HEATING OF LOW - POWER INDUCTION MOTOR UNDER NO-LOAD MODE AND DIFFERENT COOLING CONDITIONS

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Abstract
The paper discusses heat transfer and the step response of a low-power induction motor to no-load mode under fan cooled and naturally cooled conditions. In Latvia University of Agriculture (LUA) in the electric drive laboratory the experimental tests were performed on a 1.1 kW totally enclosed fan cooled three phase induction motor with a fan mounted on a shaft for fan cooled conditions and with a fan taken off for naturally cooled conditions. The transient temperatures are measured in nine points of the stator end windings and in two points of the stator frame using thermocouples. Temperature is measured by using K type thermocouples and Pico-Log TC – 08 data logger. The current and voltage are measured by using Simple Logger II L562 two channel data logger. Measurement data are processed and archived using data loggers Pico-Log Recorder, Simple Logger II and Data View software. The experimental test results show that ventilation plays an essential role in the heating process of small power induction motors. Mathematical and virtual models of induction motor windings heating are represented to simulate the heating process of induction motor under no-load mode and different cooling conditions.
Key words: induction motor, no-load mode, heat dissipation, cooling conditions, modeling.

Introduction

Approximately 90% of the electric motors used in industry and homes are either three-phase induction motors or single-phase induction motors. Three-phase induction motors (IM) are used as drive motors in pumps, lifts, cranes, hoists, lifts, compressors, fans, driving lathe machines, crushers, mills, conveyors, etc. IM have high reliability and simple construction, but annual motor failure rate is conservatively estimated at 3-5% per year, and in extreme cases, up to 12% (Venkataraman et al., 2005). IM failures cause essential direct and technological losses, involving motor change and repair, as well as interruption of the production process.

IM failures may be classified as follows: 1) electrically related failures ~35%; 2) mechanically related failures ~ 31%; 3) environmental impact and failures related to other reasons ~ 34% (Venkataraman et al., 2005; Boldea and Nasar, 2010). Statistics of IM failure reasons show that many of them are caused by the overheating of the different parts involved in IM operation. The most sensitive part of IM to thermal overloads is the stator windings. The main limiting factor of an IM, is the stator windings temperature. Exceeding the temperature limit, results in acceleration of the oxidation process in insulation materials that eventually leads to IM being damaged. Because of this, an adequate protection system and accurate monitoring of IMs is very important to prevent thermal overloads.

Detailed description of experimental and analytical research methods and results of the transient heating of IM parts and thermal modelling is given in literature (Kylander, 1995; Zhang, 2010; Sniders and Gedzurs, 2012). The experimental investigations are performed on low-power totally enclosed fan cooled (TEFC) induction motor under stall, no-load, rated and overload conditions. The heating process of the IM is researched with different loads. The ambient temperature and cooling conditions are constant during all tests. Investigations of induction motors, protection systems and operation conditions have been performed in grain elevators. Investigations show that part of IM operates in enclosed dusty places (Gedzurs, 2013). Induction motor casings are covered by a layer of the dust, which decreases or blocks air flow from the cooling fan. That causes overheating of the IM parts due to lower heat transfer, even at loads lower than rated.

The objective of the study is to get experimental characteristics and thermal parameters during the heating process of the IM stator windings and frame under no-load fan cooled and naturally cooled conditions.

Materials and Methods

The heating process research was performed on a three phase induction motor: 4AX80A4Y3; 220/380 V; 4.9/2.8A; IP44; insulation class - B, m = 14.5 kg; P = 1.1 kW; n = 1400 min^{-1}; s = 0.67; η = 0.75; $\cos\varphi$ = 0.81. Tests were performed in LUA in the electric drive laboratory. The block diagram of the experimental setup for conducting tests is shown in Figure 1. The test bench was fitted with laboratory measuring equipment – voltmeters (V), ammeters (A) and wattmeters (W) for monitoring of the three phase current, voltage and power. For temperature measuring of IM stator frame (casing) and windings, eleven miniature K-type thermocouples BK-50 (air probe – SE000) were installed. All thermocouples were connected to a data logger Pico-Log TC-08 with built in cold junction compensation (the accuracy of

