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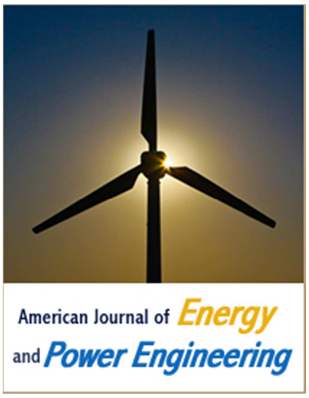

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Experimental Research and Simulation of Induction Motor Stator Winding Non-Stationary Heating

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Abstract
The paper discusses the transient heating process and the response of a small-powered induction motor to a permanent constant rated load and single-phasing mode with stalled rotor all under a standard electrical supply system (400 V, 50 Hz) for cold and warm initial conditions and a constant ambient temperature. Experimental investigations were performed on a 1.1 kW totally enclosed, fan-cooled three-phase induction motor ABB M2AA90S-4. The transient temperatures are measured at 9 separate points on the stator windings and in 2 points of the motor casing using thermocouples and loggers for data processing and archiving. The test results show that heating of induction motor stator windings is a non-stationary process with variable temperature rise time and sensitivity factors. For stator winding non-stationary heating simulation an adaptive self-tuning model with open access transfer function module and modules of temperature dependent winding resistance R, heat dissipation H and heat capacity C calculation are composed in MATLAB-SIMULINK. The variable temperature rise time and sensitivity factors are calculated using experimental data. Simulation results demonstrate adequacy of developed model to experimental data. Analyses show that the maximum difference of simulation and experimental results is ±2 °C.

1. Introduction

Despite induction motors (IM) high reliability and simplicity of construction, annual motor failure rate is conservatively estimated at 3-5% per year, and in extreme cases, up to 12% [1]. 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) electrical related failures ~ 35%; 2) mechanical related failures ~ 31%; 3) environmental impact and other reasons related failures ~ 33% [1]. Analysis of IM failure reasons show that many of them are caused by prolonged heating of the different parts involved in IM operation. Also the use of soft starters and frequency drives increase the heating of IM parts due to higher harmonics [2, 3]. The most sensitive part of an IM to thermal overloads are the stator windings and the end windings especially are the hottest points of the motor [4]. Therefore, it is very important to predict the thermal condition of the induction motor and to develop a desirable accurate and flexible thermal model of IM operation under prolonged overload.

A detailed description of experimental and analytical research methods and results of the transient heating of IM parts and thermal modeling are given in [4,5,6,7]. But the thermal models that are mainly used in the IM design process require complex calculations and parameters of induction motors that are hard to obtain. A simpler model can be used, often referred to as a thermal network model [5]. Commonly for the heating process of IM stator windings the first-order thermal model with constant parameters [8] or two level variable parameters, different for initial and for final periods can be used [1]. There are also other simplified approaches to obtain a heating model of IM parts [9]. However, the thermal and electrical parameters of IMs vary continuously during the transient heating process of IM parts.

Main tasks of this work is to get experimental characteristics and thermal parameters of IM to develop an adaptive self-tuning heating model for IM stator winding heating simulation in MATLAB-SIMULINK.

2. Test Bench Set-Up

Thermal research object is three phase induction motor: ABB M2AA90S-4; 220-240/380-420 V; 4.6/2.66A; IP55; insulation class - F, m = 13 kg; P = 1.1kW; n = 1410min^{-1}; s = 0.06; efficiency class - IE1 η = 75%; cosφ = 0.81. Measured stator circuit parameters - resistance R_s = 6.9 Ω, reactance X_s = 18.7 Ω and calculated impedance Z_s = 20 Ω at ambient temperature θ_a = 24 °C. Direct current electric generator (P-22Y4, 220V, 5.9A, P=1kW, n=1500min^{-1}) and lamps rheostat for IM loading is used. The block diagram of the test bench set-up for experimental tests is shown in Figure 1. The test bench is fitted with the adequate laboratory measuring equipment – voltmeters (V), ammeters (A) and watt meters (W) for monitoring of three phase current, voltage and power. For precise measuring of IM stator casing (frame) and windings temperature 12 K-type thermocouples BK-50 (air probe – SE000) are used. All thermocouples are connected to a data logger Pico-Log TC-08 with built in cold junction compensation (accuracy of temperature reading – ±0.2% of temperature value ±0.5 °C). The IM case temperatures are measured at two points - inside the terminal box and between the ribs of the motor case. The stator winding temperatures are measured in the slot and end winding at the shaft (drive) and fan sides. For measuring of the 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) are used. Heating tests are performed under rated load for cold initial conditions – meaning all parts of the IM are at ambient temperature (θ_o = θ_a), overloads and IM stalling under single-phasing is performed for warm conditions – meaning the initial temperature of IM is equal to steady state temperature of IM parts under rated load. Supply voltage and frequency are traditional and uniform with rated values (400V, 50Hz). IM load is determined by coefficient in relation to stator current – $k_i = I_s/I_r$, where I_s – actual stator current, A; I_r – rated stator current, A.

