Investigation of induction motor temperature distribution in traction applications

A A Pugachev¹ and A S Kosmodamianskiy²

¹ Bryansk State Technical University, 7, 50-letiya October Blvd, Bryansk, 241035, Russia
² Moscow State University of Railway Engineering, 9 Obrazcova St., Moscow, 127994, Russia

E-mail: alexander-pugachev@rambler.ru

Abstract. The relevance of thermal behavior investigation of traction induction motors is shown. The brief survey of techniques to monitor the temperature of an induction motors is carried out. The detailed multi-node equivalent thermal circuit of an induction motor is designed for steady state. The calculation technique of some units' thermal resistances by using of construction features and geometric sizes of an induction motor is shown. Results of thermal processes calculation for 14 kWAO-63-4 induction motor are shown. The adequacy of proposed thermal model is proved by means of good convergence of calculated results with the results obtained by the experimental investigation on the same induction motor. As a result of investigation, it is established that the slot winding of the stator located about on 2/3 of its length from the cooling air entrance has the highest value of temperature.

1. Introduction

Different researches dedicated to induction motor electric drives show that the thermal conditions of the motor affect both motor reliability and performance of the control systems [1,2]. The windings temperature is established to defy lifetime insulation; it is one of a main factors causing an insulation aging [3]. So, it was found by V.M. Montsinger [4] that the degradation speed of winding insulation doubles at 8 degree rising over the maximum operating temperature. Moreover, the windings temperature changing leads to the quality derating of the control systems [5]. It concerns, first of all, the complex control systems, such as vector control and direct torque control systems, in which the accuracy of speed control depends on accuracy of the stator and rotor resistance identification. Also, the temperature changing affects the efficiency of an electric drive. It becomes crucial for drives with control systems providing the minimum of power losses. To overcome or mitigate the temperature influence, the control systems have to have the correct data about actual temperature in real time. This problem has essential meaning in traction electric drives where thermal condition of electric drives is harder predictable due to a peculiarity of operation mode. So, regardless of exact traction application, i.e. railway or mining railway locomotives, the traction induction motors operate, mostly, with high torques and low speeds that causes the higher thermal stresses on the motor windings. The other factor to influence complexity of thermal state of the traction motor is a cooling system set, in many cases, separately from the actual thermal condition. In some part of general and mine locomotives park, the auxiliary motors driving the cooling fans and pumps are supplied directly from the synchronous
generator installed on a vehicle. Since recently, due to relevance of this problem, the auxiliary electric drive started to be equipped with frequency converter allowing to vary the cooling air or water speed and flow. This approach needs the actual data of the induction motor temperature in real time too. Thus, the task of thermal conditions investigation in an induction motor has very important meaning for the traction electric drive. This article presents results of temperature distribution research in the induction motor in steady state. The equivalent thermal circuit was developed for theoretical investigation, the laboratory setup with the 14 kW motor as a physical model of a traction electric drive [6] was used for the experimental one.

2. Brief survey of calculation induction motor temperature techniques

Analysis of techniques and gauges of determination and/or measurement of temperature of some elements of induction motors has shown the following. The contact sensors and devices installed directly on available parts of a winding of the stator have the largest accuracy of determination of temperature. Their broad use under operating conditions of locomotives is complicated for a number of reasons: complexity of these devices, need of intervention in a design of induction motors, severe ambience (including a wide range of humidity and vibration), etc. Besides, contact sensors take temperature only in the spot of their installation while distribution of temperature on the whole volume of the motor, including windings, has uneven character. Thus, to organize the thermal condition monitor of the motor correctly, the sensor has to measure the temperature of the hottest spot. Contrary to this, to modify parameters of control system controllers, it needs to trace not the maximum temperature or temperature of a single spot, but the average temperature thorough the windings. So, the implementation of locally mounted sensors is not the way to reach it. To summarize all above, it is necessary to stress that both average and maximum values of windings temperature has to be determined or measured to satisfy requirements of electric drive control system and traction induction motor cooling system.

The other way to determine temperatures is to apply non-invasive techniques based on microprocessor systems. Nowadays, there are a number of such techniques developed and implemented [7-15]. The summary of these approaches is shown in Figure 1.

![Figure 1. Classification of non-invasive techniques of determination of windings temperature](image-url)

As it could be seen from Figure 1, the non-invasive techniques can be divided into three categories. The first one based on utilization of thermal models of an induction motor is the first technique to be implemented. It fits perfectly the aim of detailed investigation of temperature distribution in both
steady state and transient mode. The second category, i.e. indirect determination of temperature by identification of stator and rotor resistance value, allows one to produce data of average temperatures with a high level of accuracy. The last category based on artificial intelligence techniques was introduced recently and combines some features of two first techniques. Each of considered techniques has some advantages and drawbacks that are enlightened quite fully in different researches [7-15]. Based on survey and analysis of these works, it was decided to implement an analytical model based on equivalent thermal circuit to calculate temperature distribution in a steady state. The thermal circuit is developed in the way that power losses are introduced as current sources; heat transfer between units of an induction motor, internal and ambient air by means of conduction, convection and radiation is introduced as resistances.

