Mathematical models analysis for the thermal state of mining trucks traction motors determining

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Abstract
The mathematical models analysis for calculation of the thermal state of mining trucks traction electric motors with electromechanical transmission, which undergo intense heat during operation has been conducted. It has been established that the mathematical apparatus that underlies the traditional approaches for determining the electric cars thermal state is not enough to calculate the mining truck traction engines heat due to inability to take into consideration their design parameters and significant changing loads for short periods of time that occur while performing transportation by a dump truck.

Keywords: OPEN PIT, PIT-RUN DUMP TRUCK, TRACTION MOTOR, FOURIER LAW, ELECTROMECHANICAL TRANSMISSION, THERMAL ANALYSIS, MATHEMATICAL MODEL

More than 200 units of technological vehicles manufactured mainly by "BelAZ-Holding" with carrying capacity of 120-136 tons and equipped with electromechanical transmission are employed in Kryvyi Rig region open pits. [1]. Up to 95% of mining ores and rocks are transported by this type of machine.

Transportation of the rock mass with this type of transmission cars is characterized by a considerable share of time periods on the rise when traction electric motors operate in the mode of maximum thrust [2]. The latter state increases the likelihood of anchor windings of traction motors overheating that usually leads to premature destruction of the protective insulating coating and shortening of the electric car life. Temperature stress during operation can cause increasing number of electric motors failures that is observed for mining truck BelAZ-75 131 employed in the transportation of rock mass in Kryvyi Rig region mines. In order to establish the influence degree of thermal loads on the thermal state of traction electric motors under certain circumstances it is necessary to provide analysis of the relevant mathematical models based on the theory of heat-mass exchange.

In order to tackle this problem it is usually considered unsteady three-dimensional temperature field in homogeneous solids with the source of heat distribution over volume. Within this solid elementary volume is adopted $dV=dx\cdot dy\cdot dz$, heat balance is formed for the elementary time interval dt, based on the energy conservation law with the assumption that all the heat that is released by inside source dQ_i and put from outside in elementary volume dQ_o by heat conductivity, changes internal energy of the substance dU in a volume dV [4,5,6,7]:

$$\frac{dQ_i}{dt}+\frac{dQ_o}{dt}=\frac{dU}{dt}. \tag{1}$$

Consider each component of heat loss.

The amount of heat introduced by heat conductivity dQ_i is determined in accordance with Fourier law, whereby heat dQ_i that passes through the isothermal surface element dF for the period of time dt is proportional to a temperature gradient $\partial\theta/\partial n$:

$$dQ_o=-\lambda\cdot\int_o^t\int_F\frac{\partial\theta}{\partial n}\cdot dF\cdot dt, \tag{2}$$

where λ is thermal conductivity coefficient (W /m·K).

Full heat flow, which is inserted in an elementary parallelepiped, considering the Fourier law (2), is defined with dependencies (3):

$$dQ_o=dQ_x+dQ_y+dQ_z=\lambda\cdot(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2})\cdot dx\cdot dy\cdot dz\cdot dt, \tag{3}$$

The amount of heat that is released in the elementary volume by domestic sources of energy:

$$dQ_i=q_v\cdot dV\cdot dt, \tag{4}$$

where q_v is heat density, thus heat loss strength in volume unit (J /s ·m^3).

Current unit for a resistance conductor determined the last:

$$q_v=I^2\cdot R, \tag{5}$$

where I is current unit for the time period, (A), R is resistance under alternating voltage (Ohm).

The internal energy of a substance dU alters according to parallelepiped weight $\rho\cdot dV$, thermal capacity of a conductor c (J/kg ·K) and the increment of temperature $\partial\theta$

$$dU=c\cdot\rho\cdot dV\cdot\frac{\partial\theta}{\partial t}\cdot dt, \tag{7}$$

where p is the density (kg / m3).

Putting equations (3), (4), (7)in the energy conservation law (1), following the reductions temperature increment speed (K/s) in the elementary volume dV is defined:

$$\frac{\partial\theta}{\partial t}=\frac{\lambda}{c\cdot\rho}\cdot(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2})+\frac{q_v}{c\cdot\rho} \tag{8}$$

This differential equation of thermal conductivity in partial derivatives (8) is used for solving the problems in the temperature field definition.

The unit $\lambda/(c\cdot p)$ is called temperature conductivity coefficient a. The equation (8), taking into consideration the Laplace operator $\nabla^2 t$ and a specified coefficient a, acquires the form [8]:

$$\frac{\partial\theta}{\partial t}=a\cdot\nabla^2 t+\frac{q_v}{c\cdot\rho} \tag{9}$$

Conductor temperature in the equation (8)–(9) is presented in implicitly that greatly complicated its solution till a certain period of time.

In this regard, analytical way of conductor temperature change rate determining for a long time remained the method based on identifying heat transfer coefficient, i.e, thermal power, which is given to the environment when the temperature of the conductor is above ambient temperature (J/s·K) [9]: $A=F\cdot a$, where F is cooling surface area (m2) and a is specific heat transfer coefficient.

The heat transfer coefficient depends on the shape of the body, that is blown around, and rate of cooling air and thermal conductivity:

$a = Nu \cdot \frac{\lambda}{d}$, where d is a cooled surface diameter, (m), *Nu* – Nuselt criterion.

