Improving shunting-export locomotive towline when operating in strip mine based on its stationary thermal model

D Ya Antipin, D A Bondarenko, V I Vorobiev

Bryansk State Technical University, 7, 50 let Oktyabrya Blvd., Bryansk, 241035, Russia

E-mail: dilekter@gmail.com

Abstract. There is the technique of improving shunting-export rolling stock towline when operating in a strip mine on the basis of its stationary thermal model founded on calculating the thermal resistances and permitting to determine the temperature of the most thermally loaded node. The technique was tested for the model of the engine AO-63-4 and shunting-export locomotive TEM7. There is the method of calculating thermal resistances of separate units on the basis of design features and the geometrical sizes of the asynchronous motor. It is concluded that the rods of the engine rotor AO-63-4 are most intensively heated.

1. Introduction

Shunting-export locomotive towline, which operates under conditions of strip mines, must implement the specified traction to ensure the required quality of the transition process in addition to the stringent requirements of the energy and mass-dimensional indicators. Operation under such conditions can cause overheating of traction electrical equipment, which leads to disrupting the settings of optimal control systems for any quality indicator. The traction drive perfection taking into account its thermal condition will allow to reduce expenses on auxiliary needs and to provide its optimum thermal mode that will increase its reliability and durability.

It is known that one of the main causes of aging and destructing the insulation is an increased temperature level of the motor windings, and the main role is played not by their average values, but by the actual local temperature values of specific parts of the machine windings and their adjacent units, depending on the load, conditions and cooling mode.

In work [1], it is established that in the entire speed change range of the electric locomotive movement, the stator winding heats up more intensively than the rotor winding. Moreover, with the speed increase of the locomotive, the difference between the temperature of the stator winding and the temperature of the rotor rods increases. Studies have shown that the stator winding is most intensively heated in the slotted part.

In work [2], it is shown that more intensive heating occurs in the rotor rods, while the stator overheating has smaller values (for a machine with 4 kW power, the temperature excess of the rotor rods over the stator winding reaches 18°C; for a machine with 15 kW power that is 44 °C under the nominal parameters of the supply network and a load close to the nominal).

The results of work [3] sufficiently coincide with the results of work [2] in terms of detecting the limiting heating motor assembly.
In work [4], the thermal state of the engine AIR100S4 with 3 kW capacity in the nominal mode was examined. It is found that the frontal parts of the stator winding have the highest temperature, slightly lower than the temperature of the slot part of the stator winding, which is explained by the best heat transfer conditions.

Similar results were obtained in works [5, 6]: the temperature of the stator winding laid into the slots, is typically 5-10 °C lower than in the end parts on the side opposite to the ventilation hatch. The authors explain this fact by the good heat conductivity of the stator and rotor steel (axial ventilation takes away part of the heat from the grooves and teeth of the stator through the air gap, while in the radial direction the heat is dissipated through the steel of the stator and the motor housing).

For the past several years, there have been a trend of replacing existing insulation materials windings of traction motors for insulation materials of a higher insulation class. Studies have been conducted [7], which showed that the basic resource of the traction motor with F and H class insulation can achieve $2.5 \times 10^6$ km depending on operating, which is twice longer than that with B class insulation However, as it is shown by the operation results, resource motors with F class insulation compared to motors with B class insulation haven’t increased twice, but by 20...30%. This discrepancy between the expected effect and the operating results indicates the method of the accelerated insulation tests on the models that are carried out for all insulating materials of traction motors does not sufficiently take into account the impact of operating conditions and design features of the machines.

Summarizing the analysis, it should be noted that, despite the relatively large number of works in the field of study of the asynchronous motor thermal state, this direction of research is still relevant. To predict the thermal state of an asynchronous motor during its operation, it is necessary to develop its own mathematical model designed for a particular type of electric motors. Checking the adequacy of the mathematical model should be carried out according to the data obtained during the experimental tests on the engine under study, or its physical model.