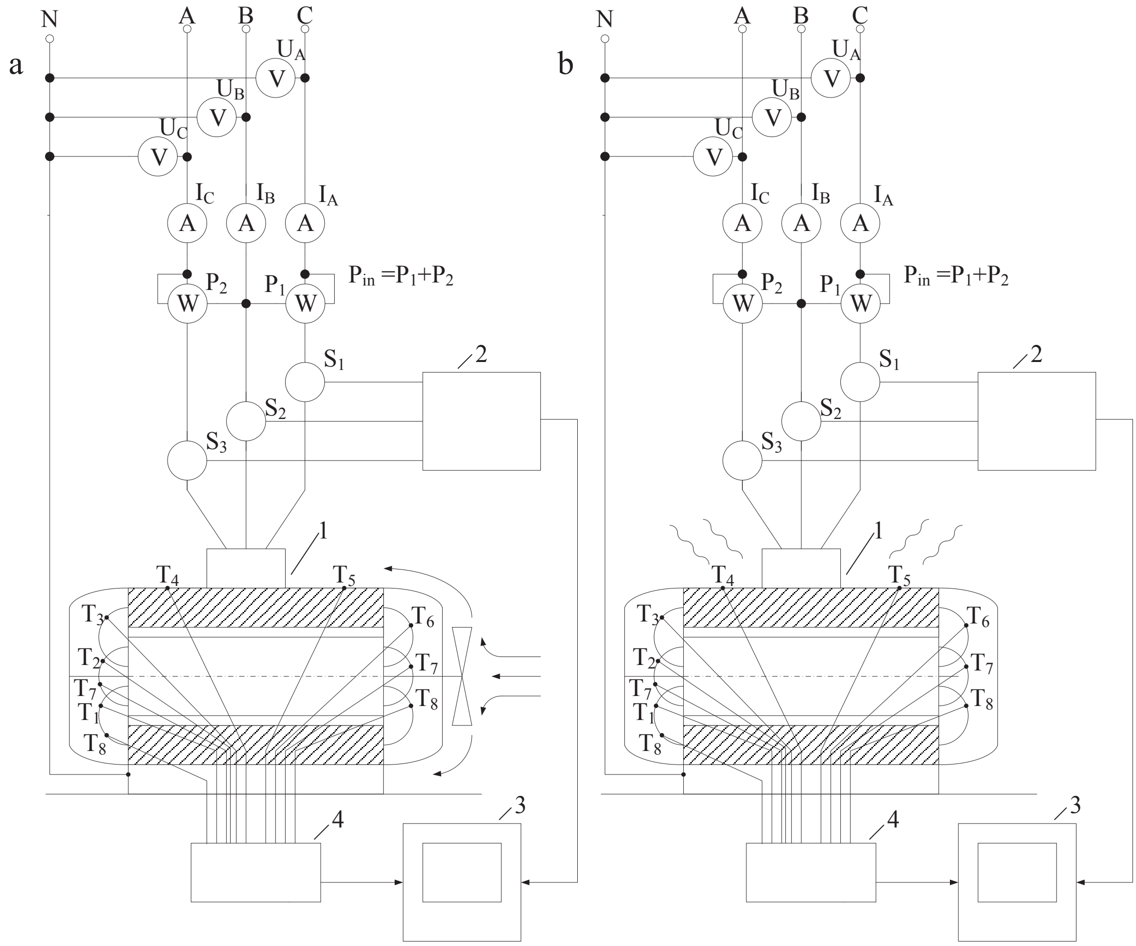

Figure 1. Experimental setup for induction motor heating process research:
a - setup for fan cooling conditions; b - for naturally cooling conditions; 1 - Induction motor;
2 - Simple Logger II data logger; 3 - Computer; 4 - TC - 08 data logger; S_1 - current sensor;
S_2,S_3 - voltage leads; T_1 ... T_{11} - thermocouples; A - ammeter; V - voltmeter; P - wattmeter;
I - electric current; U - voltage; P - power.

