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OPTIMIZATION OF THERMAL MODES AND COOLING SYSTEMS OF THE INDUCTION TRACTION ENGINES OF TRAMS

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Розроблено методику оптимізації теплових режимів та параметрів системи охолодження асинхронних тягових двигунів трамваїв. Оптимізовано режими роботи за критерієм ефективності. Режими руху за встановленим графіком та профілем на ділянці колії оптимізовано за критерієм витрат енергії методом Гамільтона-Якобі-Беллмана. Оптимізовано параметри вентилятора тягових двигунів за критерієм ефективності системи охолодження методом Вейля

Ключові слова: трамвайний вагон, асинхронний двигун, оптимальні режими роботи, вентилятор охолодження

Разработана методика оптимизации тепловых режимов и параметров системы охлаждения асинхронных тяговых двигателей трамваев. Оптимизированы режимы работы по критерию эффективности. Режимы движения по установленному графику и профилю на участке пути оптимизированы по критерию расхода энергии методом Гамильтона-Якоби-Беллмана. Оптимизированы параметры вентилятора тяговых двигателей по критерию эффективности системы охлаждения методом Вейля

Ключевые слова: трамвайный вагон, асинхронный двигатель, оптимальные режимы работы, вентилятор охлаждения

1. Introduction

The processes of energy conversion in the traction engines of tram carriages are accompanied by its losses in the elements of design due to physical processes at energy conversion [1, 2]. Temperature of the elements of design of traction engines increases over the time of operation and can exceed permissible structural limits [2, 3]. This is especially true for temperature of the insulation of the motor windings, which is constrained by a class of the applied insulation [3, 4]. To reduce temperature in the elements of design of engines, the cooling systems are employed that increase the efficiency of heat exchange in the engine design elements through the application of ventilation by air [5, 6], by water [4, 7], or grease [8]. Cooling systems require additional expenses for their effective work, which, in turn, reduces engine efficiency, as well as of the electric rolling stock in general [9], and increase overall noise level [10]. Thus, creating an effective cooling system for the electric rolling stock is one of the relevant scientific-technological tasks of railroad transport.

2. Literature review and problem statement

There are possible ways of solving the problem: reducing losses in the elements of traction engines design [1, 11] and increasing the efficiency of air-cooling system [2, 9], as well as the installation of a water cooling system [4]. Optimization of the processes of designing the traction engines, common at the enterprises of leading electrotechnical manufacturers, makes it possible to create traction engines optimal by efficiency [2, 12]. However, the operating modes of the electric rolling stock, which moves at different speeds and at different loading regimes [13], considerably reduce the overall efficiency of electric rolling stock [14]. Determining motion modes optimal by energy consumption enables to increase the efficiency of cooling system of traction engines, as well as of electric rolling stock in general [15].

Thermal processes in the traction engines are characterized by large values of a time constant, which can amount to 10...30 minutes [16]. Heating the engine to a constant temperature can last for 35...100 minutes [17]. However, the electromechanical processes when the electric rolling stock moves are more dynamic. The mode of operation of a traction drive can change several times per minute [18]. Therefore, to determine the thermal state of a traction engine, it is necessary to consider thermal load over the entire period of operation [15]. When using a traction drive, common modes are overshooting [13] and mechanical (pneumatic) braking [13]. Conversion of energy under these modes does not occur in a traction engine [19]. The engine is in the process of cooling, its maximum temperature can drop. This will require a significantly less powerful cooling system.

As noted in [19], for determining the temperature of elements of traction engines designs, it is necessary to model the thermal state at electric rolling stock motion. Thus, it is required to solve an integrated problem on creating a procedure for determining the optimal thermal modes of a traction drive operation, as well as parameters of the cooling system of traction engines. The procedure should take into account an operating schedule of the electric rolling stock, as well as a rail profile. It is also necessary to consider thermal loads on the elements of engine design.

3. Research goal and objectives

When conducting the studies, our goal was to develop a procedure for the optimization of thermal modes of induction traction drive, as well as parameters of the cooling system of engines.

To accomplish the set goal, the following tasks had to be solved:

– optimization of operating modes of induction traction drive;

– optimization of motion modes of a tram carriage along a track section with an assigned motion schedule and profile;

– optimization of parameters of the fan for cooling the traction engines;

– performing an analysis of results of the modeling of thermal modes of ATE operation.