3. Equivalent thermal circuit of induction motor

The motor in the model is presented in the form of the nonlinear closed thermal object in which thermal flows through passive units (frame, shaft) can be redistributed between active units of the motor in which power losses depend on their temperatures. Heat exchange between the frame and the external environment is determined by free convection and heat radiations. The cooling conditions on a surface of elementary units are set with criteria equations of the forced convection, free convection and thermal radiation [16]. The developed equivalent circuit allows one to calculate local temperatures in 53 different nodes of the induction motor (Figure 2a), including the temperature of an internal air in the input and output of the cooling air. Of 53 nodes, 31 nodes are active ones, i.e. they generate power losses and, consequently, heat, and 22 nodes are passive ones.

![Figure 2. Sketch (a) and fragment of equivalent thermal circuit of induction motor:](image)

1 – 10, 18 - frame, 11, 17 - internal air, 12 – 16 - stator yoke, 19, 20, 26, 27 - end parts of stator winding, 21 – 25 - slot part of stator winding, 28 – 32 - upper par of stator teeth, 33 – 37 - the lower part of stator teeth, 38 – 39 - bears, 40, 46 - end ring of rotor winding, 41 – 45 - bars of rotor winding, 47 – 53 - rotor shaft; black nodes - source of power losses (active nodes), hollow nodes - passive nodes

The next assumptions are accepted for the model: the main nodes of the induction motor represent some kind of a cylindrical element; thermal flows in the radial and axial directions are separated and independent from each other; thermal flows in the radial and axial directions define the average value
of temperature of a cylindrical element; there are no circular thermal flows; uniformity of distribution of heat emissions. Thermal processes for each node are determined by equations of thermal balance, a heat transfer to the cooling air and heat conductivity to the next nodes. The two independent thermal models of cylindrical elements displaying values of three temperatures are applied with use of presented assumptions. The first model represents the solution of the equations of heat conductivity in radial direction, the other does in axial direction. In each model the potentials of two nodes represent temperature equivalent on the corresponding surface, and the potential of the third node represents the average temperature of whole cylindrical element. The source of thermal emissions (i.e. current source) is entered into a node of the scheme which potential is equivalent to average temperature. For calculation of thermal resistance of model, it is necessary to have information on the geometrical sizes of a cylindrical elements and values of heat conductivity in the axial and radial directions respectively.

The fragment of the developed equivalent circuit is shown in Figure 2b, the whole circuit is symmetric relatively the vertical axle and the right side (not shown) reflects the left side shown in Figure 2b. The general equation for each node is the following:

$$ P_i = \frac{\theta_i}{R_{i,j}} + \sum_{j=1}^{53} \frac{\theta_i - \theta_j}{R_{i,j}}, \quad i=1,2,3...53, $$

(1)

where $P_i$ - the power losses, $\theta$ - the temperature of the respective node, $R$ - the thermal equivalent resistance between respective nodes, subscripts of $i$ and $j$ - the number of node. Based on equation (1), 53 equations were designed for the circuit shown in Figure 2b.

The determination of the power losses, that cause the heating of the motor, in different nodes are carried out on a base of T-type equivalent circuit of electromechanical and electromagnetic processes. The determination of main principles and equations of power losses are described in detail in [1,17]. It should be stressed, that, for more accuracy, the saturation, replacing of the rotor current and nonlinear dependence of power losses in the stator yoke from the stator current frequency are taken into account.

Finally, equations of the circuit (Figure 2b) were written in the matrix form:

$$ \theta = G^{-1}P, $$

(2)

where $\theta$ - matrix of 53 nodes temperature, $G$ - matrix of heat conductivity between nodes (in inverse proportion to thermal resistance), $P$ - matrix of power losses. The matrix of $G$ has the dimension of 53x53, matrixes of $\theta$ and $P$ have the dimensions of 53x1.

4. Results of theoretical investigation

The implementation of the developed model of thermal processes was carried out for the 14 kW induction motor of AO-63-4. The analysis of obtained results allows one to draw a conclusion that the most heated nodes of the motor are windings of the stator and rotor on the average cross section. The value of temperature of the stator winding is on average 5 °C higher than the rotor winding temperature along the full length of the motor. The least heated node of the motor is the motor frame. The temperature distribution over the length of the stator and rotor windings is shown in Figure 3. The zero reference corresponds to the end part of the stator winding on the side of cooling air supply.
Figure 3. Temperature distribution in the stator winding (circles) and the rotor winding (rectangles) over the length of windings at the stator current $I_s = 0.7 I_{s,rat}$ (a), $I_s = 0.85 I_{s,rat}$ (b) and $I_s = 1.0 I_{s,rat}$ (c).

Results show that both stator and rotor windings are stressed by the highest value of temperature by about 2/3 of its length from the cooling air supply. Also, it could be concluded that the higher the stator current, the greater the difference between temperatures of the stator and rotor windings (maximum difference reaches 12 °C).

