuperative braking are similar. We shall apply a method of vector objective functions, proposed in article [23]. We choose a vector function with the following parameters as the objective function for the acceleration mode; for convenience of calculations, we shall denote a maximum of performance efficiency through the function of minimization:

$$F_{c1} = \begin{bmatrix} 1 - \eta_1 \to \min, \\ -F_d \to \min. \end{bmatrix} \quad (2)$$

We shall select as an objective function for maintaining the mode of predetermined motion speed:

$$F_{c3} = F_{c4} = 1 - \eta_1 \to \min. \quad (3)$$

For the mode of recuperative braking, vector objective function takes the form:

$$F_{c5} = \begin{bmatrix} 1 - \eta_1 \to \min, \\ F_d \to \min. \end{bmatrix} \quad (4)$$

Objective functions make it possible to determine optimal operating modes of the traction drive when using different regimes of PWM.

To assess effectiveness of the traction drive, we selected components of the control vector as parameters: modulation coefficient K_m; the magnitude of rotor sliding s; the mode of operation of the transducer – one-time or spatial-vector PWM.

The study will employ two ITM whose parameters are listed in Table 1. The traction motor of a tram carriage has small electrical magnetic moment, but a rather large frequency of rotation. In contrast, the traction motor of a diesel locomotive has large electrical magnetic moment and the low frequency of rotation. In other words, we explore two boundary cases of the existing range of ITM parameters.

Table 1

Parameters of traction motors of the tram and the diesel locomotive

Type of rolling stock	Tram	Diesel locomotive
Mark of rolling stock	Tatra T3 VPA	2TE25A
Country of origin of rolling stock	Ukraine	Russia
Type of traction motor	AD 931	AD 917
Country of origin of traction motor	Ukraine	Ukraine
Capacity of traction motor under prolonged mode	54	470
Rated rotation frequency, rpm	1,773	990
Motor performance efficiency under rated mode, %	0.93	0.96
Power coefficient, r.u.	0.84	0.88
Number of traction motors coupled with one transducer	1	3
Type of semiconductor key	Eupec BSM 400 GA 170 DLC	Infineon FZ1500R33HE3
Country of origin of semiconductor key	Germany	Germany

In order to solve the optimization problem, we applied the optlab package for MATLAB software, which makes it possible to easily alternate different methods for solving optimization problems [24]. To solve this problem, we propose employing at the first stage a method based on genetic algorithms, which is widely used in the optimization of parameters and modes of operation of electric machines [25].

Genetic algorithms possess one shortcoming – they find the optimal solution with low accuracy. To exclude this drawback, we propose a combined method. It consists of a genetic algorithm and the Nelder-Mead method at the final stage of the search. This technique was validated in papers [7, 8] in order to search for the optimal modes of traction drives.

5. Results of optimization of operating modes of the induction traction drive of a diesel locomotive

Based on results of the calculations, we shall construct main characteristics in accordance with the criteria of operational efficiency of the traction drive of a diesel locomotive for different modes of operation.

Fig. 1 shows optimal dependences of performance efficiency and electromagnetic torque of the traction drive of a diesel locomotive under the mode of maintaining preset motion speed.