4. Optimization of operating modes of an induction traction drive

The effectiveness of a traction drive can be represented in the form of expressions proposed in article [20]:

$$\eta_1=\left[\begin{array}{l}\left\{\begin{array}{l}U_{op}=1,\\ \eta_1\to\max,\\ F_d\to\max,\\ |F_d|<|F_k'|,\\ v_{\text{пс}}<v_{\max},\\ F_d>0,\end{array}\right.;\left\{\begin{array}{l}U_{op}=2,\\ \eta_1\to\max,\\ |F_d|<|F_k'|,\\ v_{\text{пс}}<v_{\max},\\ F_d>0,\end{array}\right.\\ \left\{\begin{array}{l}U_{op}=3,\\ \eta_1\to\max,\\ |F_d|<|F_k'|,\\ v_{\text{пс}}<v_{\max},\\ F_d<0,\end{array}\right.;\left\{\begin{array}{l}U_{op}=5,\\ \eta_1\to\max,\\ F_d\to\min,\\ |F_d|<|F_k'|,\\ v_{\text{пс}}<v_{\max},\\ F_d<0,\end{array}\right.\end{array}\right. \tag{1}$$

where η_1 is the efficiency of ATE link – an autonomous voltage inverter (AVI), U_{op} is the operating mode of a tram traction drive, F_d is the force of traction or braking created by the tram, F_k' is the force limit for the coupling of the contact wheel–rail, v_{nc} is the speed of the rolling stock, v_{max} is the designed motion velocity. $U_{op}=4$ is mode of overshooting – idling, which is why it is not considered when determining the effectiveness of a drive.

Determining the efficiency of the link ATE–AVI is carried out based on the approaches proposed in papers [21], which include the following: to solve the problem on determining the optimal modes of a traction drive operation, it is necessary to solve four problems of the conditional optimization of parameters of a traction drive operation (under acceleration modes $U_{op}=1$, under the mode of recuperative braking $U_{op}=5$, under the mode of maintaining the assigned motion speed $U_{op}=2, 3$). For each of these problems, it is necessary to consider two modes: the application of one-time or a spatial-vector pulse-width modulation (PWM). The mode of acceleration and the mode of recuperative braking are similar. We shall apply the method of vector objective functions, proposed in article [22]. We shall select a vector function with the following parameters as the objective function for the acceleration mode:

$$F_{c1}=\begin{bmatrix}1-\eta_1\to\min\\ -F_d\to\min\end{bmatrix}. \tag{2}$$

The first component is chosen in such a way that when we minimize it, the maximization of the efficiency of a traction drive occurs.

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

$$F_{c5}=\begin{bmatrix}1-\eta_1\to\min\\ F_d\to\min\end{bmatrix}. \tag{3}$$

We shall select as an objective function for maintaining the assigned motion speed:

$$F_{c3} = F_{c4} = 1 - \eta_1 \rightarrow \min. \qquad (4)$$

Thus, we selected the objective functions for determining the optimal mode of traction drive operation, which make it possible to determine the optimal modes of traction drive operation when using different modes of PWM.

The magnitude of losses, therefore the efficiency of the drive can be determined based on the slip of traction engine, engine voltage (phase or linear) and rotation frequency. Operating modes are defined for all motion velocities – ATE rotation frequency, rotation frequency is a constant predetermined indicator assigned when solving a problem on finding the optimal operation mode of a traction drive.

To employ the known methods of optimization, it is advisable to use relative parameters for solving an optimization problem. That is why, instead of voltage, one should use a relative parameter – coefficient of modulation, which is very widely applied in the conversion technique. Connecting this parameter to the linear and phase voltage is attained using expression:

$$K_m = \frac{2U_{l1}}{U_d} = \frac{2U}{\sqrt{3}U_d}, \qquad (5)$$

where U_{l1} is the linear voltage of traction engine, U_d is the voltage at the AVI input.

Under the mode of one-time PWM, voltage curve shape is not changed and its amplitude can be regulated only by changing the frequency of output voltage. This mode is used when traction engine reaches the maximal sufficient voltage [1].

Modulation factor for it is equal to:

$$K_m = \frac{2\sqrt{6}}{\pi} \approx 1{,}56. \qquad (6)$$

Thus, the vector of parameters for solving the problem under the spatial-vector PWM mode takes the form

$$X_{PV} = \begin{bmatrix} s \\ K_m \end{bmatrix}, \qquad (7)$$

and under the one-time PWM mode it takes a scalar form

$$X_O = s. \qquad (8)$$

Thus, we defined parameters for the conditional optimization of operating modes of a traction drive when applying the spatial-vector and one-time PWM.

A constraint is given in the form of inequalities imposed on the parameters.

Slipping is imposed with by constraints:

$$s = X_{PV1} = \begin{bmatrix} [0, s_{kr}], U_{op} = 1{,}2 \\ [-s_{kr}, 0], U_{op} = 3{,}5 \end{bmatrix}, \qquad (9)$$

where s_{kr} is the critical slip value.

