RIGA TECHNICAL UNIVERSITY
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INVESTIGATION OF INDUCTION MOTOR COMPLICATED DYNAMIC REGIMES BY MEANS OF MATHEMATICAL MODELING METHOD

Summary of Doctoral Thesis

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CONFIRMATION

Hereby I confirm that I have worked out the present Doctoral Thesis, which is submitted for consideration at Riga Technical University for the degree of Doctor of engineering sciences. This work is not submitted in any other university for obtaining the doctor’s degree.

Marina Konuhova……………………………………..… (Signature)

Date………………………………..

Work is written in English language, it contains preface, 4 chapters, conclusions, 5 appendixes, 92 pictures and 10 tables. Total amount of this work is 155 pages. Bibliography includes 130 used literature sources.

CONTENTS

TOPICALITY OF THE WORK

Generally used induction motors (IM) still are the main electrical drive fashion; it is used in all manufacturing fields. There is no any rind of techniques or household applications where are not used induction motors. These motors have a lot of advantages. Induction motors essential advantages should be nominated long life, small noise level and high efficiency. In spite of more frequently applied controlled induction drive usage now there are majority of drive used induction motors without control. It's used for water supply, heating, fans and conditioning, compressors and other equipment. For now there are 20-25% of drives require (in accordance with technological processes needs) precise rotation speed and torque control at steady-state and transient processes.

Power electronics and microprocessors device fast development is assisted electrical drive informative part development and there is less attention paid to energy elctromechanical transformation processes in power channel. At the same time should be noted that power converter at controlled drive cost is 3-5 times more expensive than drive itself.

Therefore to succeed induction motor high proceeding reliability it should be researched its physical features, it should be précised motors parameters calculation methods, it should be investigated motors operation in different regimes etc.

To search out electric machine dynamic means to answer question – which way electric machine operating in independent conditions parameters change affects independent variables optimal parameters and change nature.

Induction motors operation dynamic regimes research taking into account electromagnetic transient process initiated by motor position change is actual nowadays induction drive application practice question. Induction motor develops considerable electromagnetic torques, which might several times exceed rated value, even maximal value. Thus it is necessary to search these torques, because these torques is the reason of dangerous mechanical tensions appearance in electric drive system kinematics' circuit elements.

GOAL OF THE WORK AND TASKS

The goal of thesis is presentation of induction motor mathematical modeling method, which allows depending on problem to be solved definition to choose one of developed models for induction motor complicated dynamic regimes modeling and investigation.

To achieve this goal in thesis there are solved following general tasks:

- present induction motor mathematical descriptions analysis and optimal model choice;
- research methodology creation and required for that mathematical model creation;
- induction motor operation method of mathematical modeling usage at voltage unbalance;
- research of induction motor undamped field effect on operation regimes linked to switching processes;

- created induction motor operation regimes research methods scope of applications definition. Recommendations for its application;
- experimental research execution and got results analysis.

THE METHODS OF INVESTIGATION

In thesis are used: electric machines mathematical theory concepts, dynamic energy electromagnetic transformation processes description methods, Eiler and Runge – Kut 4^{th} order digital methods, mathematical modeling and programming in FORTRAN. Theoretical investigations were examined using experimental methods.

SCIENTIFIC NOVELTY OF THE WORK

There are created programs complexes allowing to model and research IM operation regimes.

There is created new method for IM operation research at voltage unbalance using ordinary symmetrical IM mathematical model.

There is created new method for research of IM residual field impact on operation regimes linked to switching processes.

It was analyzed credible parameters acquisition solutions for IM dynamic regimes modeling.

PRACTICAL APPLICATION

Created programs complexes might be used for IM dynamic regimes modeling independent on IM type, structure specific and parameters.

Created programs complexes might be applied by engineers and researchers for in practice to make correct choice of induction motors automation, protection and control devices.

APPROBATION

1. "The research into the self-starting mode of the induction motor". RTU 48. Starptautiskā zinātniskā konference, Rīga, Latvija, oktobris, 2007.
2. "Development of the model for the investigation of the induction motor under asymmetric supply modes". X International Scientific – Technical Conference Problems of Present-day Electrotechnics-2008, Kijeva, Ukraina, jūnijs, 2008.
3. "Analysis of asymmetric supply mode of the induction motor in system of d,q coordinates". RTU 49. Starptautiskā zinātniskā conference, Rīga, Latvija, oktobris, 2008.
4. "Investigation of the induction motor start up process using star-delta start". ECT 2009, 2nd International Conference on Electrical and Control Technologies, Kaunas, Lithuania, May, 2009.
5. "Investigation of the undamped field effect to the electromagnetic processes in the induction machines". RTU 50. Starptautiskā zinātniskā konference, Rīga, Latvija, oktobris, 2009.
6. "Research of the effect of the rotor constant upon the attenuation characteristic if the induction motor residual voltage under the switching regime". XI International Scientific – Technical Conference Problems of present-day electrotechnics-2010. Kijeva, Ukraina, jūnijs, 2010.