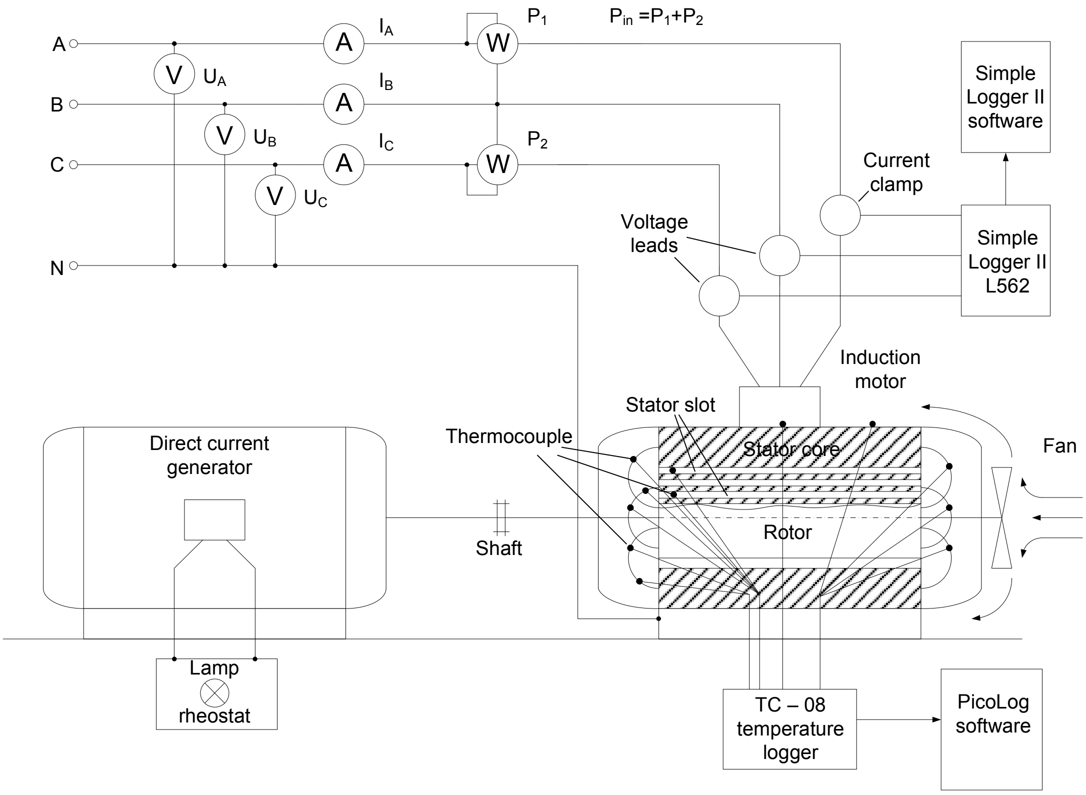

Fig. 1. Test bench set-up for induction motor heating experimental research.

3. Experimental Research Results

Figure 2 shows thermal response of the IM parts to a permanent rated load. Initial temperature of the IM parts equal to ambient temperature $\theta_o = \theta_a = 24$ °C Stator current I = 2.46 A, $k_i = I_s \cdot I_r^{-1} = 2.46 \cdot 2.66^{-1} = 0.92$. The steady-state temperature of the shaft side end winding is 70.5 °C, but the steady-state temperature of the stator slot winding is lower - 66.5 °C. This justifies the mounting place of the temperature sensors for the IM winding protection against overheating. Steady-state temperature of the IM case inside the terminal is 13 °C higher than the outside terminal box due to difference ventilation efficiency.