A constraint on the modulation factor:

$$K_m = X_{PV2} = \begin{bmatrix} [0, 1{,}414], U_{op} = 1{,}2 \\ [-1{,}414, 0], U_{op} = 3{,}5 \end{bmatrix}. \qquad (10)$$

Constraints on slip under the mode of one-time PWM

$$s = X_0 = \begin{bmatrix} [0, s_{kr}], U_{op} = 1{,}2 \\ [-s_{kr}, 0], U_{op} = 3{,}5 \end{bmatrix}. \qquad (11)$$

Constraints of the actual value of the ATE phase current under conditions of the possibility of the occurrence of short circuits in the semiconductor equipment and control instruments.

$$I_1 = \frac{I_{Cm}}{\sqrt{2}} < I_{max}, \qquad (12)$$

where I_{max} is the maximum ATE phase current value.

Constraints on the adhesion between a wheel and a rail

$$\left|F_d\right| < \left|F_k'\right|. \qquad (13)$$

The constraints imposed predetermine the space of parameters under which the operation of a traction drive is possible.

To assess the effectiveness of a traction drive, it is rational to choose as the parameters the following components of the control vector:

– modulation factor (K_m), its magnitude determines the value of phase voltage of the traction engine;

– the magnitude of slip (s) of the rotor;

– operating mode of the converter – one-time or spatial-vector PWM.

These magnitudes are relative and it is convenient to use them for the evaluation of operating modes of drives with different capacity. In order to obtain a solution to the problem on analysis, we developed the following algorithm.

Step 1. Set the magnitudes n_{zad}, $K_{m,}$ t_{zad} and s. For the one-time PWM mode, K_m=1.56.

Step 2. Set the mode of operation for the converter of one-time or spatial-vector PWM.

Step 3. Determine the magnitude of phase voltage of the motor and the frequency of power supply of the motor.

Step 4. Determine the value of saturation coefficient.

Step 5. Determine phase current of the motor.

Step 6. Determine a power factor.

Step 7. If the converter operates under the mode of spatial-vector PWM, proceed to step 11.

Step 8. Determine parameters of ATE equivalent circuit for the currents of higher harmonic.

Step 9. Determine the actual values of voltage and current of higher harmonic.

Step 10. Determine the losses in copper and steel from the currents of higher harmonic in a traction engine.

Step 11. Determine additional and mechanical losses in the engine by [23].

Step 12. Determine losses in the converter by [24, 25].

Step 13. Determine active power consumed by the engine.

Step 14. Determine the power that is consumed or relayed to the link of constant voltage.

Step 15. Determine the losses of efficiency of the traction drive and electromagnetic moment.

Testing the adequacy of a mathematical model for the calculation of parameters and determining the optimal operating modes of ATE is conducted in the following way. Comparison of results of the calculation of traction characteristic of induction traction engines with the data obtained as a result of experimental research. The AS 931 characteristics obtained at DP of "Plant Electrotyazhmash" (Ukraine) correspond to data on a standard engine given in Table 1. As evidenced by data on the efficiency and total losses given in Table 1, the maximum deviation in the calculation of losses is 7.42 %, which is fully acceptable.

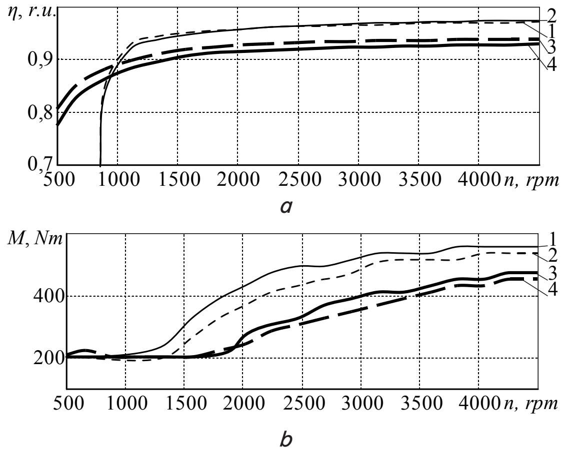
Table 1

Comparison of results of the calculation of characteristics and the AS931 experimental data

Power on the shaft, kW	27	41	54	54	54
Phase voltage, V	172	261	345	345	345
Moment on the shaft, Nm	287	289	290	159	117
Rotation frequency, rpm	890	1350	1773	3250	4400
Efficiency, %	0.901	0.9212	0.93	0.932	0.927
Power factor, a.u.	0.87	0.86	0.84	0.855	0.867
Efficiency by the calculation results, %	0.9015	0.921	0.9352	0.929	0.922
Total losses, W	2.673	3.231	3.78	3.672	3.942
Total estimated losses, W	2.6595	3.239	3.4992	3.834	4.212
Power frequency, Hz	23.8	35.4	47.2	110	150
Deviation, %	0.51	0.25	7.42	4.41	6.85

We adopted a combined genetic algorithm as a method for the optimization: global search is executed by genetic algorithm with a one-point crossover and selection by the roulette principle. At the final stage of employment of the optimization procedure, the optimum refining is carried out using the Nelder–Mead method in line with [1, 20, 21].