2. Materials and methods

The authors have developed a mathematical model of steady-state thermal processes for the calculation and analysis of temperature changes in different asynchronous motor nodes. The engine in it is presented in the form of the nonlinear closed thermal object in which thermal streams through passive elements (a bed, a shaft, etc.) can be redistributed between active nodes of the machine in which losses depend on their temperatures. The heat exchange of the frame with the external environment in the model is determined by the conditions of free convection and thermal radiation. The model is based on the method of equivalent thermal circuits, which allows determining the stationary temperature distribution in the selected number of engine components.

Cooling conditions on the surface of elementary units are given using the criteria equation of forced convection, free convection and thermal radiation [8 – 10].

The obtained nonlinear model allows one to calculate the values of local temperatures in 10 elementary nodes of its construction (Figure 1), including the coolant temperature at the airflow inlet section. Thermal processes in it are defined for each node by equations of thermal balance, heat transfer to cooling air and thermal conductivity to neighboring nodes.

The following assumptions are made for mathematical description of heat transfer processes in the asynchronous motor:
- the main structural components of the asynchronous machine are a particular modification of the cylindrical shape;
- thermal flows in the radial and axial direction are independent of each other;
- heat flows in radial and axial directions determine the mean value of the cylindrical member temperature;
- there are no circular heat fluxes;
- there is uniformity of heat dissipation distribution.
Using these assumptions, there are two independent thermal models of cylindrical bodies, each representing the values of three temperature ranges. One model represents the equation solution of heat conductivity in radial direction, the other in the axial one. In each model, the potentials of the two nodes are equivalent to the temperature on the corresponding surface, and the potential of the third point is the average value of the entire cylindrical element. The source of heat generation is introduced into the circuit point, the potential of which is equivalent to the average temperature. To calculate the thermal resistance of the model, it is necessary to have information on the geometric dimensions of the cylindrical element, as well as the values of the thermal conductivity \( \lambda_a \) and \( \lambda_o \) in the axial and radial directions, respectively.

As an example, we calculate the thermal resistance of the equivalent thermal circuit of the core replacement (Figure 2) and stator windings (Figure 3).

Axial resistance between the stator yoke and the air at the bearing caps (Figure 2):

\[
R_3 = \frac{l}{6\pi \lambda_o \left( r_{out}^2 - r_{int}^2 \right)}. 
\]
(1)

The yoke proper radial resistance Figure 2 is:

\[
R_4 = \frac{1}{4\pi \left( r_{out}^2 - r_{int}^2 \right) \lambda_p l_x} \left( \frac{4r_{out}^2 r_{int}^2 \ln \left( \frac{r_{out}}{r_{int}} \right)}{r_{out}^2 - r_{int}^2} - r_{out}^2 - r_{int}^2 \right). 
\]
(2)

Radial resistance between the stator yoke and the housing (Figure 2) is:

\[
R_5 = \frac{1}{2\pi \lambda_p l_x} \left( 1 - \frac{2r_{int}^2 \ln \left( \frac{r_{out}}{r_{int}} \right)}{r_{out}^2 - r_{int}^2} \right). 
\]
(3)

Radial resistance between the yoke and stator teeth (Figure 2):
Here $\lambda_1$, $\lambda_2$, and $\lambda_3$, are the coefficients of thermal conductivity of the core charge sheets in axial and radial directions respectively; $r_{\text{out}}$ is the outer radius of the stator; $r_{\text{int}}$ is the outer radius of the stator teeth; $l$ is the length of the stator core.

\[ R_6 = \frac{1}{2\pi \lambda_I l s} \left( \frac{2r_{\text{out}}^2 \ln (r_{\text{out}}/r_{\text{int}})}{r_{\text{out}}^2 - r_{\text{int}}^2} - 1 \right). \]  

(4)

Figure 3. Stator winding: a – a sketch of the stator winding, b – equivalent thermal circuit of the stator winding.