Commonly a stationary heating process of an IM stator windings can be expressed with the following differential equation with a fixed average temperature rise time factor (time constant) and with fixed a average temperature rise sensitivity factor (transfer coefficient), calculated by using experimental data (Fig. 2):

$$T \cdot \frac{d\Delta\theta}{dt} + \Delta\theta = K \cdot P_l, \qquad (1)$$

where θ – temperature of stator windings, °C;

$\Delta\theta = \theta - \theta_o$ –temperature rise of stator windings, °C;

$P_l = I^2 \cdot R$ - single phase cooper losses in stator windings, W

I – stator current, A;

R – resistance of stator windings, Ω;

$K \approx 1.1$ °C·W^{-1} - average temperature rise sensitivity factor;

$T \approx 10$ min - average temperature rise time factor;

t – time, min.

Simulation results in MATLAB-SIMULINK, using stationary heating model (1) with fixed average K and T values (Fig. 2) show that the simulated heating process of the IM stator winding differs from the experimental results substantially. Therefore, heating of the IM stator winding is a non-stationary process with variable heating time T and sensitivity K factors as the functions of temperature rise ($T = f(\Delta\theta)$ and $K = f(\Delta\theta)$).

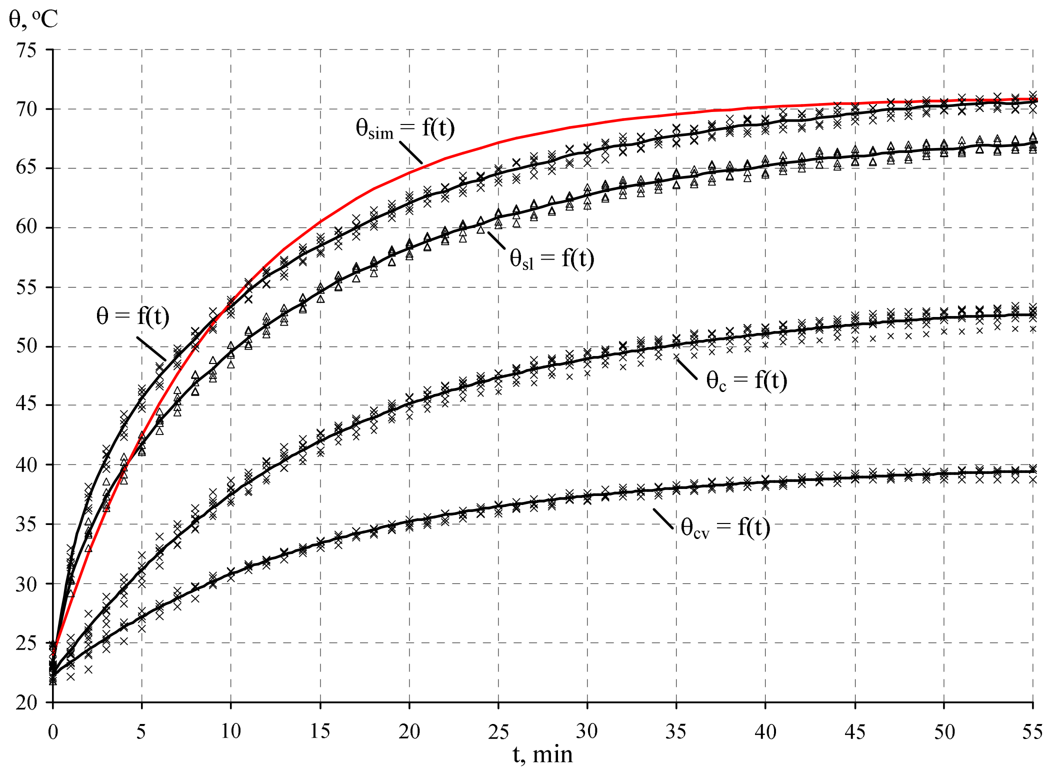

Fig. 2. *Heating of induction motor parts under permanent rated load and cold initial conditions: θ - temperature of stator end winding, °C; θ_{sim} -simulated temperature of stator end winding with constant K and T, °C; θ_{sl} - temperature of winding in stator slot, °C; θ_c - temperature of IM case inside terminal box, °C; θ_{cv} - temperature of IM case outside terminal box, °C.*