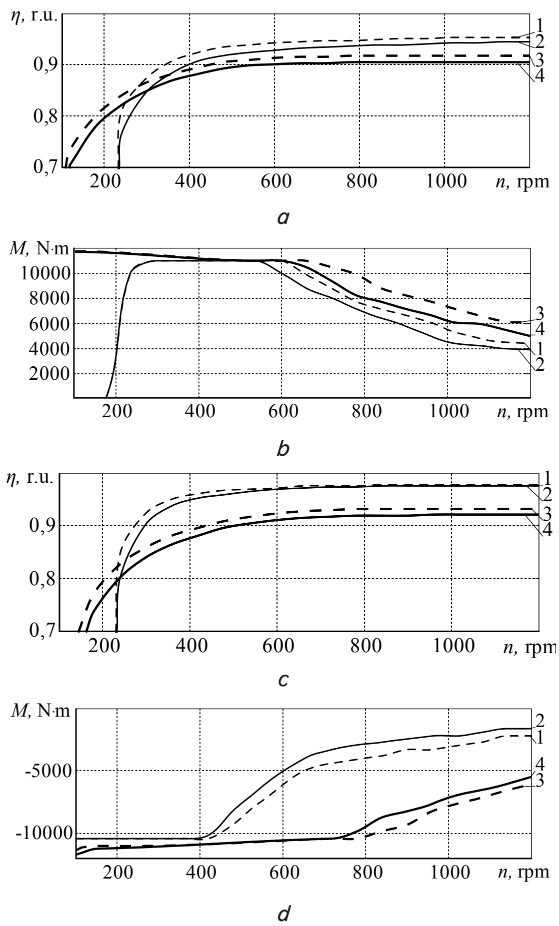

Fig. 1. Optimal dependences of the AD917 parameters on rotation frequency n of the traction drive of a diesel locomotive under the mode of preset motion speed: *a* — performance efficiency during traction, *b* — electromagnetic torque during traction, c — performance efficiency when braking; *d* — electromagnetic torque when braking; 1 — while applying one-time PWM and at motor temperature 40 °C, 2 — while applying one-time PWM and at motor temperature 180 °C, 3 — while applying spatial-vector PWM and at motor temperature 40 °C, 4 — while applying spatial-vector PWM and at motor temperature 180 °C

Fig. 2 shows optimal dependences of performance efficiency and electromagnetic torque of the traction drive of a diesel locomotive under the mode of acceleration and braking.

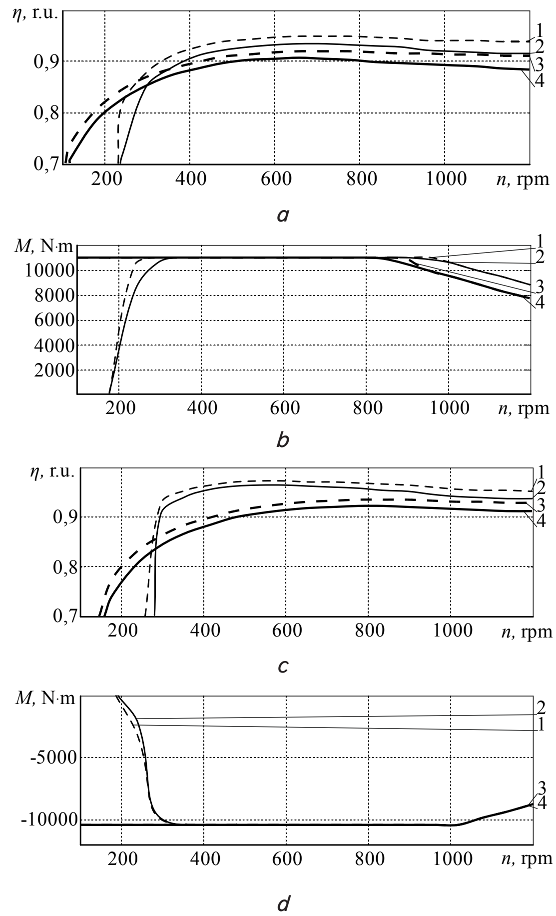

Fig. 2. Optimal dependences of the AD917 parameters on rotation frequency n of the traction drive of a diesel locomotive under the modes of maximal torque: *a* — performance efficiency during traction, *b* — electromagnetic torque during traction, *c* — performance efficiency when braking; *d* — electromagnetic torque when braking; 1 — while applying one-time PWM and at motor temperature 40 °C, 2 — while applying one-time PWM and at motor temperature 180 °C, 3 — while applying spatial-vector PWM and at motor temperature 40 °C, 4 — while applying spatial-vector PWM and at motor temperature 180 °C

For ease of comparison, we shall also present similar characteristics to the traction drive of a tram, obtained in paper [8].

Fig. 3 shows optimal dependences of performance efficiency and electromagnetic torque of traction drive of the tram Tatra T-3 VPA under the mode of maintaining preset motion speed.

Fig. 4 shows optimal dependences of performance efficiency and electromagnetic torque of traction drive of the tram Tatra T-3 VPA under the modes of acceleration and braking.