Radial resistance between the yoke and the stator (Figure 3):

\[ R_{12} = \frac{2d_i}{\pi \lambda_1 r_{\text{sw}} n} + \frac{1}{2\pi \lambda_1 l F n} \]  

(5)

Axial resistance between the slot and the frontal parts of the stator winding (Figure 3):

\[ R_{13} = \frac{l}{6 \lambda_4 S_c n} \]  

(6)

Radial resistance between the slot part of the winding and the stator core (Figure 3):

\[ R_{14} = \frac{4d_i}{\pi \lambda_4 r_{\text{sw}} n} + \frac{1}{\pi \lambda_4 l F n} \]  

(7)

Radial resistance between the slot part of the stator winding and the air gap (Figure 3):

\[ R_{15} = \frac{1}{\pi \lambda_4 l F n} \]  

(8)

Here $r_{\text{sw}}$ is the equivalent radius of the winding, $d_i$ is the thickness of insulation, $S_c$ is the cross-sectional area of copper in the groove, $F$ – coefficient of thermal conductivity in the radial direction, $\lambda_i$ – the thermal conductivity of the groove, $\lambda_v$ – varnish conductivity, $n$ is the number of conductors in the slot.

Similarly, there is the thermal resistance of the remaining elements and nodes of the asynchronous engine. The complete synthesized equivalent thermal circuit of the asynchronous motor substitution is shown in Figure 4. Subscript indices designate the numbers of elements (in accordance with Figure 1), $R$ is the resistance to heat flow between them.

From the point of view of heat generation there are considered active the core of the stator 2, the teeth of the stator 3, stator windings 4, the frontal part of the stator winding 6, the bars of rotor 8 and the core of rotor 9. On the basis of the results [11-14] the power determination of heating losses is in different nodes on the basis of the equivalent substitution scheme corresponding to electromechanical and electromagnetic processes in the asynchronous motor. In determining the loss power, there are the saturation phenomena along the main magnetic path, the effect of displacement of the rotor current, as well as the nonlinear dependence of steel losses on the stator current frequency.

As a result of the synthesis of the equivalent thermal substitution scheme, the heat equilibrium equation was obtained:
\[ \Theta = G^{-1} P, \]  

where \( \Theta \) is matrix of overheating the engine certain components; \( G \) is the matrix of the thermal conductivities between the nodes (inversely proportional to thermal resistance); \( R \) is the capacity matrix of heating losses. The matrix \( G \) has a dimension of \([10 \times 10]\), matrix \( \Theta \) and \( P \) and \( R \) have a dimension of \([10 \times 1]\).

\[ \text{Figure 4. Equivalent thermal equivalent circuit of the induction motor.} \]

The engine of AO-63-4 with the 14 kW capacity was chosen as the studied engine. The choice of this engine is due to the fact that it is equipped with a complex physical model of the traction electric drive with asynchronous motors [15-18]. The paper [19] shows the adequacy of physical modeling of a traction motor with 14 kW power.

3. Conclusions
The results of calculating the power losses are shown in Table 1. The power calculation is carried out for the control law \( u/f_s = \text{const} \), where \( u \) is the stator winding voltage, \( f_s \) is the stator current frequency. As the studied modes of operation there are the modes, which are the heaviest from the point of thermal load, i.e. corresponding to the large moments of resistance.

In Table 1 there are accepted designations: \( u_s^* = u/u_{s\,\text{nom}}, f_s^* = f_s/f_{s\,\text{nom}} \) are relative values of the stator current voltage and frequency; \( \omega^* = \omega/\omega_{0\,\text{nom}}, M^* = M/M_{\text{nom}} \) are rotation frequency relative values of the rotor shaft and the moment; \( V_{col}^* = V_{col}/V_{col\,\text{nom}} \) is the relative speed of cool air; subscript «nom» denotes the nominal value of the respective quantities; \( \omega_{0\,\text{nom}} \) is the rotation frequency of the stator magnetic field with \( f_s^* = 1 \). Frequency value of \( f_s^* \) was selected according to the frequency values of the current diesel generator set of shunting-export TEM7 locomotive for operation in the conditions of strip mines for different positions of the driver controller, the values \( V_{col}^* \) are chosen according to air flow for cooling the locomotive traction motors at the driver controller’s appropriate positions [20].
Table 1. Results of calculating power losses in the selected engine components AO-63-4