Nuselt criterion is a variable index which value is determined by empirical dependence on the Reynolds number, which determines cooling air movement mode, and is elected for each case separately [9].

Taking into consideration heat transfer coefficient it has become possible to determine the temperature profile of the electric motor [8]:

$$\frac{\partial \theta}{\partial t} = \frac{P - A \cdot \tau}{C}, \qquad (10)$$

where *P* is heat generation engine, i.e. thermal capacity resulting from loss of energy during its electromechanical conversion (J/s); τ is excess engine temperature above ambient temperature (K); *C* is engine heat capacity (J/K).

If the engine runs with a constant power *P = const*, so, based on the equation solution (10), the temperature of heating will vary by exponential curve, that is, with the change of time temperature reaches steady-state meaning [10]:

$$\tau(t) = \tau_c \cdot (1 - e^{-t/T_\theta}) + \tau_b \cdot e^{-t/T_\theta}, \qquad (11)$$

where $\tau_c = P/A$ is exceeding of the established heating temperature of the engine over the ambient temperature (C °), τ_b is initial excess of heating temperature of the engine above the ambient temperature (C °), $T_\theta = C/A$ is thermal time constant, (s).

The represented dependence (11) permits to set the temperature of the engine heating under certain parameters of its cooling analytically, but it can be used only for engines that operate in continuous mode (class S1), which limits its use to describe heating traction motor mining trucks, that operates with variable loads depending on the total road resistance movement.

For a more detailed calculation of temperature indications the method of equivalent thermal circuits is used [7]. With it and on the bases of dependence (11) three mathematical models of thermal process in an electric car were formed; they were being used for some time during the engine design at engineering plants [11].

The first model is used to determine the temperature of winding gear anchor θ_{ca} [11, 12], taking into consideration that the overheating of the anchor tooth surface and anchor slot surface are virtually close to each other:

$$\theta_{ca} = \frac{(I_{a\infty}{}^{2} \cdot r_a \cdot t_r + \Delta P_k + \Delta P_c) \cdot [1 + \frac{\alpha}{\lambda_w \cdot p'} \cdot (t_1 + \frac{m_k \cdot \pi \cdot d_k}{2 \cdot Z})] + \Delta P_c \cdot (1 - \frac{\alpha}{\lambda_w \cdot p'} \cdot t \cdot \frac{0{,}5 \cdot \tau}{l_a})}{\alpha \cdot [\pi \cdot D_a \cdot (l_a + 0{,}5 \cdot \tau) + \frac{m_k \cdot \pi \cdot d_k}{2} + l_a]} \cdot k' \qquad (12)$$

where r_a is armature winding resistance (ohms); ΔR_k is switching losses (W); ΔP_c is losses in copper armature winding of the main groove pitch (W); t_r is coefficient of increasing resistance of copper at the expected temperature; λ_w is specific insulation thermal conductivity (W/cm^{2}° C); *p* – estimated perimeter groove (cm^2), t_1 – grooving point on the surface of the anchor (cm), m_k - number of ventilation ducts in the core anchors, d_k – duct diameter (cm), *Z* – number of anchor grooves, ΔR_s – losses in steel (W), τ –pole point (m), l_a – core anchor length (m), k – clarifying factor that depends on the type of performance of rear frontal parts (open and closed), α –coefficient of insulation heat conductivity (W/° C·cm).

Excess temperature of the armature poles coils over ambient temperature θm can be defined with using another model proposed by the same author, on the assumption that the heat losses are allocated through a coil winding insulation and heat transfer coefficient is equal on all sides of the coil [11, 12]:

$$\theta_c = \frac{P_c \cdot (1 + \frac{\alpha}{\lambda_w})}{\alpha \cdot l_a \cdot p'} \qquad (13)$$

where P_c are losses in copper coil at the expected excess temperature, W; *p*– estimated perimeter coil cm^2; l_a – average length of the coil, cm.

The third model allows us to calculate the excess temperature compensation of winding $\theta_{мко}$ over the cooling air [11]:

$$\theta'_{мко} = \frac{(I_{\infty}{}^{2} \cdot r_{ко} \cdot t_r) \cdot (1 + \frac{\alpha \cdot S_s}{\lambda_h \times S_h}) \cdot \Delta P_{ско}}{\frac{\alpha \cdot \lambda_f}{\lambda_f + \alpha'} \cdot S_{лоб} \cdot (1 + \frac{\alpha \cdot S_s}{\lambda_h \times S_h}) + \alpha \cdot S_{ст}} \qquad (14)$$

where S_s – heat emission from the surface of the pole tip (cm^2), S_h – heat emission from the coil to the surface of the pole tip (cm^2), λ_h – specific insulation of thermal conductivity (W/c °·C), λ_f

– thermal conductivity of frontal connections (W/cm$^2\cdot$°C), $\Delta P_{\text{ско}}$ – losses in the steel pole piece (W).

The presence of the factor t_{r} represented in models (12), (14) doesn’t allow to consider them as final functional relationships, that determines solving the problem of defining the temperature of copper windings selection with the method which only gives approximate temperatures. Another drawback of these models is the lack of time factor consideration. Besides, without detailed information about design data of electrical machines numerical implementation of thermal models is impossible.

Thus, the traditional modes of electrical cars temperature state defining do not allow to determine with a sufficient degree of certainty mines dump trucks traction motors heating and their components in specific conditions.

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