Having obtained optimal dependences of parameters of the traction drives of a tram carriage and a diesel locomotive, we shall pass over to their comparative analysis.

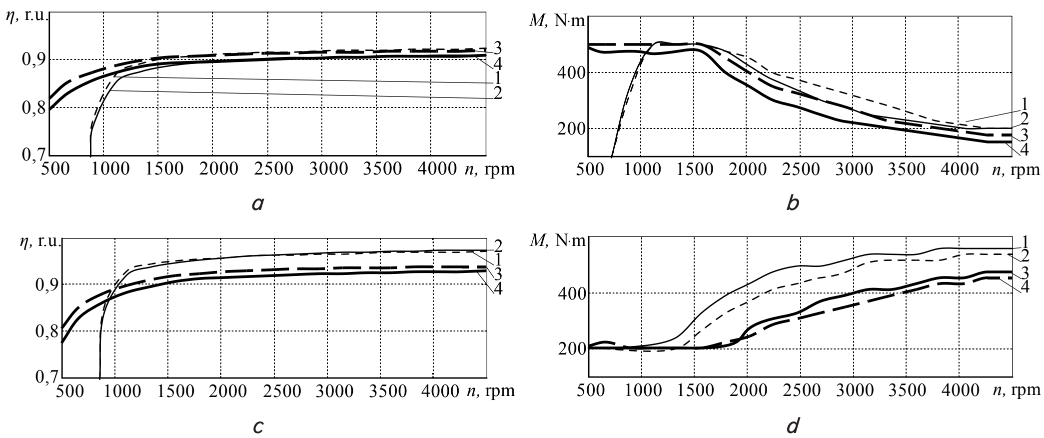

Fig. 3. Optimal dependences of the AD931 parameters on rotation frequency n of the traction drive of a tram under the mode of preset motion speed: *a* — performance efficiency during traction, *b* — electromagnetic torque during traction, *c* — performance efficiency when braking; *d* — electromagnetic torque when braking; 1 — while applying one-time PWM and at motor temperature 40 °C, 2 — while applying one-time PWM and at motor temperature 180 °C, 3 — while applying spatial-vector PWM and at motor temperature 40 °C, 4 — while applying spatial-vector PWM and at motor temperature 180 °C

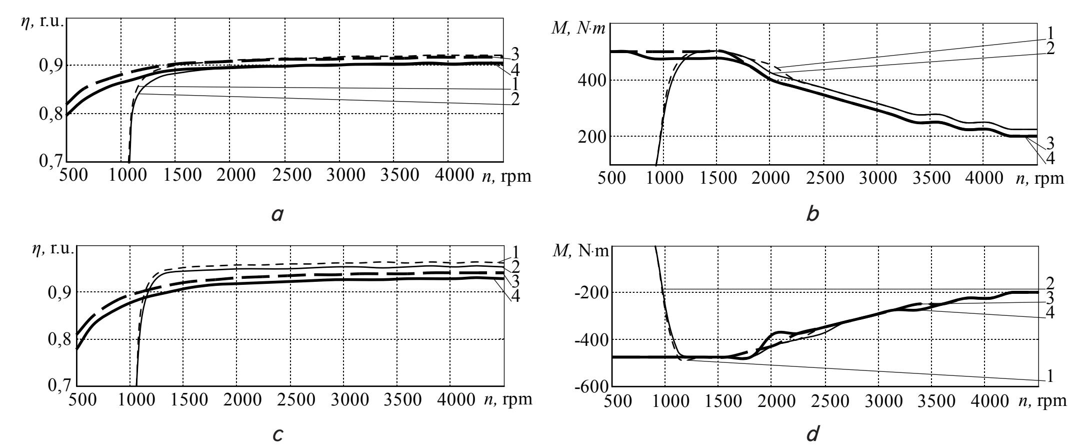

Fig. 4. Optimal dependences of the AD931 parameters on rotation frequency n of traction drive of the tram under the mode of maximal torque: *a* — performance efficiency during traction, *b* — electromagnetic torque during traction, *c* — performance efficiency when braking; *d* — electromagnetic torque when braking; 1 — while applying one-time PWM and at motor temperature 40 °C, 2 — while applying one-time PWM and at motor temperature 180 °C, 3 — while applying spatial-vector PWM and at motor temperature 40 °C, 4 — while applying spatial-vector PWM and at motor temperature 180 °C