7. “Non-overlapping concentrated windings in homopolar inductor machines”. SPEEDAM-2010. Pisa, Italy, June, 2010.
8. “Mathematical modeling of induction motor transient processes during stator winding interruption”. RTU 51. Starptautiskā zinātniskā konference, Rīga, Latvija, oktobris, 2010.

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INTRODUCTION

Electric energy consumption over the word last thirty years almost trebled, but consumption of electric energy in industry for the same time grew for 260% (Fig. 1.) The source – International energy agency information [*International Energy Agency, Key World Energy Statistics 2007*].

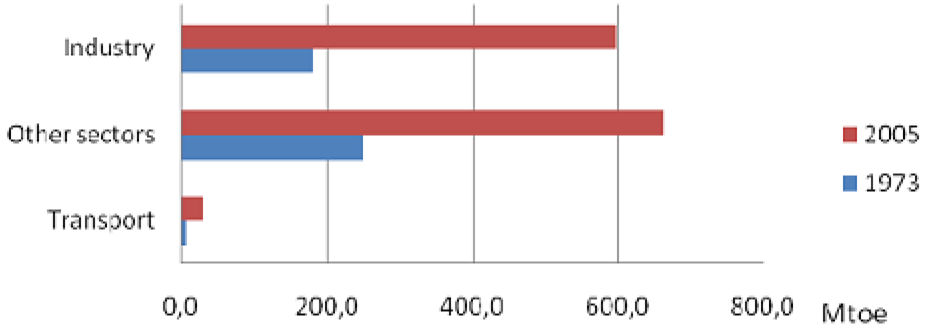


Fig.1. Diagram "Electric energy consumption over the world"

In accordance with statistics data 60% electric energy consumption in EU industry falls on induction machines [*International Energy Agency, Key World Energy Statistics 2007*] (Fig. 2.). From above said we easily conclude that IM is most wide electric machines type used in industry.

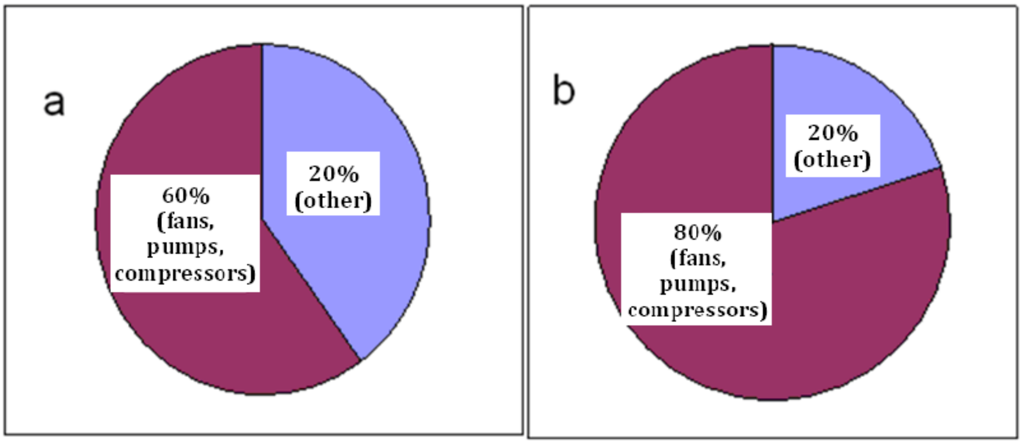


Fig.2. Electric drives electric energy consumption in European Union: a) industry; b) commercial sector

Induction motors with squirrel-cage rotor are most wide-spread type of motors. They are relatively cheap and have not expensive maintenance. IM wide used in the drive of metalworking, woodworking and other purpose machinery, in press-forming, weaving, sewing, hoisting and earth-moving machines, fans, pumps, compressors, centrifuges, escalators, in electric hand tools, household devices etc. Actually there is no any field of activity without induction motors in use.

As far induction machines have so important role in industry, there are a number of requirements to them, main of which is high efficiency and continuity during operation, service and maintenance simplicity. To provide these requirements it should be clearly understood physical phenomena running in electric machine during transient process. It must be ability to define currents, voltage, torques variation values. To design efficiently electric machines, which are sufficient at any operation mode and withstand emergency situation nowadays engineer should have skills to forecast electric machine reaction to load-on and load reset regimes.

Transient processes do not last long. But arising transient processes considerably impact electric machine operation and affect network and drive system totally.

Transient processes are more diverse and complicated than steady-state processes, which are generally transient processes particular case. Transient processes appear in electric machines when on machine terminal changes voltage or frequency, varying load on shaft, switching machine on or off, reversing, short circuit occurring, changing machine parameters etc. Actually transient processes proceed under several factors influence. Dynamic affecting factors combinations might be very diverse (change of voltage, frequency, equivalent parameters, load etc), thus making research it have to be ability to choose “the main” and no reason to make task too complicated.

1. THE METHODIC OF MATHEMATICAL MODELING OF INDUCTION MOTOR AND MATHEMATICAL MODELS

To analyze IM operation during transient processes it is important and often determinative factor the choice of electric motor mathematical model. Efficient solution of such kind of tasks is usage of mathematical model in orthogonal coordinates, where use as an initial variables electric machine voltages and currents.