Fig. 1 shows optimum traction characteristics for the tram Tatra T-3 VPA (the country of origin is Czechoslovakia), which was substantially modernized in Ukraine, under operating modes.



a

b

Fig. 1. Optimal dependences of AD931 parameters on rotation speed n of the traction drive of a tram under the mode U_{op}=3: *a* – efficiency η; *b* – electromagnetic moment M; 1 – when applying a one-time PWM and at engine temperature 40 °C, 2 – when applying an one-time PWM and at engine temperature 180 °C, 3 – when applying a spatial-vector PWM and at engine temperature 40 °C, 4 – when applying a spatial-vector PWM and at engine temperature 180 °C

Definitive determining of the operating modes of the link ATE-AVI is to conducted by the criterion of efficiency (1), depending on the rotation speed and temperature of the motor windings.

When applying a one-time PWM mode, under the mode of traction and braking there emerges a zone at n=0...620 rpm where the work of the traction drive is impossible. At low frequencies of rotation, the phase current increases due to the impossibility of reducing the voltage of the engine.

5. Optimization of motion modes of a tram carriage

We shall consider the representation of a train motion equation in the software-oriented form that will allow us to use it for the determining the optimal laws of control in accordance with the Hamilton-Jacobi-Bellman method [26, 27].

Forces and resistances are calculated as follows.

The force of acceleration F_A (for one time step)

$$F_A = m\frac{v(t)-v(t-tstep)}{tstep}, \tag{14}$$

where m is the mass of the train, term

$$a = \frac{v(t)-v(t-tstep)}{tstep}, \tag{15}$$

where a is the equivalent constant acceleration, which a train is exposed to, at velocity difference v(t)–v(t–tstep) over one time step, predetermined by the assumption that the acceleration is constant for every time step, while the velocity linearly depends on time within a single time step.

The main rolling resistance F_{rr} (for one time step).

Because velocity depends linearly on time for each transition (time step), then the rolling resistance for each time step can be computed in accordance with the mean step speed, which is equal to:

$$v_{avg} = \frac{v(t)+v(t-tstep)}{2}. \tag{16}$$

Thus, the main resistance to motion for each time step is:

$$F_{rr} = a_{rr} + b\,v_{avg} + c\,v_{avg}^2, \tag{17}$$

where a_{rr}, b, c are the coefficients of resistance, for the tram carriage T-3 VPA with the weight of a full load 30000 kg: a_{rr} =1500 N, b=0 N s/m, c=1.5 N c^2/m.

Hence, the force required to move the tram at tstep:

$$F_{tot} = (1+\gamma)F_A + F_{rr} + F_s + F_{rk}, \tag{18}$$

where F_s F_{rk} are the resistance forces due to slopes and curves that are defined by the following ratios:

$$F_s = m\,g\frac{i}{1000}, \tag{19}$$

$$F_{rk} = \frac{c_{r0}}{R-c_{r1}}m, \tag{20}$$

where c_{r0}, c_{r1} are the constant known coefficients that are determined by [26, 27]; R is the radius of the curve, i is the slope, g is the acceleration of free fall.

The required energy for the motion of a train at tstep taking into account the constraints and assumptions that velocity varies linearly over time, based on [26, 27] is determined:

$$\begin{cases} E=\sum_{t=tstep}^{T}\frac{sign}{\left(\eta_1\right)^{sign}}\begin{pmatrix}(1+\gamma)F_A+a_{rr}+\\ +b\,v_{avg}+\\ +c\cdot v_{avg}^2+\frac{c_{r0}}{R-c_{r1}}\cdot m+\\ +mg\frac{i}{1000}\end{pmatrix}\times\\ \times\frac{v(t)+v(t-tstep)}{2}\cdot tstep\\ \left|\begin{matrix}(1+\gamma)F_A+a_{rr}+b*v_{avg}+\\ +c*v_{avg}^2+\frac{c_{r0}}{R-c_{r1}}\cdot m+mg\frac{i}{1000}\end{matrix}\right|\le\\ \le 9{,}81\,k_s m\cdot 1000,\end{cases} \tag{21}$$

where k_s is the adhesion coefficient that for a tram is 0.16, v_{avg} is the average motion speed per step.