temperature reading – ± 0.2% of temperature value ± 0.5 °C). The stator frame surface temperatures were measured in two points with thermocouples T_7 and T_8. They were mounted at the frame shaft side and fan side. The stator winding temperatures are measured for each phase (A, B, C) by nine thermocouples attached to the end windings. Six thermocouples (T_1, T_2, T_3, T_4, T_5, T_6) were placed at the shaft (drive) side end windings, other three thermocouples (T_9, T_{10}, T_{11}) - in the end windings at the fan side. The temperature of shaft side end windings was measured in 2 areas – near frame (T_1, T_2) and near rotor (T_3, T_4, T_5, T_6). The thermocouples were inserted into natural gaps in the end windings and bonded by thermal bandage. For measuring of IM stator current and voltage – the current sensor (current clamps 3XTA011AC), voltage leads and data logger Simple Logger II L562 (accuracy – current ± 0.5% of reading + 1 mV, voltage – ± 0.5% of reading +1 V) were used.

All heating tests were performed under cold initial conditions – the initial temperature of IM parts was equal to ambient temperature ($\theta_0 = \theta_a$). The input voltage and frequency were uniform with rated values (400V, 50 Hz) in all phases. The tests of the windings and frame transient temperatures were performed for two conditions of IM operation: 1) no-load with the fan on the shaft (fan cooled); 2) no-load without the fan (naturally cooled). Nonlinear regression method was used for the mathematical and statistical analysis of the data. To simulate the heating process of the IM windings MATLAB SIMULINK software was used.

Results and Discussion

Experimental test results of the IM thermal response to no-load and fan cooled conditions are shown in Figure 2. The initial temperature of the IM parts is equal to the ambient temperature $\theta_o = \theta_a$ = 24 °C. The temperature of IM parts reaches steady-state value 50 minutes after the start of the test. The steady-state temperature of the shaft side end windings is 65 °C. The fan side end winding temperature is lower by 3 °C. The steady-state temperature of the shaft side stator frame temperature is 42 °C, 5 °C higher than the fan side stator frame temperature. The difference between the fan side and shaft side temperatures of the IM parts is due to different convection heat transfer and shows the efficiency of ventilation.

Figure 3 shows the results of the IM thermal response to no-load and naturally cooling conditions. The insulation class B allows continuous overheating of windings until θ_{max} = 120 °C. The test should be stopped when the temperature of windings reaches 120 °C. Switch-off point temperature of the shaft side end windings is 120 °C – frame side and 117 °C – rotor side. The lower temperature of the rotor side is caused by the ventilation effect of the rotor blades. A nonlinear regression equation (1) is used for the experimental data approximation. The standard error S of regression value for IM end winding heating under fan cooled conditions is S = ± 0.73 °C and for naturally cooled conditions S = ± 1.24 °C.

$$\theta(t) = \theta_{max} - \Delta\theta_{max} \cdot e^{-\frac{t}{T}} = (\Delta\theta_{max} + \theta_o) - \\ - \Delta\theta_{max} \cdot e^{-\frac{t}{T}} = \Delta\theta_{max} \cdot (1 - e^{-\frac{t}{T}}) + \theta_o, \quad (1)$$

where θ – temperature of IM part, °C;
θ_o – ambient temperature, °C;
θ_{max} – steady-state temperature of IM part, °C;
$\Delta\theta_{max} = \theta_{max} - \theta_o$ – maximum temperature raise, °C;
T –thermal time constant, min;
t - time, min.

The measured active power and current under no-load and fan cooled conditions is P_1 = 150 W; I_1 = 2.25 A, during no-load and naturally cooled – P_2 = 145 W; I_2 = 2.2 A. The measured active resistance of winding at 25 °C is R = 7.2 Ω. At no-load all active power converts to losses. No-load losses consist of electrical losses in the stator and rotor, magnetic losses and mechanical losses. No-load electrical losses in the rotor are small and can be neglected. Therefore, heating of windings is produced by electrical loses in the stator windings P_1 and can be calculated knowing the stator current and active resistance.