Figure 3 shows heating of the IM parts if one of the supply phases is cut off and the motor is stalled. The initial end winding temperature is $\theta_o = 70$ °C and after 30 seconds the temperature increases almost linearly to θ = 149 °C with rise speed $v_\theta \approx 2.6$ °C·s^{-1}. The temperature of the end winding of the disconnected (fault) phase during first 8 seconds practically stays invariable $\theta_{of} = 65$ °C and after that gradually increases to $\theta_f = 77$ °C. During the 30 seconds of the heating process the temperature of IM casing increases only by 1 °C. That testifies an adiabatic character of the stator windings heating process under rotor standstill. Stator current in each of two the operating phases is I = 10.4 A at θ = 70 °C and decreases to I = 9.1 A at θ = 149 °C. Knowing the temperature rise speed and copper losses the thermal capacity of the stator winding is calculated C ≈ 330 J·°C^{-1}.

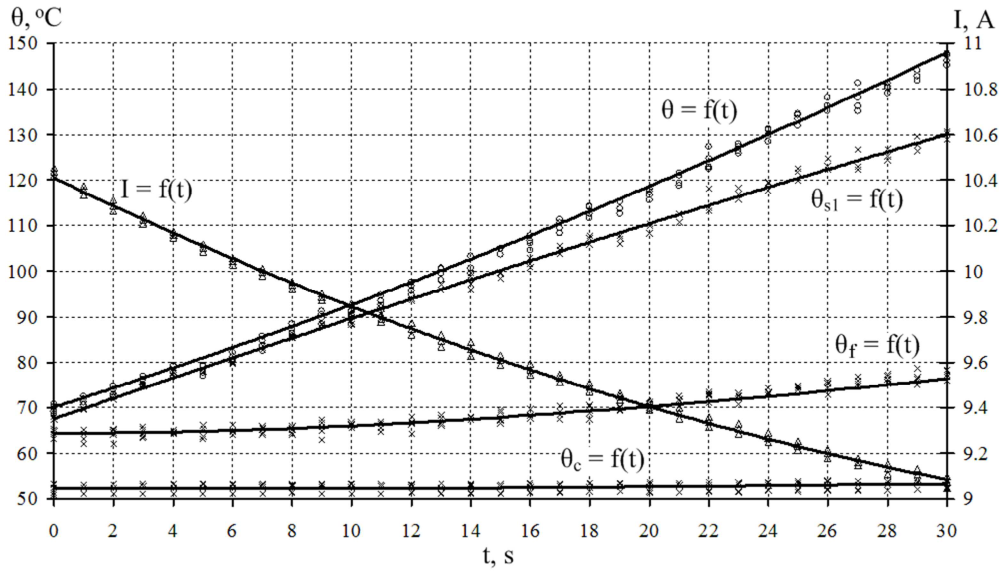

Fig. 3. *Heating of induction motor parts under single-phasing standstill and warm initial conditions: θ - temperature of stator end winding, °C; $θ_f$ - temperature of disconnected(fault) phase stator end winding, °C; $θ_{sl}$ - temperature of winding in stator slot, °C; $θ_c$ - temperature of IM case inside terminal box, °C.*

4. Non-Stationary Mathematical and Simulation Model of IM Stator Winding

Non-stationary differential equation of the IM stator winding heating:

$$T(\theta)\cdot\frac{d\Delta\theta}{dt}+\Delta\theta=K(\theta)\cdot P_l \tag{2}$$

where K(θ) = 1·H(θ)$^{-1}$ – temperature rise sensitivity factor, °C·W^{-1};

H(θ) – variable heat dissipation, W· °C^{-1};

T(θ) = C(θ)·H(θ)$^{-1}$ – temperature rise time factor, min;

C(θ) – variable heat capacity, J °C^{-1};

t – time, min.