For the time step of transition from the state n–1 to the state n, from the equation uniformly accelerated motion, a traveled distance can be received as follows:

$$\Delta x_n=v_{n-1}\,\Delta t_n+\frac{1}{2}a_n\,\Delta t_n,$$

$$\Delta x_n=v_{n-1}*\Delta t_n+\frac{1}{2}\frac{v_n-v_{n-1}}{\Delta t_n}\Delta t_n^2\Rightarrow$$

$$\Rightarrow\Delta x_n=v_{n-1}\,\Delta t_n+\frac{1}{2}v_n\,\Delta t_n-\frac{1}{2}v_{n-1}\,\Delta t_n\Rightarrow$$

$$\Rightarrow\Delta x_n=\frac{1}{2}\left(v_{n-1}+v_n\right)\Delta t_n\Rightarrow$$

$$\Rightarrow x_n-x_{n-1}=\frac{1}{2}\left(v_{n-1}+v_n\right)\Delta t_n\Rightarrow$$

$$\Rightarrow x_n=x_{n-1}+\frac{1}{2}\left(v_{n-1}+v_n\right)\Delta t_n, \tag{22}$$

where x_n, v_n, a_n are the position of a train, its velocity and acceleration at step n.

For time step 1

$$x_t=x_{t-tstep}+\frac{1}{2}\left(v_{t-tstep}+v_t\right)tstep, \tag{23}$$

where x_t is the final position of the train for one tstep; $x_{t-tstep}$ is the original position of the train for one tstep.

Expression (23) gives the final position of the train for a transition when one knows the initial position, the initial and resulting velocity, as well as the value of a time step.

Solving the problem on the optimization of motion modes was carried out for the section of a track from the tram depot "Saltivske" to the the turning circle 602 microdistrict, Kharkiv, Ukraine, and in the opposite direction. Results of solving the traction problem during tram motion under optimal mode are shown in Fig. 2.

Thus, we obtained the curves of the motion of a tram carriage, optimal by the criterion of energy consumption, along the track section with a given profile and motion schedule, we received the operating modes of the traction drive and ATE.

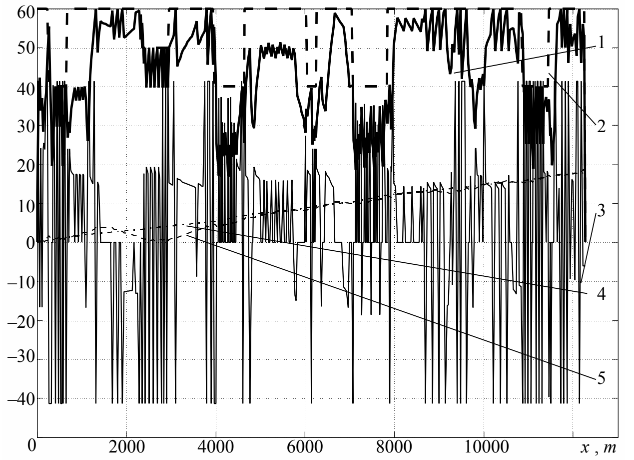


Fig. 2. Results of solving the traction problem during motion of the tram carriage Tt-3 VPA with the traction engine AD931 along the track sections when traveling distance x from the tram depot " Saltivske" to the turning circle 602 microdistrict, the city of Kharkiv and in the opposite direction: 1 — motion velocity (v), km/h; 2 —speed limit, km/h; 3 — traction force (F_{rr}) kN; 4 — motion time (t), min, 5 — energy consumption (E), kW·h

6. Optimization of the parameters of a fan for cooling the traction engines

To accomplish the set goal, we proposed applying the methods of conditional optimization of parameters of the cooling and ventilation system of a tram carriage ATE.

We selected, as a criterion for the research, the criterion of economic efficiency $k_{e,e}$, due to the fact that the main expenses in the operation of a tram traction drive are the cost of its operation, which is linked to a rather long life cycle of transportation vehicles (from 10 to 50 years), which is determined by expression [27]:

$$k_{e,e}=Q_{ohl}/Q_a, \tag{24}$$

where Q_{ohl} is the energy consumption for cooling, Q_a is the loss of energy in active parts of ATE.

Performance efficiency of a cooling fan is predetermined by its dimensions, that is: outer diameter (D_l) and the width of a blade (b_l), which one may choose as parameters. All other dimensions can be kept in line with a basic engine design.

Constraints imposed when solving an optimization problem on the parameters of a cooling and ventilation system can be divided into the following groups.

Restrictions in the form of inequalities imposed on the optimization parameters:

$$b_{min}<b_l<b_{max}, \tag{25}$$

$$D_{min}<D_l<D_{max}, \tag{26}$$

where b_{min}, b_{max} are the minimal and maximal permissible width of a fan blade, D_{min}, D_{max} are the minimal and maximal permissible diameter for the blades of a fan. These parameters are predetermined by the design of ATE.

Constraints imposed on the maximal overheating over the temperature of cooling medium of the elements of design of traction engines, which occurs during motion of a locomotive with wagons along the track section with a given profile and motion schedule

$$u_{max} < u_{dop}, \tag{27}$$

where u_{max}, u_{dop} are the vectors of overheating columns of the ATE elements and permissible values for such overheating.