For simulation of IM stator winding heating under continuous no-load operation mode for fan -cooled and for natural convection cooling conditions, the mathematical model of transient heating is compiled. Non-stationary heating may be described by differential equation (2):

$$P_1 = C \cdot \frac{d\Delta\theta}{dt} + H \cdot \Delta\theta \quad (2)$$

where P_1 – electrical losses in stator windings, W;
$\Delta\theta = \theta - \theta_o$ - temperature raise, °C;
C – thermal capacity, J·°C^{-1};
H – heat dissipation, W·°C^{-1}.

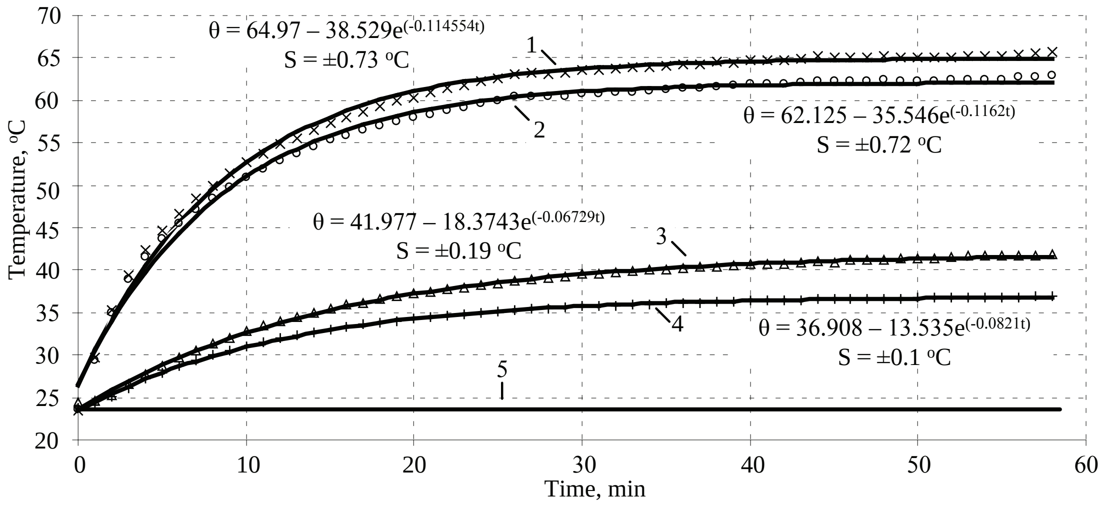

Figure 2. Response of induction motor parts temperature under no-load and fan cooled conditions:
1 - temperature of stator end windings - shaft side; 2 - temperature of stator end windings - fan side;
3 - temperature of stator frame - shaft side; 4 - temperature of stator frame - fan side;
5 - ambient temperature.