Using Laplace transform to the differential equation (2), an operator equation (3) and a transfer function (4) for transient temperature simulation of the IM stator winding is obtained:

$$T(\theta)\cdot\Delta\theta(s)\cdot s+\Delta\theta(s)=K(\theta)\cdot P_l(s)\,, \tag{3}$$

where Δθ(s) – Laplace transform of temperature rise of stator winding , °C;

P_l (s) – Laplace transform of copper losses in stator winding, W;

s – Laplace variable, s^{-1}.

$$W(s)=\frac{\Delta\theta(s)}{P_l(s)}=\frac{K(\theta)}{T(\theta)\cdot s+1} \tag{4}$$

The heat dissipation H(θ) of the winding surface can be calculated by empirical formula [10]:

$$H(\theta)=H_o+a\cdot\Delta\theta+b\cdot\sqrt{\Delta\theta} \tag{5}$$

where H_o ≈ 0.78 W·°C^{-1} – initial heat dissipation at $θ_o$;

a ≈ 0.0015 W·°C^{-2} – empirical coefficient;

b ≈ 0.007 W·°C$^{-1.5}$ – empirical coefficient.

To calculate the stator winding resistance an analytical expression is used:

$$R=R_{\theta o}\cdot(1+\alpha\cdot\Delta\theta) \tag{6}$$

where $R_{θo}$ = 6.9 Ω – measured stator winding resistance at $θ_o$ = 24 °C;

α = 4.26·10^{-3} 1·°C^{-1} – resistance-temperature coefficient of cooper.

Using experimental data (Fig.2. and Fig.3.) an empirical expression is composed to calculate variable heat capacity:

$$C(\theta)=C_o+c\cdot\Delta\theta \tag{7}$$

where C_o ≈ 330 J·°C^{-1} – initial heat capacity equal to thermal capacity of IM stator winding;

c ≈ 15 J·°C^{-2} – empirical coefficient.

The block-diagram of the non-stationary model for the IM stator winding heating process simulation is compiled in MATLAB-SIMULINK (Fig.4.), according to mathematical algorithms (2-7). The simulation block-diagram consists of several self – tuning modules and links for heating parameters adaptation to the variable temperature of the IM stator winding according to expressions (5, 6 and 7): "H-tuning link", "R-tuning link" and "C-tuning link". The open access adaptive model of IM stator winding non-stationary heating ("P_l·K", "T^{-1}", "T", "1/s" and unit feedback) allows to import, calculated step by step, temperature dependent variable parameters all over simulation time, therefore the simulation results have been adapted to actual heating process. An input module "simin" is used for measurement data of the temperature dependent stator current transportation from MATLAB workplace to the simulation model. Using inputs from electrical current square function "u^2" and "R tuning link" the copper losses "P_l" are calculated. A steady-state temperature rise of the end winding $\Delta\theta_{max}$ is calculated by "$P_l \cdot K$" using inputs from "P_l" and "H tuning link". The temperature rise time factor T is calculated by "T" using input links from H(θ) and C(θ) calculation modules.

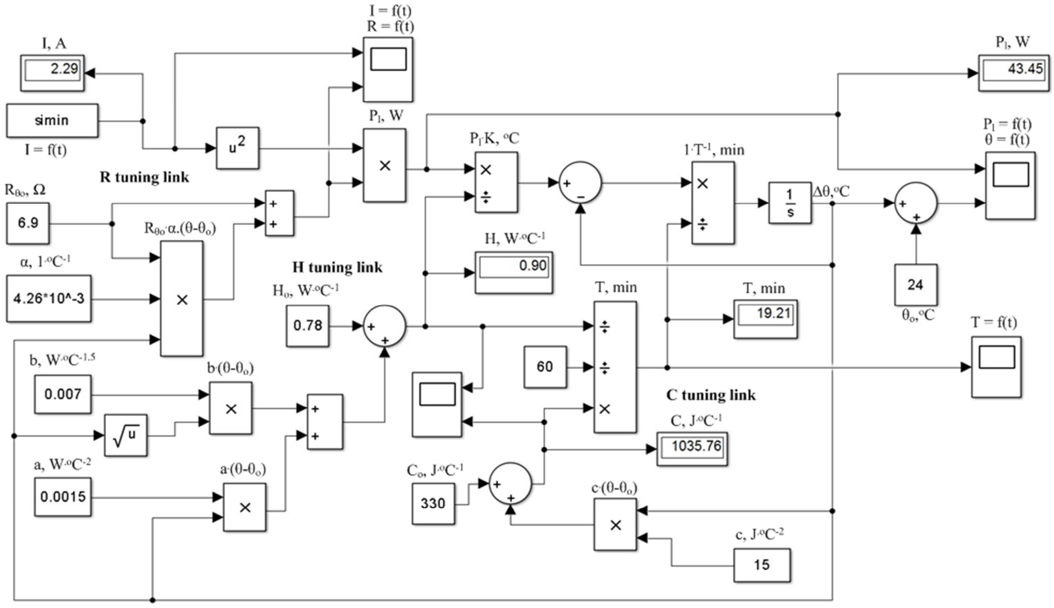

Fig. 4. Block diagram of the adaptive self - tuning simulation model of IM stator winding heating with temperature dependent resistance R, heat dissipation H and heat capacity C tuning links.