Solving the optimization problem is performed on the example of the motion of the tram carriage T-3 VPA with the traction engine AD931, Ukraine. We selected a track section from the tram depot "Saltivske" to the turning circle 602 microdistrict in the city of Kharkov and in the opposite direction. The motion was repeated four times. We have given basic technical characteristics of traction drives, as well as results of determining the optimal trajectories of the motion of a tram. Next, we determined losses in the elements of ATE of a tram based on the procedure given in articles [1, 20, 21, 23], results of which are shown in Fig. 3.

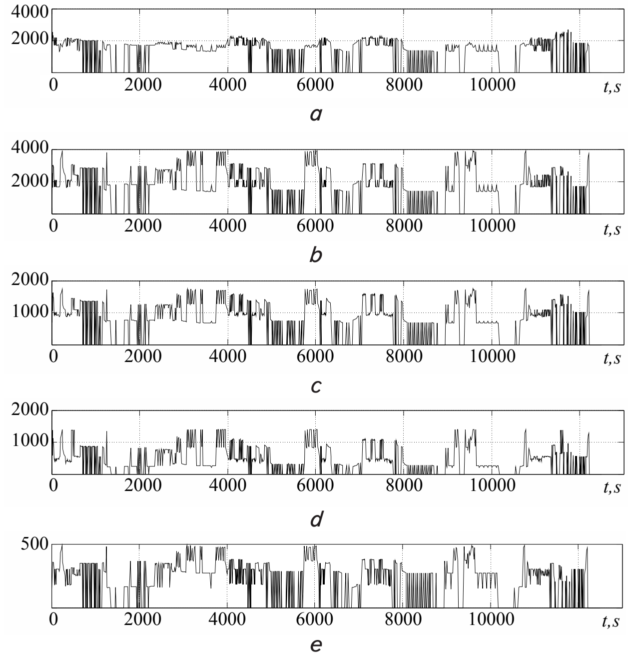


Fig. 3. Losses in a traction motor depending on operation time t: *a* — in the steel of the stator P_1, W; *b* — in the rotor P_2, W, *c* — in the groove part of the stator winding P_3, W, *d* — in the frontal part of the stator winding P_4, W, *e* — mechanical P_5, W

By applying results of these dependences, energy consumption in the ATE active parts can be determined by expression

$$Q_a = \sum_{n=1}^{5} \int_{T} P_n, \tag{28}$$

where P_1 are the losses in the steel of the stator; P_2 are the losses in the rotor, P_3 are the losses in the stator winding groove, P_4 – in the frontal part of the stator winding, P_5 are the mechanical losses.

Results of the loss calculation are the original data to solve an analysis problem, which is based on the method of modeling thermal regimes, which is given in article [28]. According to this procedure, we propose to apply a universal equivalent thermal scheme, which allows us to perform thermal calculation of non-stationary operating modes of ATE when using different cooling systems. Paper [29] considered the use of a universal thermal scheme for the thermal calculations of induction motors of controlled electric drives for the engines with a degree of protection IP44, IP54, to which AD 931 is related. Its equivalent thermal circuit is shown in Fig. 4. To calculate the equivalent thermal circuit, we propose to use the method of nodal potentials for electric circles.

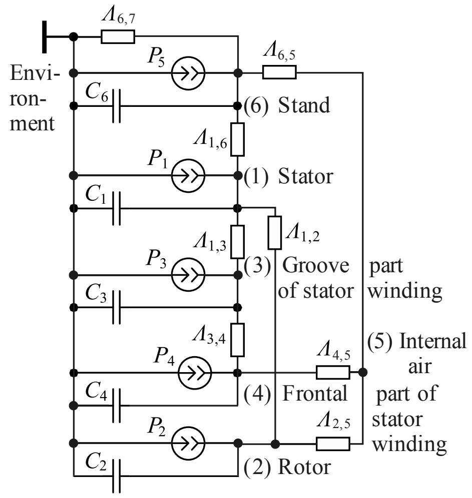


Fig. 4. Equivalent thermal circuit for ATE with a degree of protection IP44, IP54

Based on it, for the proposed universal equivalent thermal circuit, one can construct a system of differential equations of thermal balance. In a matrix form, the system is represented by a system of equations:

$$\frac{d}{dt}u = \left[C\right]^{-1} \cdot \left[DP + L \times u\right], \tag{29}$$

where u are the matrices-columns of average overheating above the temperature of cooling medium in the appropriate structural elements of electric machine; C is the matrix of thermal conductivities of the appropriate structural elements, upon which ATE is divided; DP is the matrix-column of capacities of heat release in the appropriate structural elements of ATE; L is the matrix of thermal conductivities.