Making analysis of IM dynamic operation regimes the first modeling stage traditionally it is used conventional assumptions, which allows to research ideal machine instead of real electric machine.

Idealized machine characterized so:

1) no magnetic circuit saturation, hysteresis, iron loss;
2) no current displacement in windings cupper;
3) magnetic inductions magnetizing forces curves sinusoidal distribution in space;
4) windings dispersion inductance independence of rotor location;
5) windings complete symmetry.

These assumptions, which idealize machine, however allow retaining proceeding in real machine processes reflection in permitted error limits. At the same time for idealized machine it is possible to succeed sufficiently precise equalities with fully permissible precision for engineer calculations.

Executed IM existing mathematical models analysis showed that the usage of mathematical model in three phase coordinate system is difficult because describing three phase induction machine transient processes equations system contain many unknown variables and equation system contains also stator and rotor alternating mutual inductance. Therefore we give preference to two phase IM mathematical models. Such a models we get from generalized electric machine equations in different coordinate systems using “space vector” concept.

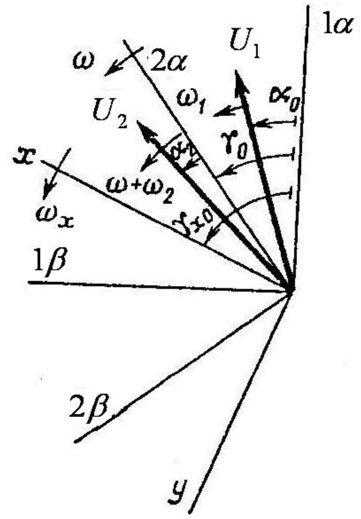


Fig.1.1. Coordinate system and voltages space vectors

Transforming generalized electric machine equations in coordinate system x, y, which is common for stator and rotor and rotates with free rotation frequency ω_x, we got voltage balance equations in axes x, y (Fig. 1.1):

$$U_{1x} = \frac{d\psi_{1x}}{dt} - \omega_x \psi_{1y} + R_1 i_{1x}; \tag{1.1}$$

$$U_{1y} = \frac{d\psi_{1y}}{dt} - \omega_x \psi_{1x} + R_1 i_{1y}; \tag{1.2}$$

$$U_{2x} = \frac{d\psi_{2x}}{dt} - (\omega - \omega_x)\psi_{2y} + R_2 i_{2x}; \tag{1.3}$$

$$U_{2y} = \frac{d\psi_{2y}}{dt} - (\omega - \omega_x)\psi_{2x} + R_2 i_{2y}. \tag{1.4}$$

Where $U_{1x}, U_{1y}, U_{2x}, U_{2y}$ - stator and rotor voltages components in x, y coordinate system;

$i_{1x}, i_{1y}, i_{2x}, i_{2y}$ - stator and rotor currents components in x, y coordinate system;

$\psi_{1x}, \psi_{1y}, \psi_{2x}, \psi_{2y}$ - stator and rotor flux linkages components in x, y coordinate system;

R_1, R_2 - stator and rotor active resistances;

ω_x, ω - coordinate system and rotor angular rotation frequency.

Substituting values of frequencies $\omega_1, \omega_2, \omega, \omega_x$ we could examine induction machine in any coordinate system.

Diversity of model we got is that there are included torque electromotive forces:

$\omega_x \psi_{1y}$; $\omega_x \psi_{1x}$; $(\omega - \omega_x)\psi_{2y}$; $(\omega - \omega_x)\psi_{2x}$

From equations (1.1)-(1.4) making a number of mathematical transformations for IM dynamic operation regimes were developed four IM mathematical models.

The first IM model in coordinate system α, β (marked ***model I)*** is presented by equations (1.5)-(1.7):

$$\left.\begin{aligned}
\frac{d\psi_{1\alpha}}{d\tau} &= U_m \cdot \cos(\tau) - R_1 \cdot i_{1a} \\
\frac{d\psi_{1\beta}}{dt} &= U_m \cdot \sin(\tau) - R_1 \cdot i_{1\beta} \\
\frac{d\psi_{2\alpha}}{d\tau} &= -R_2 \cdot i_{2a} + \omega\,\psi_{2\beta} \\
\frac{d\psi_{2\beta}}{d\tau} &= -R_2 \cdot i_{2\beta} - \omega\,\psi_{2\alpha}
\end{aligned}\right\}, \tag{1.5}$$

$$\frac{d\omega}{d\tau} = (M_{em} - M_l)/T_M \;, \tag{1.6}$$

$$\left.\begin{aligned}
i_{1\alpha} &= (X_2 \cdot \psi_{1\alpha} - X_{ad} \cdot \psi_{2\alpha})/del \\
i_{1\beta} &= (X_2 \cdot \psi_{1\beta} - X_{ad} \cdot \psi_{2\beta})/del \\
i_{2\alpha} &= (X_1 \cdot \psi_{2\alpha} - X_{ad} \cdot \psi_{1\alpha})/del \\
i_{2\beta} &= (X_1 \cdot \psi_{2\beta} - X_{ad} \cdot \psi_{1\beta})/del
\end{aligned}\right\}, \tag{1.7}$$