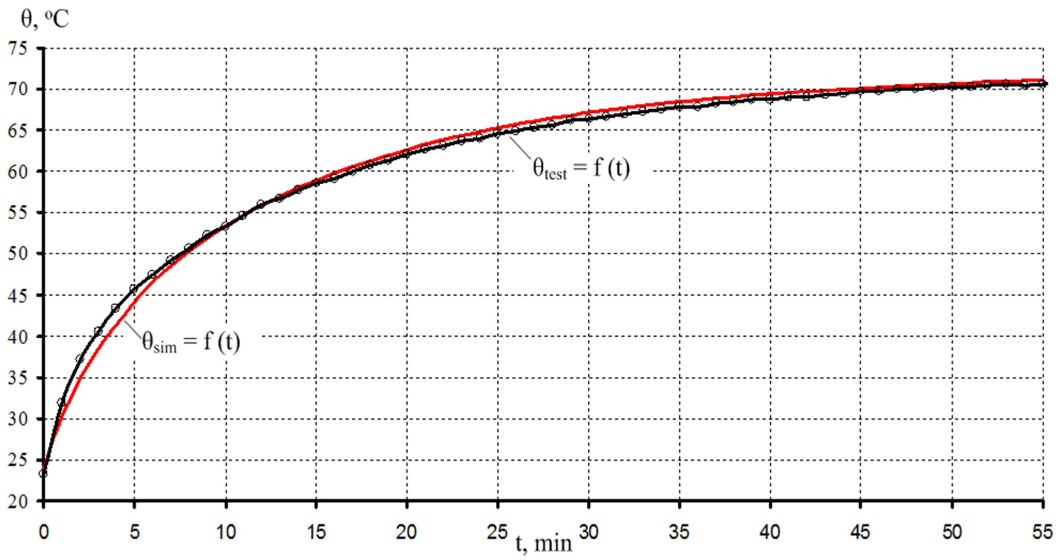

Fig. 5. Non-stationary heating temperature curves of IM stator end winding: θ_{test} - average temperature obtained from tests, °C; θ_{sim} -simulated temperature, °C.

5. Simulation Results of Non-Stationary Heating Process of IM Stator Winding

The simulation of non-stationary heating process of the IM stator end winding is carried out for rated operation condition using the experimental data. Comparison of simulated and experimental heating curves is shown in Figure 5. The maximum difference between simulation and experimental results is about 2 °C at the beginning of heating process and about 1 °C difference at the steady state of the heating process. It shows that the adaptive non-stationary heating model with variable temperature rise time T and sensitivity K factors as a functions of winding temperature rise can be used to simulate the non-stationary heating process of the stator end winding where temperature rise at maximum.

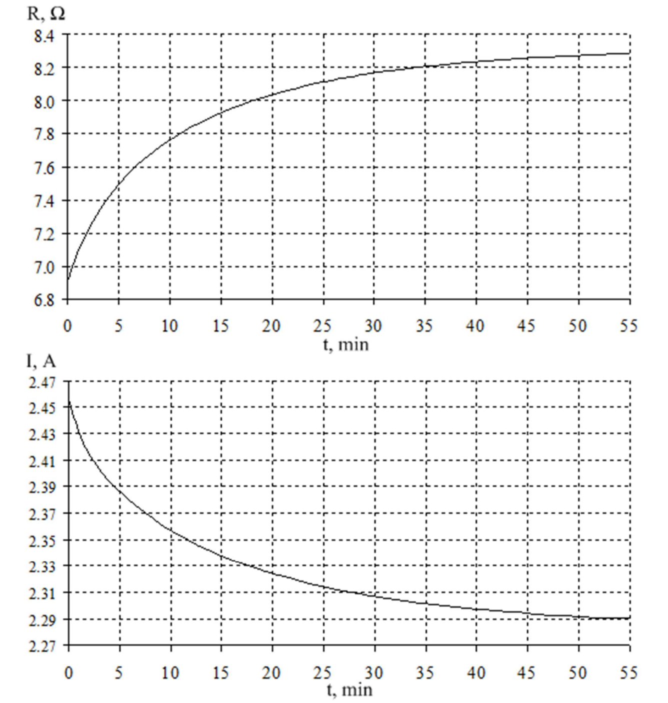

Fig. 6. *Simulated characteristics of stator winding resistance R and measured stator current I.*