7. Analysis of the results of optimization of operating modes of traction induction drives of the tram and the diesel locomotive

To operate the traction drive at low frequencies of rotation, a mode of spatial-vector PWM is applied, which makes it possible to maintain a preset maximal torque over practically an entire mode of operation from 50 up to 620 rpm. It should be noted, however, that at frequencies of rotation there can occur a limit to the capability of implementing recuperative braking due to a decrease in the electromagnetic torque. The regions of implementation of maximum torques and performance efficiency of the drive at low temperatures of the traction motor are almost the same. The limitation of electromagnetic torque at the level of around 490 N·m at rotation frequencies to 1220–1730 rpm occurs due to the limitation on clutch. However, at a rise in the temperature, the increase of electromagnetic torque occurs via reduced performance efficiency, which manifests itself under the mode of traction to 0.52 %. Power of traction while maintaining predetermined speed decreases to 27–53 N·m, and when braking – to 48 N·m, which is due to the increasing active resistance of windings of the stator and the rotor of the motor. Reduction of electromagnetic torque is optimal to execute through a change in the ITM sliding, the character of change in the modulation coefficient varies insignificantly. At rotation frequencies exceeding 1550 rpm, there starts a gradual decrease in the electromagnetic torque, due to the limitations on ITM current. Since the modulation coefficient has reached its maximum value while the voltage in the motor does not increase, then this limitation turns into a constraint on the power of the traction drive. Electromagnetic torque under the mode of one-time PWM outperforms the torque at spatial-vector PWM by 54–112 N·m, with performance efficiency close in values, which is why the application of one-time PWM at larger frequencies of rotation is rational.

The physical processes that occur during operation of the link ITM-AVI of the diesel locomotive 2TE25A are similar to the processes in the traction drive of a tram. A special feature is the fact that the limitation on clutch is set at a higher level of electromagnetic torque. This level is 11.000–11.500 N·m Maximum rotation frequency is 1.200 rpm. A transition to the limitation on current occurs for the modes of maintaining preset motion speed at a rotation frequency ranging from 420 to 780 rpm.

The application of one-time PWM under the mode of traction and braking leads to the occurrence of a zone at rotation frequency from 0 to 620 rpm where the work of the traction drive is impossible. At low rotation frequencies, there is an increase in the phase current due to the impossibility of reducing voltage of the motor, which is typical both for the drive of a tram and a diesel locomotive.

We established and constructed the dependence of change in the point of transition from spatial-vector to one-time PWM on the temperature of TM, Fig. 5 for the tram, Fig. 6 for the diesel locomotive.

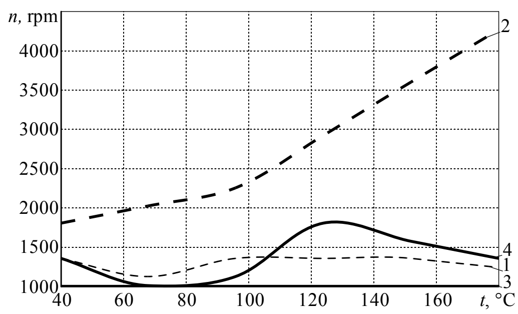

Fig. 5. Point of transition of the tram traction drive from the mode of spatial-vector to one-time PWM under the modes: 1 – acceleration, 2 – maintaining preset motion speed at F_d>0, 3 – maintaining preset motion speed at F_d<0, 4 – recuperative braking

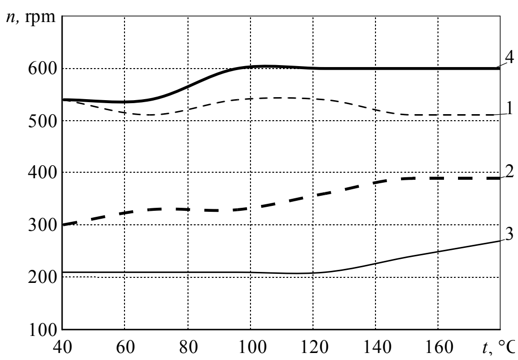

Fig. 6. Point of transition of the diesel locomotive traction drive from the mode of spatial-vector to one-time PWM under the modes: 1 – acceleration, 2 – maintaining preset motion speed at F_d>0, 3 – maintaining preset motion speed at F_d<0, 4 – recuperative braking.