The magnitudes of capacities of heat release are calculated by the losses in the elements of ATE, which change over time, depending on the mode of operation of the traction drive outlined in Fig. 1 and in article [28]. In addition, conductivities of the equivalent circuit change depending on the flow of air created by the fan and depend on the parameters that are adopted to solve the analysis problem.

To determine constraint (4), we perform analysis of the changes in overheating of the elements of ATE over the entire time of modeling the thermal modes by expression

$$u_{max} = MAX(u). \tag{30}$$

Power that is lost during fan operation is determined by expression [15]

$$P_{ven} = \frac{\Delta p \, Q_v}{\eta_v}, \tag{31}$$

where Δp is the pressure of air in the fan, Q_v is the flow of air in the fan, η_v is the fan efficiency, which are determined based on the results of ventilation calculation in line with the procedure given in [29], and depend on the geometry of a fan and the frequency of its rotation.

Power losses on cooling are found by expression

$$Q_{ven} = \int_T P_{ven}, \tag{32}$$

where T is the time interval of tram motion.

The result of solving the analysis problem is finding a criterion for the optimization by expression (1).

Judging by results of solving the test problems on the optimization of parameters of an ATE fan, the best result was demonstrated by the Weyl method using generalized golden section.

The course of solving the problem is shown in Fig. 5 (diamond denotes the optimal point, circle – the starting point).

We received the following optimal values: outer diameter of fan D_l=308.2 mm, width of the fan blade b_l – 15.7 mm.

The criterion of optimality in the considered problem reached the value of 0.0408. Compared with the basic design, it was reduced by 27.6 % (0.052).

Results of modeling of the thermal regimes of ATE at optimal values of the fan parameters are shown in Fig. 6.

The graphs shown in Fig. 6 demonstrate that the largest overheating is observed in the frontal part of ATE stator winding, which is 139.6 °C at second 3363 from starting the motion and it does not exceed a permissible value of 140 °C. Thus, the fan of induction traction engine, of external diameter 308.2 mm and width of the blade of 15.7 mm, ensures the required level of cooling when a tram carriage moves along a track section from the tram depot "Saltivske" to the turning circle 602 microdistrict in the city of Kharkov, and in the opposite direction.

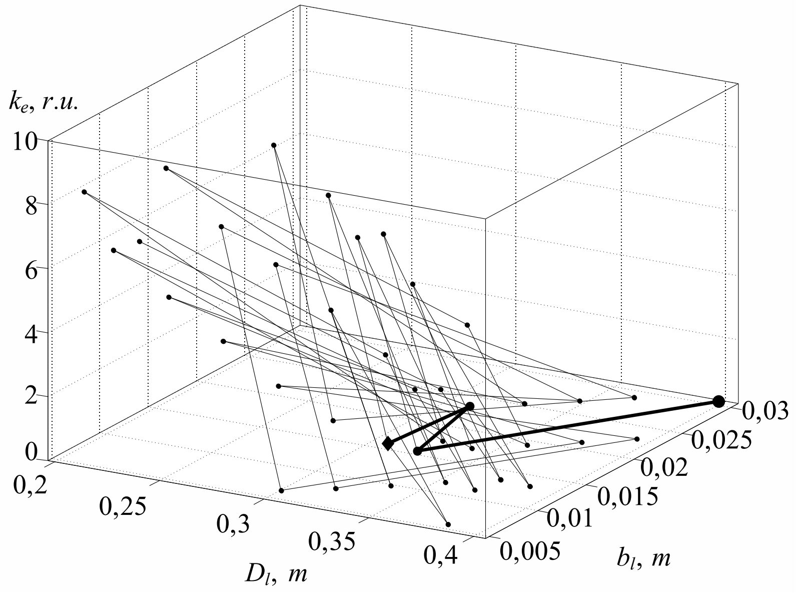


Fig. 5. The course of solving the problem on minimization by the criterion of operation efficiency of cooling fan k_e depending on its external diameter D_l and width of the blade b_l

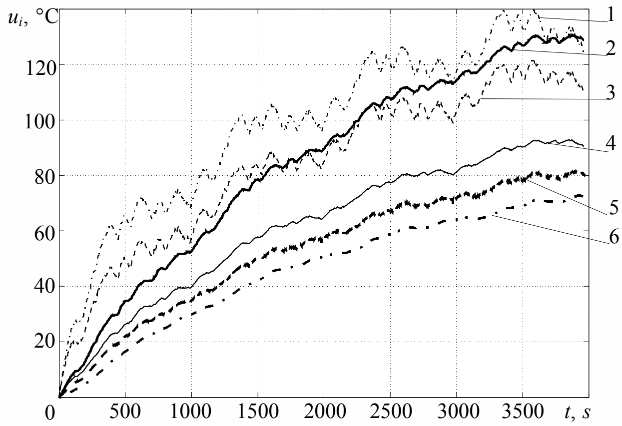


Fig. 6. Results of modeling the thermal state of the traction engine AD931, installed in the tram carriage T-3 VPA, that moves along the track sections from the tram depot "Saltivske" to the turning circle 602 microdistrict in the city of Kharkiv and in the opposite direction, repeated four times. Dependences of overheating u_i over the temperature of cooling medium °C on time *t*: 1 — the frontal part of the stator winding, 2 — of the rotor; 3 — of the groove part of stator winding; 4 — the stator core, 5 — internal air, 6 — stand