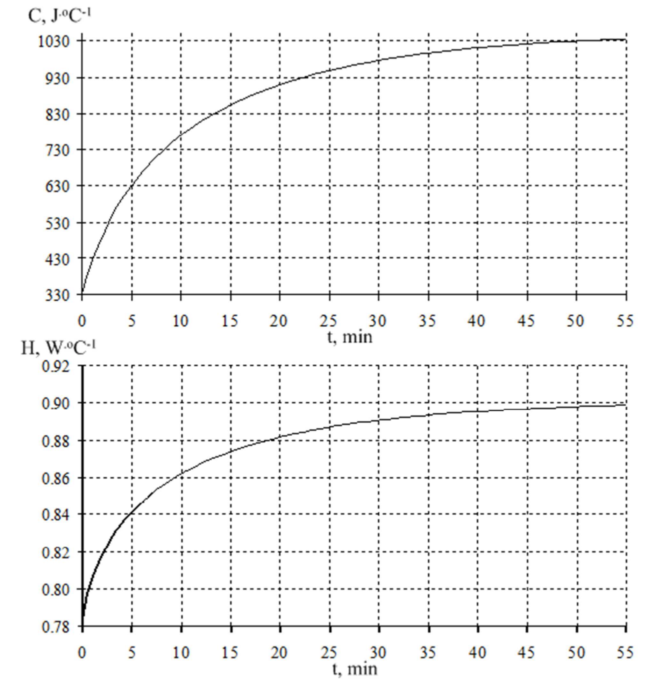

Fig. 7. *Simulated characteristics of heat capacity C(θ) and heat dissipation H(θ) .*

Figure 6 shows simulated characteristic of stator resistance - R = 6.9 Ω at θ_o = 24 °C and R = 8.3 Ω at θ = 71 °C. The stator current I = 2.46 A at θ_o = 24 °C is decreasing to I = 2.29 A at θ = 71 °C due to increase of the stator resistance. During the heating process heat dissipation is increasing and at steady state conditions it is 9% higher than at initial conditions (Fig. 7.) because of the bigger difference between the IM and ambient temperatures. The heat capacity increased 3 times because more thermal masses (stator core, IM case, etc) are involved during the whole heating process of the IM. Cooper losses per phase are higher by 9% at the steady state conditions and temperature rise time factor T(θ) change is mainly affected by the heat capacity of the IM.

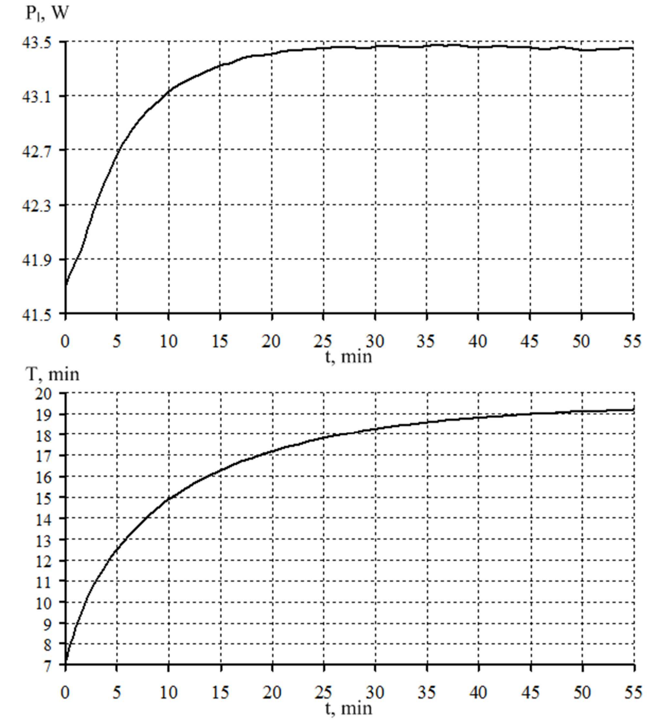

Fig. 8. *Simulated characteristics of copper losses P_l and temperature rise time factor T(θ).*