where $del = X_1 \cdot X_2 - X_{ad} \cdot X_{ad}$;
$M_{em} = X_{ad}(i_{1\alpha} i_{2\beta} - i_{1\beta} i_{2\alpha})$;
$M_l = SM \cdot \omega_2^2 + SMK$;
SM - proportional to rotation frequency static torque value;
SMK - independent of rotation frequency static torque value;
$\psi_{1\beta}, \psi_{1\alpha}, \psi_{2\beta}, \psi_{2\alpha}$ - stator and rotor flux linkages components in α, β coordinate system;
$i_{1\alpha}, i_{1\beta}, i_{2\alpha}, i_{2\beta}$ - stator and rotor currents components in α, β coordinate system;
$U_m \cos(\tau), -U_m \sin(\tau)$ - stator supply voltage;
$R_1, R_2, X_1, X_2, X_{ad}$ - induction motor parameters in relative units;
M_{em}, M_l - electromagnetic and load torques;
T_M - machine time constant in electric radians.

Here equation (1.6) is rotor movement equation, but currents values - (1.7), received from flux linkages expressions. This IM model in α, β coordinate system allows without additional transformations compare one phase outcome with experimental data.

The second IM model is solved relative to currents in d, q coordinate system (marked ***model II)*** and is presented in matrix form:

$$\begin{bmatrix} u_{1d} \\ u_{1q} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 & 0 & 0 & 0 \\ 0 & R_1 & 0 & 0 \\ 0 & 0 & R_2 & 0 \\ 0 & 0 & 0 & R_2 \end{bmatrix} \cdot \begin{bmatrix} i_{1d} \\ i_{1q} \\ i_{2d} \\ i_{2q} \end{bmatrix} + \begin{bmatrix} -\omega_x \psi_{1q} \\ \omega_x \psi_{1d} \\ -(\omega_x - \omega)\psi_{2q} \\ (\omega_x - \omega)\psi_{2d} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_{1d} \\ \psi_{1q} \\ \psi_{2d} \\ \psi_{2q} \end{bmatrix} \tag{1.8}$$

$$\frac{d\omega}{dt} = [X_{ad}(i_{2d} i_{1q} - i_{2q} i_{1d}) - M_l], \tag{1.9}$$

where flux linkages values we may substitute as follows:

$$\frac{d}{dt}\begin{vmatrix} i_{1d} \\ i_{1q} \\ i_{2d} \\ i_{2q} \end{vmatrix} = \begin{vmatrix} -C_1R_1 & +C_1 f_1 & +C_1X_{ad} & +C_1X_{ad}\omega \\ -C_1 f_1 & -C_1R_1 & -C_1X_{ad}\omega & +C_2X_{ad} \\ C_3R_1 & -X_1 f_2 & -C_2X_1 & -f_3 \\ X_1 f_2 & +C_3R_1 & +f_3 & -C_2X_1 \end{vmatrix} * \begin{vmatrix} i_{1d} \\ i_{1q} \\ i_{2d} \\ i_{2q} \end{vmatrix} + \begin{vmatrix} C_1 & 0 & 0 & 0 \\ 0 & C_1 & 0 & 0 \\ 0 & 0 & C_1 & 0 \\ 0 & 0 & 0 & C_1 \end{vmatrix} * \begin{vmatrix} U_{1d} \\ U_{1q} \\ U_{2d} \\ U_{2q} \end{vmatrix}, \quad (1.10)$$

where u_{1d}, u_{1q} - stator supply voltage;

$i_{1d}, i_{1q}, i_{2d}, i_{2q}$ - stator and rotor currents components in d,q coordinate system;

$\psi_{1\beta}, \psi_{1\alpha}, \psi_{2\beta}, \psi_{2\alpha}$ - stator and rotor flux linkages components in d,q coordinate system;

coefficients values are calculated in accordance with following expressions:

$$C_1 = \frac{1}{X_d^{'}} = \frac{1}{X_1 - \frac{X_{ad}^2}{X_2}}; \; C_2 = \frac{R_2}{X_2} \cdot C_1; \; C_3 = \frac{X_{ad}}{X_2} \cdot C_1;$$

$$f_1 = \left(X_1 - \frac{X_{ad}^2}{X_2} \right)\omega_x + \frac{X_{ad}^2}{X_2}; \; f_2 = \omega \cdot C_3 \; ; \; f_3 = (C_1X_1(\omega - \omega_x)).$$

This IM model in d,q coordinate system is set in currents, which allows including mathematical model in researches for defining the motor operation impact on power supply system.