| №  | \( f_s^* \) | \( n_s^* \) | \( \omega^* \) | \( M^* \) | \( V_{em}^* \) | \( \Delta P_2, \text{Вт} \) | \( \Delta P_3, \text{Вт} \) | \( \Delta P_4, \text{Вт} \) | \( \Delta P_5, \text{Вт} \) | \( \Delta P_6, \text{Вт} \) | \( \Delta P_7, \text{Вт} \) |
|----|-------------|-------------|-------------|--------|-------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 1  | 1           | 1           | 0.9         | 1      | 1           | 90.1                 | 150.4                | 310.8                | 305.1                | 460.1                | 21.9                 |
| 2  | 1           | 1           | 0.86        | 1.5    | 1           | 87.5                 | 149.7                | 485.1                | 473.9                | 721.8                | 35.8                 |
| 3  | 0.5         | 0.5         | 0.43        | 1      | 0.45        | 50.4                 | 106.7                | 322.7                | 323.8                | 483.9                | 17.9                 |
| 4  | 0.25        | 0.25        | 0.24        | 1      | 0.2         | 39.75                | 72.2                 | 323.6                | 336.3                | 512.7                | 9.9                  |

Results of calculating engine component overheating AO-63-4 are shown in Table 2.

Table 2. The results of calculating the allocated overheating of engine components AO-63-4

| №  | \( \theta_1, \text{°С} \) | \( \theta_2, \text{°С} \) | \( \theta_3, \text{°С} \) | \( \theta_4, \text{°С} \) | \( \theta_5, \text{°С} \) | \( \theta_6, \text{°С} \) | \( \theta_7, \text{°С} \) | \( \theta_8, \text{°С} \) | \( \theta_9, \text{°С} \) | \( \theta_{10}, \text{°С} \) |
|----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1  | 86.8            | 130.7           | 130.3           | 131.8           | 131.3           | 113.4           | 98.9            | 132.1           | 131.4           | 109.3           |
| 2  | 126.7           | 189.2           | 191.0           | 189.8           | 191.5           | 165.6           | 144.4           | 192.7           | 191.8           | 159.5           |
| 3  | 84.67           | 147.6           | 149.2           | 148.4           | 149.7           | 131.8           | 105.8           | 150.7           | 149.9           | 117.6           |
| 4  | 83.96           | 171.9           | 173.6           | 173.3           | 174.7           | 157.2           | 116.6           | 175.8           | 174.8           | 129.8           |

Calculated overheating values (Table 2) showed a high convergence with the results of experimental studies (temperature sensors installed in the engine can measure the temperature of housing 1, stator core 2, the frontal part of stator winding 6, rotor core 9) [21-22], which indicates the correctness of the calculation.

As the results of the calculation show, the rotor rods are the most overheated node of the asynchronous motor. The most thermally loaded elements of the stator are the slot and frontal parts of the winding, with the superheat values being relatively similar, the exact position of the most heated node depends on the cooling air speed, the parameters of the supply voltage and the resistance moment. At the independent method of cooling, the location and the temperature of the hottest node depend negligibly on the rotor shaft rotation frequency.

It is obvious that working at low positions of the driver’s controller (No. 3 and 4 in table 1 and 2), the flow rate and speed of the cooling air is significantly lower than its nominal values, which leads to reduced heat loss.

Given that the traction motor is experiencing the greatest overcurrent at low positions, because only at start-up the maximum torque (current) is effective, temperature values from the heat-loaded components of the engine in these modes have a crucial influence on the operation as a whole. As can be seen from Table 2, at the low positions of the driver’s controller, the winding operate at the limit values of the insulation temperature. When the moments increase above the nominal value, which is normal at start-up, the insulation experiences overheating above the permissible level. When the locomotive is heavy, when moving on long climbs at low speeds, when the duration of work under the influence of large moments becomes comparable to constant heating, the insulation temperature exceeds the permissible value rather long, which leads to accelerated aging insulation. To prevent such effect, it is necessary to equip the traction motors cooling system with the automatic temperature control systems with the feedback on the temperature of the most heated node.

The proposed method provides an increase of reliability and durability of exploited shunting-export locomotives and traction electric equipment in conditions of high loading at strip mines, and thereby reduces the cost of their life cycle.