6. Conclusions

1. Experimental research of the IM stator winding heating shows that temperature of the end winding is higher than the temperature of the stator slot winding. Therefore, a temperature sensor should be embedded in the end winding if temperature protection is used. Using experimental data, the initial values of heat capacity C ≈ 330 J·°C $^{-1}$ and heat dissipation H_o ≈ 0.78 W·°C $^{-1}$ of the stator winding are calculated to develop a stationary heating model.
2. Simulation results using a stationary heating model of the IM stator winding in MATLAB-SIMULINK with the fixed average temperature rise time factor T ≈ 10 min and sensitivity factor K ≈ 1.1 °C·W^{-1} show an essential inadequacy of simulated and experimentally obtained transient temperatures (Fig.2.), this testifies, that heating of the IM stator winding is a non-stationary process.
3. To obtain a adequate resemblance of simulation results to experimental data the non-stationary mathematical model with temperature dependent coefficients and the appropriate simulation model in MATLAB-SIMULINK

have been made using an open access transfer function module and modules for variable stator winding resistance R, heat dissipation H and heat capacity C self – tuning, this allows it to recalculate the variable parameters step by step during all of the simulation time and adapt simulation results to actual heating processes of the IM stator winding.

4. Simulation results obtained by the non-stationary adaptive self- tuning heating model show adequate resemblance to experimental data (Fig.5.). The presented method can be used not only for the heating process simulation of induction motors, but can be applied to other objects of heat transfer.

References

[1] Venkataraman B., Godsey B., Premerlani W., Shulman E., Thakur M., Midence R. Fundamentals of a Motor Thermal Model and its Applications in Motor Protection. In: Proceedings of 58th Annual Conference "Protective Relay Engineers", Black & Veatch Corporation, Kansas City, USA, 2005, pp. 127-144.

[2] Mukhopadhyay S.C. Prediction of Thermal Condition of Cage-Rotor Induction Motors under Non – Standard Supply Systems. International Journal on Smart Sensing and Intelligent Systems, Vol.2, No. 3, 2009, pp. 381 – 395.

[3] Solveson M. G., Mirafzal B., Demerdash N. A. O. Soft-Started Induction Motor Modeling and Heating Issues for Different Starting Profiles Using a Flux Linkage ABC Frame of Reference. IEEE Transactions on Industry Applications, Vol. 42, No. 4, 2006, pp. 973- 983.

[4] Boglietti A., Cavagnino, A., Staton D.A., Popescu M., Cossar, C., McGilp M.I. End Space Heat Transfer Coefficient Determination for Different Induction Motor Enclosure Types. Industry Applications Society Annual Meeting, IEEE, 2008, pp. 1 - 8.

[5] Kylander G. Thermal Modelling of Small Cage Induction Motors: Technical Report No. 265, Goteborg, Sweden, Chalmers University of Technology, 1995.-113 p.

[6] Boglietti A., Cavagnino A. Analysis of the End winding Cooling Effects in TEFC Induction Motors. In: Industry Applications Conference, IEEE, volume 2, 2006, pp. 797 - 804.

[7] Staton D., Boglietti A., Cavagnino A. Solving the More Difficult Aspects of Electric Motor Thermal Analysis in Small and Medium Size Industrial Induction Motors. IEEE Transactions on Energy Conversion, volume 20, issue 3, 2005, pp. 620 - 628.

[8] Zocholl S.E., Benmouyal G. Using Thermal Limit Curves to Define Thermal Models of Induction Motors. Schweitzer Engineering Laboratories, Pennsylvania (USA), Quebec (Canada), Printed in USA, 2001.-14 p.

[9] Khaldi R., Benamrouche N., Bouheraoua M. Experimental Identification of the Equivalent Conductive Resistance of a Tthermal Elementary Model of an Induction Machine. American Journal of Electrical Power and Energy Systems, Vol. 3, No. 2, 2014, pp. 15-20.

[10] Sniders. A. Adaptive Self-Tuning up Model for Non-Stationary Process Simulation. In: Proceedings of the 9th International Scientific Conference "Engineering for Rural Development". – Jelgava: LUA, 2010, pp. 192-199.