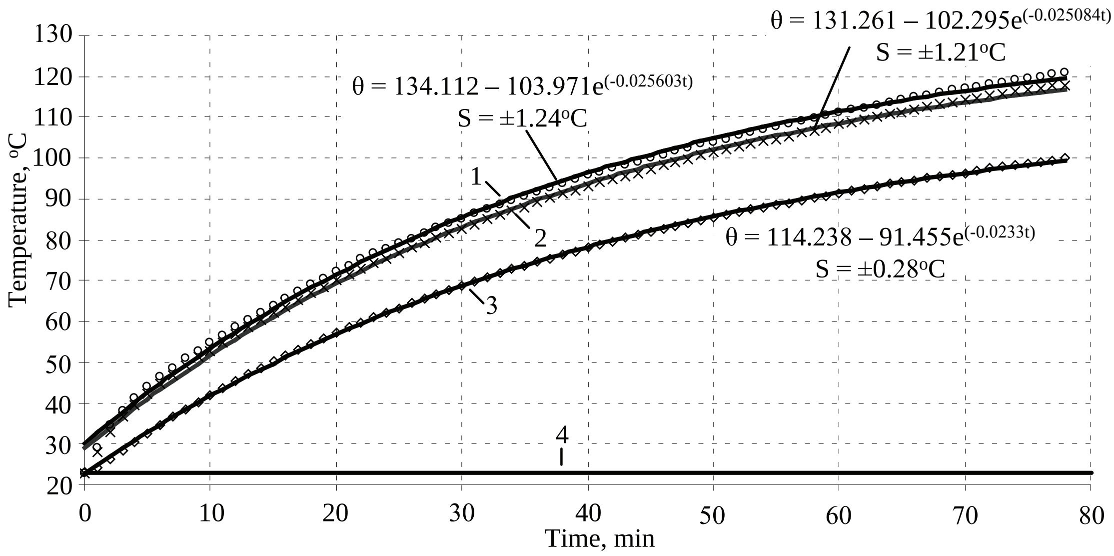

Figure 3. Response of induction motor parts temperature under no-load and naturally cooled conditions: 1 - temperature of stator end windings; 2 - temperature of stator end windings - inner side; 3 - temperature of stator frame; 4 - ambient temperature.

After modification of equation to (2), the differential equation in normal form has been obtained:

$$T\frac{d\Delta\theta}{dt} + \Delta\theta = K \cdot P_1, \quad (3)$$

where $T = C{\cdot}H^{-1}$ – IM thermal time constant, min;
$K = 1{\cdot}H^{-1}$ – IM sensitivity coefficient, °C·W^{-1}.

By solving differential equation (3), the heating process of stator windings can be described by exponential function (4):

$$\Delta\theta(t) = \Delta\theta_{max}(1 - e^{-\frac{t}{T}}) = K \cdot P_1(1 - e^{-\frac{t}{T}}), \quad (4)$$

Using Laplace transforms to differential equation (4), an operational equation and transfer function is compiled for simulation in MATLAB SIMULINK:

$$T \cdot \Delta\theta(s) \cdot s + \Delta\theta(s) = K \cdot P_1(s), \quad (5)$$

where s – Laplace variable, min^{-1}.
Δθ (s) – Laplace transform of temperature raise, °C;
$P_1(s)$ – electrical losses in stator windings, W;

$$W(s) = \frac{\Delta\theta(s)}{P_1(s)} = \frac{K}{T \cdot s + 1}, \quad (6)$$

Thermal capacity C, losses in windings P_1, heat dissipation and sensitivity coefficient K can be calculated for each of IM operation conditions using experimental tests results:

$$K_1 = \frac{\Delta\theta_{1max}}{P_{11}} = \frac{38.5}{108} = 0.35\ ^{o}C \cdot W^{-1};$$

$$H_1 = \frac{1}{K_1} = \frac{1}{0.35} = 2.8W \cdot {}^{o}C^{-1};$$

$$C = T_1 \cdot H_1 = 8.73 \cdot 60 \cdot 2.8 = 1469J \cdot {}^{o}C^{-1}; H_2 = \frac{C}{T_2} = \frac{1469}{39.06 \cdot 60} = 0.627W \cdot {}^{o}C^{-1}$$

$$P_{11} = 3 \cdot I^2 \cdot R = 3 \cdot 2.25^2 \cdot 7.2 = 108W;$$

$$P_{12} = 3 \cdot I^2 \cdot R = 3 \cdot 2.2^2 \cdot 7.2 = 103W$$

Using equation (6) and calculated thermal parameters of stator winding a virtual model in MATLAB SIMULINK has been developed (Figure 4). The following functional blocks are used: '$P_{1\ step}$'- step signal power losses generator; 'P_1', '$\Delta\theta_{max}$', 'C', 'H' – constant signal generator blocks for coefficient K and thermal time constant T calculation. Digital displays are used to visualize the input and output values: - P_1 – electrical losses, W; T – thermal time constant, min; θ – stator end windings steady-state temperature, °C. 'Scope' for visualization of stator winding temperature transient heating process - θ = f(t). Simulation results of the shaft side end winding heating process under no-load fan cooled and naturally cooled conditions are shown in Figure 5.