References
[1] Boglietti A, Cavagnino A, Staton D 2008 Determination of critical parameters in electrical machine thermal models IEEE Transactions on Industry Applications 44(4) 1150–1159
[2] Bose B 2009 Power electronics and motor drives recent progress and perspective IEEE Transactions on Industrial Electronics 56(2) 581–588

[3] Bouscayrol A, Pietrzak-David M., Delarue P 2006 Weighted control of traction drives with parallel-connected AC machines Transactions on Industrial Electronics 53(6) 1779–1806

[4] Bonnett A, Soukup G 1992 Cause and analysis of stator and rotor failures in three-phase squirrel-cageinduction motors IEEE Transactions on Industrial Electronics 28(4) 921–937

[5] Boglietti A, Cavagnino A, Parvis M, VALLAN A 2006 Evaluation of radiation thermal resistances in industrial motors IEEE Transactions on Industrial Electronics 42(3) 688–693

[6] Chai F, Tang Y, Pei Y, Liang P, Gao H 2016 Temperature field accurate modeling and cooling performance evaluation of direct-drive outer-rotor air-cooling in-wheel motor Energies 9 818

[7] Mezani S, Takorabet N, Laporte B 2005 A combined electromagnetic and thermal analysis of induction motors IEEE Transactions on Industrial Electronics 41(5) 1572–1575

[8] Bousbaine A 1999 Thermal modelling of induction motors based on accurate loss density distribution Electric Machines & Power Systems 27 311–324.

[9] Boglietti A, Cavagnino A, Staton D, Shanel M, Mueller M, Mejuto C 2009 Evolution and modern approaches for thermal analysis of electrical machines IEEE Transactions on Industrial Electronics 56(3) 871–882

[10] Pickering S, Thovex F, Wheeler P, Bradley K 2006 Thermal design of an integrated motor drive IECON 2006 – 32nd Annual Conference on IEEE Industrial Electronics ed F. Marignetti (Paris: IEEE) pp 4794–4799

[11] Huai Y, Melnik R, Thogersen P 2003 Computational analysis of temperature rise phenomena in electric induction motors Applied Thermal Engineering 7 779–795

[12] Wang J, Wang F, Kong X 2008 Losses and thermal analysis of high speed pm machine 2008 Joint International Conference on Power System Technology and IEEE Power India Conference ed M. Mahmoudi (New Delhi: IEEE) pp 1572–1575

[13] Niazi P, Toliyat H, Cheong D, Kim J 2007 A low-cost and efficient permanent-magnet-assisted synchronous reluctance motor drive IEEE Transactions on Industry Applications 43(2) 542–550

[14] Gouws R, Jaarsveldt H 2012 Thermal and efficiency analysis of a single phase induction motor with Peltier devices World Journal of Engineering 9(1) 63–70

[15] Boldea I, Tutelea L 2009 Electric machines: steady state transients and design with MATLAB (Boca Raton: CRC Press)

[16] Bilgin B, Sathyam F, Emadi A 2014 Fundamentals of electric machines’ in Advanced electric drive vehicles (Boca Raton: CRC Press)

[17] Chapman S 2005 Electric machinery fundamentals (New York: NY:McGraw-Hill)

[18] Staton D 2014 Thermal Analysis of Traction Motors 2014 IEEE Transportation Electrification Conference and Expo (ITEC) ed M. Krishnamurthy (Dearborn: IEEE) pp 1–6

[19] Bilgin B, Magne P, Malysz P 2015 Making the case for electrified transportation IEEE Transactions on Transportation Electrification (vol 1) ed A. Emadi (Toronto: IEEE) chapter 3 p 2

[20] Bennion, K 2011 Electric Motor Thermal Management National (Denver: Renewable Energy Laboratory)

[21] Moreno G, Narumanchi S, Bennion K 2014 Gaining traction: thermal management and reliability of automotive electric traction-drive systems IEEE Electrification Magazine 2(2) 42–49

[22] Chang C, Cheng C, Ke M 2009 Experimental and numerical investigations of air cooling for a large-scale motor International Journal of Rotating Machinery 2009 1–7