The third IM model is solved relatively to flux linkages in d,q coordinate system (marked ***model III)*** and is presented by equations (1.11)-(1.13):

$$\left.\begin{aligned} \frac{d\psi_{1d}}{dt} &= U_{1d} - R_1 i_d + \omega\,\psi_{1q} \\ \frac{d\psi_{1q}}{dt} &= U_{1q} - R_1 i_q - \omega\,\psi_{1d} \\ \frac{d\psi_{2d}}{dt} &= -R_2 i_{2d} + (\omega_x - \omega)\psi_{2d} \\ \frac{d\psi_{2q}}{dt} &= -R_2 i_{2q} - (\omega_x - \omega)\psi_{2d} \end{aligned}\right\}, \quad (1.11)$$

$$T_M \frac{d\omega}{dt} = [M_{em} - M_l], \quad (1.12)$$

$$\left.\begin{aligned} i_{1d} &= (X_2\psi_{1d} - X_{ad}\psi_{2d})/del \\ i_{1q} &= (X_2\psi_{1q} - X_{ad}\psi_{2q})/del \\ i_{2d} &= (X_1\psi_{2d} - X_{ad}\psi_{1q})/del \\ i_{2q} &= (X_1\psi_{2q} - X_{ad}\psi_{1q})/del \end{aligned}\right\}. \quad (1.13)$$

Here equation (1.12) is rotor movement equation, but currents values (1.13), we got from flux linkages expressions. This IM model in d,q coordinate system is presented in flux linkages, which allows making motor autonomous operation regimes analysis when it works autonomously and fed by power supply network with infinitely large capacity.

The forth IM model for flux linkages with rotor windings electromagnetic time constant in d,q coordinate system (marked ***model IV)*** is presented by equations (1.14)-(1.16):

$$\left.\begin{aligned}
U_d &= \frac{d\psi_{1d}}{dt} - \omega\psi_{1q} + R_1 i_d \\
U_q &= \frac{d\psi_{1q}}{dt} + \omega\psi_{1d} + R_1 i_q \\
0 &= -\frac{d\psi_{2d}}{dt} - \frac{\psi_{1d}}{T_r} - \frac{X_{ad}}{T_r} i_d + \psi_{2q}(\omega_x - \omega) \\
0 &= -\frac{d\psi_{2q}}{dt} - \frac{\psi_{1q}}{T_r} + \frac{X_{ad}}{T_r} i_q - \psi_{2d}(\omega_x - \omega)
\end{aligned}\right\}, \qquad (1.14)$$

$$T_M \frac{d\omega}{dt} = M_{em} - M_l \,, \qquad (1.15)$$

$$\left.\begin{aligned}
i_{1d} &= (X_2 \cdot \psi_{1d} - X_{ad} \cdot \psi_{2d})/(X_1 \cdot X_2 - X_{ad}^2) \\
i_{1q} &= (X_2 \cdot \psi_{1q} - X_{ad} \cdot \psi_{2q})/(X_1 \cdot X_2 - X_{ad}^2) \\
i_{2d} &= (X_1 \cdot \psi_{2d} - X_{ad} \cdot \psi_{1d})/(X_1 \cdot X_2 - X_{ad}^2) \\
i_{2q} &= (X_1 \cdot \psi_{2q} - X_{ad} \cdot \psi_{1q})/(X_1 \cdot X_2 - X_{ad}^2)
\end{aligned}\right\}, \qquad (1.16)$$

where $T_r = \dfrac{X_2}{R_2}$ - rotor windings electromagnetic time constant.

This IM model is presented in flux linkages with the rotor windings electromagnetic time constant. This model allows to analyze motor parameters change at rundown regime to clear up what is the dependence of rotor windings electromagnetic time constant.

Using developed four IM models (***model I***, ***model II***, ***model III***, ***model IV***), arises opportunity to model a number of dynamic operation regimes.

2. MATHEMATICAL MODELING OF INDUCTION MOTOR OPERATION IN DYNAMIC REGIMES, WHICH ARE NOT CONNECTED TO SWITCHING PROCESSES

In the second part of thesis are modeled and researched following IM dynamic operation regimes: direct start-up, start-up taking into account current displacement from slots and IM operation at voltage unbalance, respectively IM operation at one phase breakdown.

2.1. INDUCTION MOTOR DIRECT START-UP

4A90L2Y3 type IM start-up regime mathematical modeling in accordance with 1st thesis part given mathematical models shown that independently on coordinate system choice and on which parameter of IM relating currents, flux linkages or flux linkages with rotor windings electromagnetic time constant is solved mathematical model, the modeling results are identical and completely correspond to reality because currents, rotation frequencies and electromagnetic torques values received using four models are the same in the same time points, therefore for IM dynamic operation regimes is permissible to use any of them.

Using in 1st part of thesis presented IM models appears opportunity to model start-up regime for any capacity IM with different load values and load torques and to model various other IM dynamic operation regimes as well.

2.2. INDUCTION MOTOR DIRECT START-UP TAKING INTO ACCOUNT CURRENT DISLODGEMENT IN SLOT

Using IM mathematical model ***model I***, it was modeled start-up regime, taking into account current dislodgement in slots. Received modeling results were compared with values received without taking into account current dislodgement in slots.

IM currents comparison showed that in case when current dislodgement in slots was taken into account IM starting current first and second peak values are similar with first and second current peak values if current dislodgement in slots was not taken into account, but the third current peak value is considerably smaller then in case if it was not taken into account current dislodgement in slots. Generally starting currents values where it was taken into account current dislodgement in slots has faster damping than if this current dislodgement was not taken into account. In steady-state regimes values are completely same.