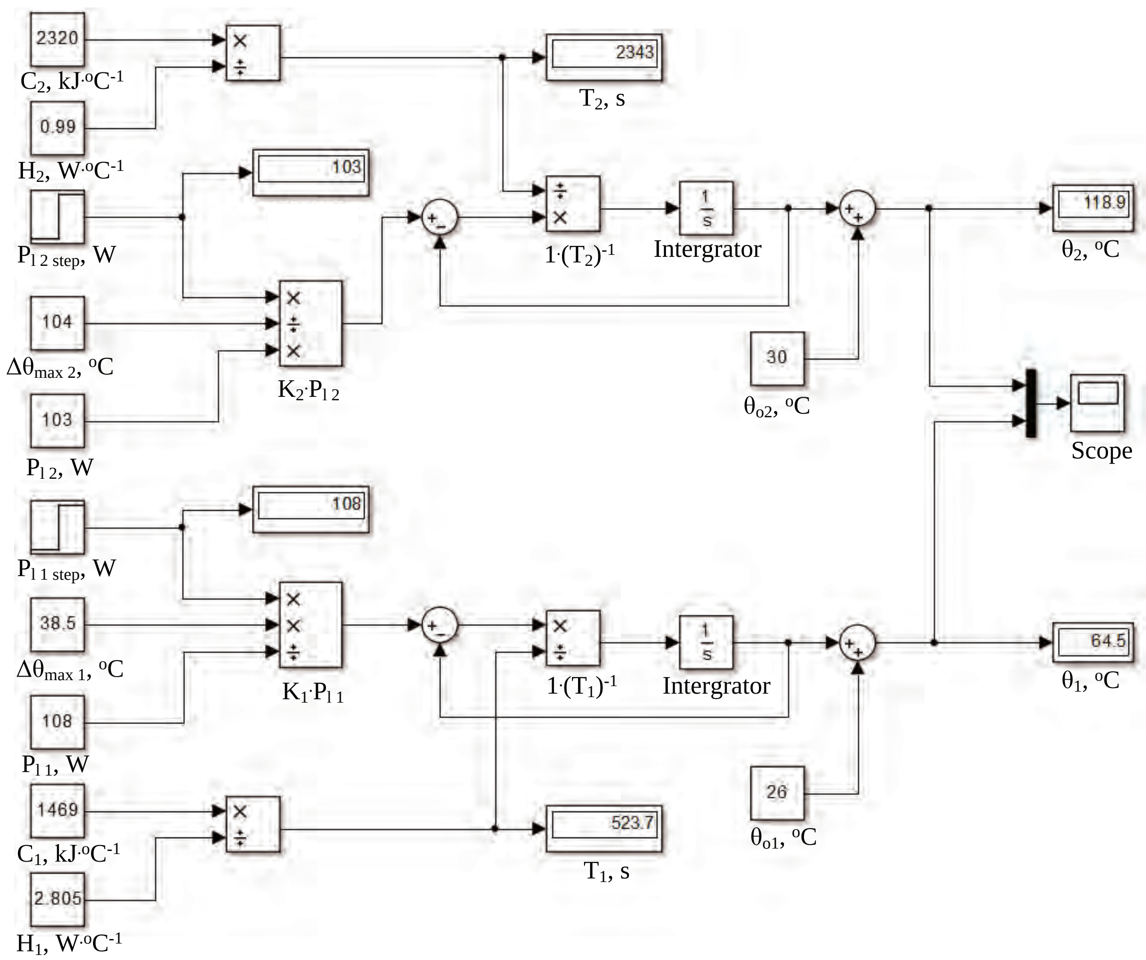

Figure 4. Simulation block diagram of heating process of IM end windings.