5. Results of experimental investigation

To verify data obtained by mathematical investigation, the experimental setup was developed and constructed. There is detailed information of this setup in [6]. Briefly, the main features of this setup in [6]. Briefly, the main features are summarized as follow. The investigated motor (physical model of the traction induction motor) is 14 kW AO-63-4 supplied from the frequency converter with $V/s = const$, where $V_s$ is the stator voltage and $f_s$ is the stator current frequency. There are current and voltage sensors for the stator winding, an incremental encoder for the rotor shaft speed measurement. Distribution of temperature in the stator winding, the rotor and the frame of the induction motor are measured by 1.5 mm chromel-copel thermocouples. Thermocouples are installed in the stator in three cross sections – on the end parts of the stator winding of both sides and in the stator iron at a distance of 45 mm from the surface (3 thermocouples in each section shifted by 120°). Thermocouples are installed in the rotor squirrel-cage rings and in the rotor iron at a distance of 40 mm from the surface.

Results obtained in the experimental setup prove the adequacy of the developed circuit. The maximum difference between temperatures determined by experimental and theoretical investigations at the respective nodes does not exceed 4°C. Results of thermovision shooting of the induction motor in the steady state captured by means of the portable Testo 875i thermal imager with temperature sensitivity 50 mK at 30 °C are given in Figure 4. These results confirm the conclusions made in the previous section about temperature distribution between different units of the induction motor.
Figure 4. Results of thermovision shooting: images of the induction motor (a, d), thermograms of the induction motor at the stator current $I_s = 15$ A, stator current frequency $f_s = 10$ Hz, the speed of the rotor shaft $n = 272$ rpm without forced cooling (b, e) and with forced cooling of 0.95 m$^3$/s (c, f).

6. Conclusion
The investigation carried out presents temperature distribution of the induction motor in the steady state. The induction motor is supplied by the frequency converter with the scalar control system of $V_s/f_s =$ const. The equivalent thermal circuit is developed for the theoretical investigation; the laboratory setup is constructed for the experimental one. The equivalent circuit allows one to calculate temperature of the 53 different nodes located over the whole volume of the induction motor, the laboratory setup allows one to measure the temperature of 13 nodes located in the frame, stator and rotor windings. Results of both investigations have a good convergence, the difference between them does not exceed 4°C. Results of investigation show that the most heated unit of the motor is the stator winding, the next unit is the rotor winding, the least heated unit is the frame. It is also established that both stator and rotor windings are stressed by the highest value of temperature by about 2/3 of its length from the cooling air supply. This conclusion leads to recommendation of choosing the slot part of the stator winding as the spot of temperature sensor installation for the development of the automatic temperature control system and another system of thermal protection of induction motors.

References
[1] Kosmodamianskiy A S, Klyachko L M, Vorobiev V I and Pugachev A A 2014 Russian Electrical Engineering 85(8) 513 – 518
[2] Rothe R, Hameyer K 2011 IEEE International Electric Machines & Drives Conference 1 1328 – 1331
[3] Champenois G, Roye D, Zhu D S 1994 Electric Machines & Power Systems 22(3) 355 – 369.
[4] Pradhan M K, Ramu T S 2005 IEEE Transactions on Power Delivery 20(3) 1962 - 1969
[5] Kosmodamianskiy A S, Vorobiev V I and Pugachev A A 2015 Russian Electrical Engineering 89(9) 527 – 533
[6] Pugachev A, Kosmodamianskiy A 2015 International Conference on Mechanical Engineering, Automation and Control Systems (MEACS) 1
[7] Mellor P H 1991 IEE Proceedings B - Electric Power Applications 138 205 - 218
[8] Huai Y, Melnik R, Thogersen P 2003 Applied Thermal Engineering 23 779 - 795
[9] Beguenane R, Benbourid M 1999 IEEE Transactions on Energy Conversion 14(3) 566 - 570
[10] Guidi G, Umida H 2000 IEEE Transactions on Industry Applications 36(6) 1619 - 1627
[11] Popov N, Vukosavic S V, Levi E 2014 IEEE Transactions on Energy Conversion 29(1) 215 - 223
[12] Zhang P, Lu B, Habetler T 2009 Pulp and Paper Industry Technical Conference 1 11 - 19
[13] Matic P R, Gecic M A, Lekic D M, Marcetic D P 2015 IEEE Transactions on Industrial Electronics 62(4) 2082 - 2089
[14] Briz F, Degner W, Guerrero J M, Diez A B 2008 IEEE Transactions on Industry Applications 44(3) 799 - 808
[15] Cho K R, Seok J K 2009 IEEE Transactions on Industry Applications 45(4) 1267 - 1275
[16] Siegel R, Howell J R 2001 Thermal Radiation Heat Transfer (CRC Press, USA)
[17] Lim S, Nam K 2004 IEE Proceedings - Electric Power Applications 151(4) 386 - 397