From values of IM starting rotation frequencies we consider that starting IM and taking into account current dislodgement motor faster succeed steady-state regime than do IM without taking into account current dislodgement in slots.

Electromagnetic torques values comparison showed that in case of modeling with current dislodgement in slots taking into account torque value at the first moment value considerably exceeds value if modeling made without current dislodgement in slots taking into account.

So, made research showed that current dislodgement in slots accounting has influence on IM current, rotation frequency and electromagnetic torque starting values, but does not effect steady-state regime.

2.3. MODELING METHOD OF INDUCTION MOTOR OPERATION REGIME AT VOLTAGE UNBALANCE

To model voltage unbalance is provided to define unbalance conditions using three phase feeder connecting IM with infinitely large power network, parameters, which allow to imitate unbalance fault on IM terminal (Fig. 2.1).

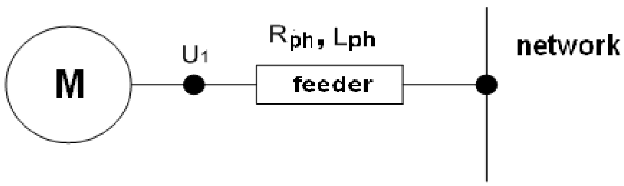


Fig. 2.1. The scheme of model

To model voltage unbalance used IM mathematical model ***model II***.

An initial static active-inductive load equation in phase coordinates express following:

$$\begin{vmatrix} U_a \\ U_b \\ U_c \end{vmatrix} = \begin{vmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{vmatrix} \times \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix} + \begin{vmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{vmatrix} \times \frac{d}{dt} \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix}, \tag{2.1}$$

where $U_{a,b,c}$ – phases voltages;

$i_{a,b,c}$ – phases currents;

$R_{a,b,c}$ – phases active resistances;

$L_{a,b,c}$ – phases inductances.

After number of mathematical transformations voltage on IM terminal (stator windings) define as a feeder voltage and voltage drop on active-inductive resistance difference, but as far on stator windings there is no neutral equations system for IM unbalance modeling gets following form:

$$\begin{vmatrix} U_d \\ U_q \end{vmatrix} = |R| \times \begin{vmatrix} i_d \\ i_q \end{vmatrix} + |L| \times \frac{d}{dt} \begin{vmatrix} i_d \\ i_q \end{vmatrix} + |X| \times \begin{vmatrix} i_d \\ i_q \end{vmatrix}. \quad (2.2)$$

Taking into account that IM and active-inductive resistance currents and currents derivative are similar, in equation (2.2) is possible to insert IM stator current in matrix form.

So, stator current equation we may put down in following form:

$$\frac{d}{dt} \begin{vmatrix} i_{1d} \\ i_{1q} \end{vmatrix} = \begin{vmatrix} Q_1 & 0 \\ 0 & Q_2 \end{vmatrix} \times \begin{vmatrix} U_{1d} \\ U_{1q} \end{vmatrix} + \begin{vmatrix} H_1 \\ H_2 \end{vmatrix}; \quad (2.3)$$

$$\begin{vmatrix} U_{1d} \\ U_{1q} \end{vmatrix} = \begin{vmatrix} U_{dtikls} \\ U_{qtikls} \end{vmatrix} - \left\{ |R| \times \begin{vmatrix} i_d \\ i_q \end{vmatrix} + |L| \times \left[\begin{vmatrix} Q_1 & 0 \\ 0 & Q_2 \end{vmatrix} \times \begin{vmatrix} U_{1d} \\ U_{1q} \end{vmatrix} + \begin{vmatrix} H_1 \\ H_2 \end{vmatrix} \right] + |X| \times \begin{vmatrix} i_d \\ i_q \end{vmatrix} \right\}, \quad (2.4)$$

where $\begin{vmatrix} H_1 \\ H_2 \end{vmatrix} = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} \times \begin{vmatrix} i_{1d} \\ i_{1q} \end{vmatrix}$, $Q_1 = Q_2 = \frac{1}{X'_d}$, $a_{11} = -\frac{R_1}{X'_d}$, $a_{12} = (\omega_x + \frac{X_{ad}^2 \omega}{X_2 X'_d})$,

$a_{21} = -(\omega_x + \frac{X_{ad}^2 \omega}{X_2 X'_d})$, $a_{22} = -\frac{R_1}{X'_d}$.