We established that under the mode of rolling stock acceleration, this transition occurs at a rotation frequency of about 1.125–1.350 rpm. for the tram, and 510–540 rpm for the diesel locomotive, while slightly changing from the temperature of the motor. The transition during recuperative braking occurs at the larger values of rotation frequency: 1.013–1.800 rpm for the tram, and 540–600 rpm for the diesel locomotive.

With a rise in temperature, rotation frequency of the point of transition for the tram increases to 1.800 rpm at a temperature of windings about 120 °C, then decreases to 1.350 rpm at a temperature of 180 °C. In the traction drive of the diesel locomotive, there is an increase in the rotation frequency of transition point at increasing temperature. Under the mode of traction while maintaining preset motion speed, rotation frequency of the transition point increases with increasing temperature for the tram from 1.800 rpm to 4.275 rpm, and for the diesel locomotive from 300 to 390 rpm. When braking, under the mode of maintaining preset speed, the transition point is located at a rotation frequency of 1.013 rpm. for the tram, and at 210–270 rpm for the diesel locomotive.

8. Discussion of results of exploring optimal operating modes of the induction traction drives

Different level of the location of transition point of the traction drive from the space-vector to the one-time PWM is predetermined by different load of the magnetic circuit of motor, as a result of different levels in the saturation coefficient. Thus, for the tram ITM, it is 1.2–1.52 r. u., and for the diesel locomotive ITM – 1.05–1.12 r. u. As a result of this, traction characteristics of the drives are different.

The application of the developed technique for determining optimal operating modes of the traction drive with ITM, which takes into account its thermal state, allowed us to establish:

– temperature of the windings of the traction motor has a significant impact on the transition point of traction drive from the spatial-vector to the one-time PWM;

– this effect is most significant for the tram traction motor, which is explained by a greater level of electromagnetic load.

The research we conducted allows us to develop control algorithms for the traction drive based on ITM, which takes into account transition point of the transducer from the regime of spatial-vector to one-time PWM depending on the temperature of windings of the motor and rotation frequency.

Fig. 5, 6 show that the dependences of change in the points of transition are significantly different, which is why the results obtained are valid only for the examined cases. For the drives with other parameters, it is necessary to undertake a similar complex of research employing the proposed methodology.

In the further development of the conducted studies, we plan to take into account losses in the systems of forced liquid cooling, as well as mechanical losses in the traction drive.

9. Conclusions

1. We carried out the identification of optimal parameters in the operating modes of autonomous voltage invertor of the traction drive of a tram and a diesel locomotive. The dependences are obtained of performance efficiency and electromagnetic torque of ITM on the rotation frequency and temperature of the windings for the following modes: acceleration, recuperative braking, and maintaining preset speed. The research was conducted for the tram carriage Tatra T3 VPA and the diesel locomotive 2TE25A, which differ in the value of electromagnetic torque and rotation frequency.

2. We established operating modes of induction traction drive of the tram Tatra T3 VPA and the diesel locomotive 2TE25A, over the entire range of rotation frequencies of ITM at spatial-vector and one-time PWM of AVI for different values of temperature of the motor's windings. A

technique was devised for this purpose, which is based on solving a problem on the optimization of parameters of the traction drive using a combined method that employs genetic algorithms and the Nelder-Mead method.

3. It was determined that dependences of change in the transition point from the spatial-vector to the one-time PWM on the temperature of ITM for a tram and a diesel locomotive are not similar. Different level of the location of this point is predetermined by the different load in magnetic circle of the motor, and, as a result, by the different level of saturation coefficient. The difference in saturation coefficient is 0.15–0.4 r.u.

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