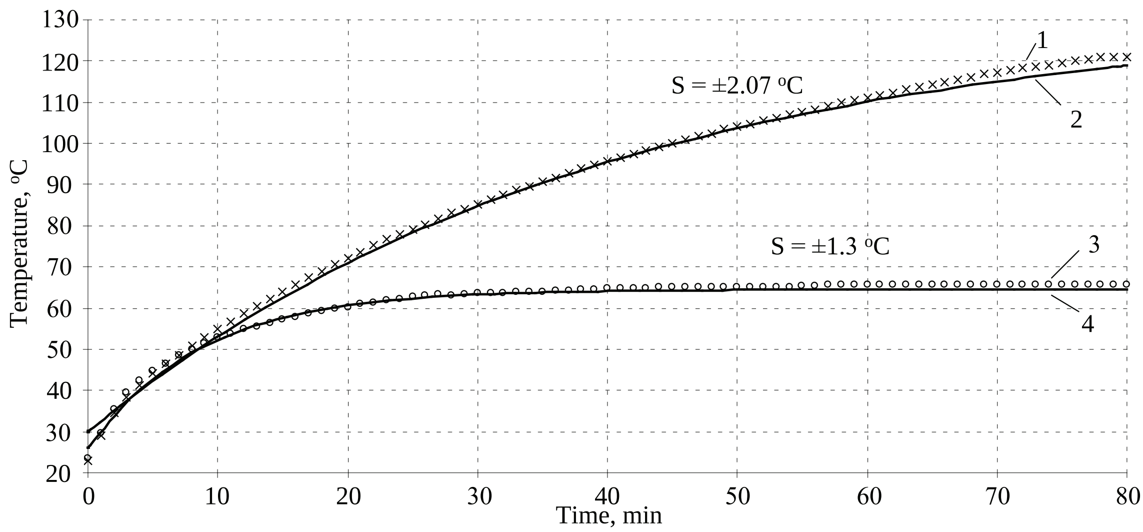

Figure 5. Simulation results of heating process of IM shaft side end windings under no-load fan cooled conditions: 1 – heating process test results under no-load naturally cooled conditions; 2 – heating process simulation results under no-load naturally cooled conditions; 3 – heating process test results under no-load fan cooled conditions; 4 – heating process simulation results under no-load fan cooled conditions.

The standard error for simulations results of no-load fan cooling conditions is S = ± 1.3 °C and under no-load naturally cooled conditions - S = ± 2.07 °C. Simulation of no-load naturally cooled conditions show that the steady-state temperature reaches 132 °C in 240 min. The results show that the virtual model is adequate and can be used to simulate the heating process and get thermal parameters under conditions that cannot be achieved experimentally due to safety reasons.

Conclusions

1. The results of the experimental tests that under no-load fan cooled conditions the stator end winding maximum temperature is θ_{max} = 65 °C, but under no-load naturally cooled conditions the winding temperature reaches the limit value of 120 °C for thermal class B in 78 min. Therefore, forced ventilation plays an essential role in the induction motor cooling process.
2. During the heating process under naturally cooled stator the current decreases by 6% and overload protection relays will not trip if the induction motor windings are overheating. Therefore, a protection device that monitors temperature of the windings directly has to be used to ensure adequate protection of IM in places under variable cooling and environment conditions.
3. The experimental data and simulation results show that windings heating process may be represented as the first order inertial model described by differential equation with constant thermal parameters for each operation conditions. Simulation results show, that the standard error under no-load fan cooled conditions is S = ± 1.3 °C and under naturally cooled conditions S = ± 2.07 °C, that testifies simulation adequacy to experimental data.
4. Simulation results under no-load naturally cooled conditions show that the steady-state temperature of the end windings is θ_{max} = 132 °C, which cannot be achieved experimentally due to safety reasons. It proves that a virtual model can be used to increase the range of investigation of IM heating under operations conditions that cannot be done experimentally.

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