Solving (2.4) relating to $\begin{vmatrix} U_{1d} \\ U_{1q} \end{vmatrix}$, we get:

$$\left\{ \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} + |L| \times |Q| \right\} \times \begin{vmatrix} U_{1d} \\ U_{1q} \end{vmatrix} = \begin{vmatrix} U_{dnetw} \\ U_{qnetw} \end{vmatrix} - |R| \times \begin{vmatrix} i_d \\ i_q \end{vmatrix} - |L| \times |H| \times |i|.$$

Resulting voltage on IM:

$$\begin{vmatrix} U_{1d} \\ U_{1q} \end{vmatrix} = \left\{ \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} + |L| \times |Q| \right\}^{-1} \times \left\{ \begin{vmatrix} U_{d_{netw}} \\ U_{q_{netw}} \end{vmatrix} - |R| \times \begin{vmatrix} i_d \\ i_q \end{vmatrix} - |L| \times |H| - |X| \times |i| \right\}. \quad (2.5)$$

Thus defining R_a, R_b, R_c; X_a, X_b, X_c values appear opportunity to imitate induction motor unbalance using simple symmetrical IM model.

2.3.1. INDUCTION MOTOR OPERATION AT ONE PHASE BREAKDOWN

Setting active-inductive resistance values we may imitate IM operating regime at one phase breakdown using simple symmetrical IM model in d, q coordinate system- ***model II***.

As an object of modeling was token IM with following parameters (relative units): P_{2N}=50 kW; R_1=0,013; R_2'=0,011; X_1=0,091; X_2'=0,1; X_{ad}= 5,7 .

First IM starts than after acceleration motor defined time operates in steady-state regime and then arise A phase breakdown.

On Fig.2.2 and 2.3 there are presented rotation speed, electromagnetic torque curves in the case when one phase breakdown arisen at motor operation.