7. Discussion of results of the optimization of thermal regimes and cooling systems of induction traction engines of tram carriages

We defined constraints on the phase current of a traction engine that predetermine a creation of the zone where a traction drive operation is impossible. For the operation of a traction drive at low frequencies of rotation, we apply the mode of spatial-vector PWM, which makes it possible to maintain the specified maximal moment practically over the entire examined mode of operation from (50...620 rpm). Constraints of electro-magnetic moment at the level of around 490 Nm at rotation frequencies to 1220...1730 rpm occurs due to the limitation on adhesion. However, when temperature increases, the electro-magnetic moment grows through the reduced efficiency, which is more pronounced under the mode of traction to 0.52 %.

When a tram carriage moved along a track section, we established the following: energy consumption amounted to 18.56 kW·h, motion time was 1098 s, which corresponds to the average motion speed of 40.1 km/h at the assigned average speed of 40 km/h. Traction force is of pulsating character, which is needed to maintain the assigned motion speed.

Solving the test problem was carried out on the example of the traction engine AD931. The engine is installed in the tram carriage T-3 VPA. The tram carriage moves along the track sections from the tram depot "Saltivske" to the turning circle 602 microdistrict in the city of Kharkov, and in the opposite direction. The motion is repeated four times. We received the following optimal values: diameter of the fan D_l=308.2 mm and width of the fan blade b_l – 15.7 mm. The optimality criterion in the considered problem was 0.0408. Compared with the basic design, it was reduced by 0.052.

Modeling of thermal modes of ATE under optimal values of the fan parameters demonstrated that the largest overheating is observed in the frontal part of the ATE stator winding. Temperature is 139.6 °C at second 3363 from starting the motion and it does not exceed a permissible value of 140 °C.

8. Conclusions

1. In order to determine the optimal operating modes of an induction traction drive:

– we proposed a criterion of effectiveness. For the modes of maximal force of traction and recuperative braking, it is determined by the force of traction. Under other modes of traction drive operation, the criterion is determined by efficiency;

– we selected the optimization parameters: modulation factor, which determines the AVI voltage and slip of the rotor, which may change the efficiency of a traction engine and the traction force;

– given the fact that the problem on optimization is multiextreme, we selected, to solve it, a combined method of solving the problem of conditional optimization; global search is executed by genetic algorithm with a one-point crossover and by selection according to the principle of roulette; at the final stage, we employed the Nelder-Mead method.

We performed the optimization of operating modes of traction drives of the tram Tatra T-3 VPA over the entire range of ATE rotation frequencies at spatial-vector and one-time PWM of AVI at different values of temperatures of the engine windings. We proposed to conduct a definitive determining of operating modes of the link ATE-AVI using the criterion of effectiveness, depending on the rotation frequency and temperature of the engine windings.

2. We defined optimal motion modes of the tram carriage T-3 VPA with induction traction engines for a track section with the assigned motion schedule based on the method of Hamilton-Jacobi-Bellman. It is proposed to determine the operating modes of a traction drive in advance based on the solution to the problem on conditional optimization of its modes.

When the tram carriage moved along a track section, we established the following. Energy consumption was 18.56 kW·h. The motion time was 1098 s, which corresponds to the average motion speed of 40.1 km/h at the assigned average speed of 40 km/h. Traction force is of pulsating character, which is needed to maintain the assigned motion velocity.

3. We devised a procedure for the optimization of parameters of the fan of a traction induction engine that moves along a track section with a given profile and schedule, whose special features are as follows:

– the procedure is based on solving the problem of conditional minimization by the criterion of economic efficiency of a cooling system using the Weyl method by the generalized golden section;

– we selected the following magnitudes as the optimization parameters: outer diameter and width of the blade;

– the problem of analysis of the cooling system of traction engines is based on modeling the thermal modes of ATE using the generalized equivalent thermal circuit.

It was found that, compared with the basic design, efficiency of the cooling system increased by 27.6 %, which corresponds to a reduction in the proposed criterion of efficiency. The optimal outer diameter of a fan is 308.2 mm; the width of the fan blade is 15.7 mm.

4. Based on the results of modeling the ATE operation with an optimal fan, it was established that the largest overheating is observed in the frontal part of the stator winding. Its temperature is 139.6 °C at second 3363 from starting the motion, which does not exceed a permissible value of 140 °C.

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