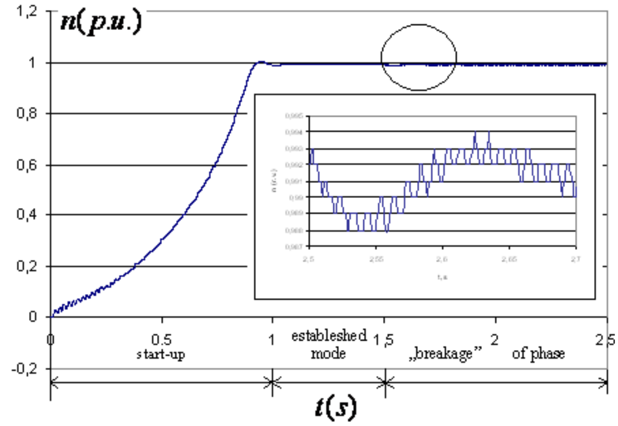


Fig.2.2. IM rotation speed curve at A phase breakdown

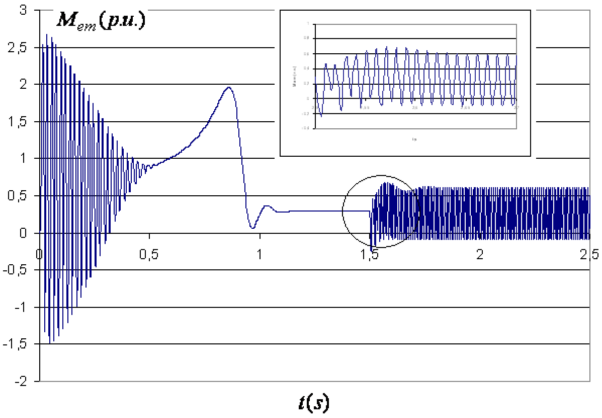


Fig.2.3. IM electromagnetic torque curve at A phase breakdown

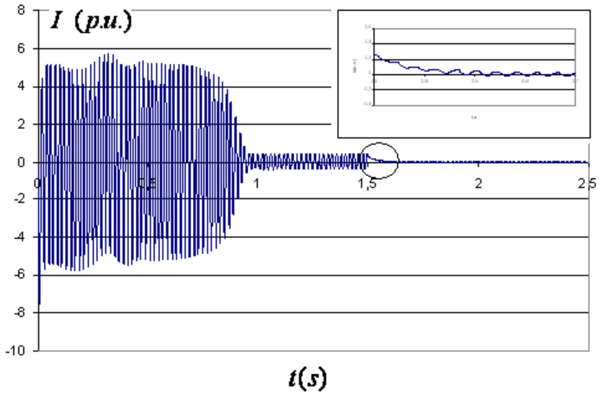


Fig.2.4. IM A phase current curve at A phase breakdown

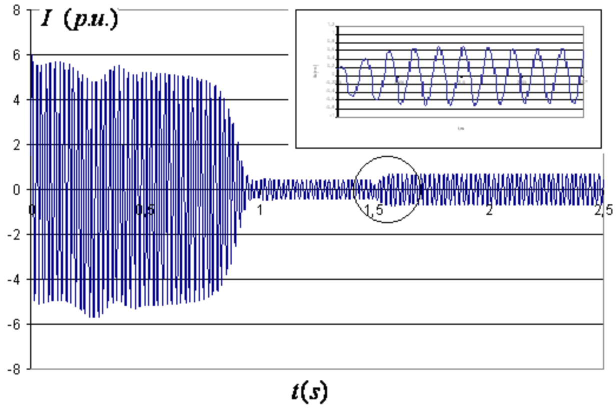


Fig.2.5. IM B phase current curve at A phase breakdown

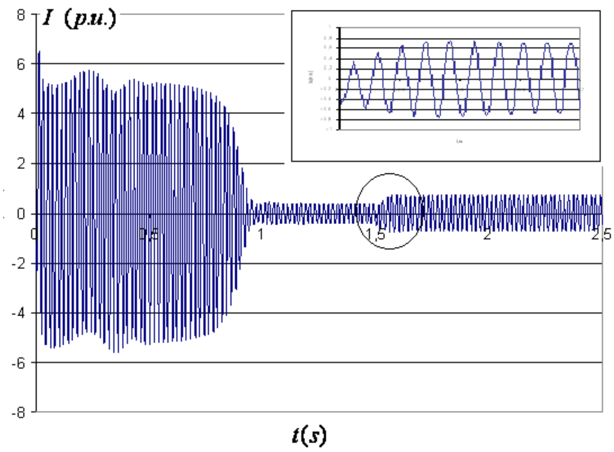


Fig.2.6. IM C phase current curve at A phase breakdown

On IM rotation speed curve (Fig. 2.2) we see that due to maximal IM gathered torque larger than load torque motor does not stop and continue to rotate.

Looking over currents in phases curves (Fig. 2.4-2.6) we could clear see that A phase current is zero, two other phases (B and C) increased for 50% and that supports theory. Thus developed methods really allow to model IM operation regimes at unbalance voltage.

2.3.2. INDUCTION MOTOR OPERATION AT VOLTAGE UNBALANCE

Setting active-inductive resistance value (Fig.2.1) was imitated IM two phases unbalance.

To model IM operation at two phases unbalance used IM with following parameters (relative units): P_{2Nom}= 250 kW; R_1=0,013; R_2'=0,011; X_1=0,091; X_2'=0,1; X_{ad}= 5,7 .

Electromagnetic torque and currents (by phases) curves at short time unbalance in two phases presented on Fig.2.7 and 2.8.

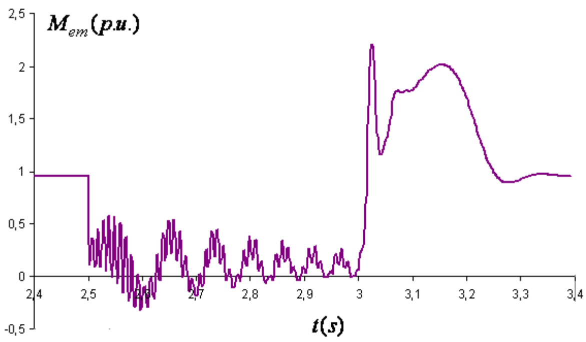


Fig.2.7. IM electromagnetic torque curve

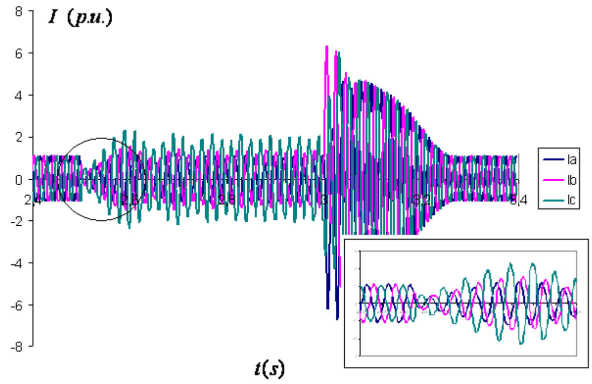


Fig.2.8. IM currents curves

From curves received modeling IM unbalance in two phases we consider, that motor electromagnetic torque proportional to current and magnetic flux. Decreasing voltage machine magnetic flux decreases and resulting decreases motor torque. As far machine load torque becomes larger than motor torque begins breaking, rotor rotation speed decreases. At the same time currents in rotor and stator increases up to values, which renew lost balance. Thus in spite of voltage decrease motor current increases.

3. MATHEMATICAL MODELING OF INDUCTION MOTOR OPERATION IN DYNAMIC REGIMES, WHICH ARE CONNECTED TO SWITCHING PROCESSES

In the third thesis part modeled and researched following IM dynamic operation regimes: rundown, switching and self start.

3.1. RUNDOWN REGIME MODELING

3.1.1. ELECTROMOTIVE FORCE AT INDUCTION MOTOR RUNDOWN

To get IM residual voltage value after switch off used IM mathematical model ***model I*** and modeled IM start-up regime. To model IM rundown regime at time point when IM is switched off power supply let us mark parameters as $\psi_{2\alpha0};\psi_{2\beta0};\omega_0;i_{2\alpha0};i_{2\beta0}$.

Parameters of IM after switch power off let us mark as $\psi_{2\alpha1};\psi_{2\beta1};\omega_1;i_{2\alpha1};i_{2\beta1}$.

IM stator current at switching power off time point becomes zero:

$$i_{1\alpha 1} = 0;\ i_{1\beta 1} = 0. \quad (3.1)$$

Thus IM rundown process features define following differential equations system:

$$\left.\begin{aligned}\frac{d\psi_{2\alpha 1}}{d\tau} &= -R_2 \cdot i_{2\alpha 1} + \omega_1 \psi_{2\beta 1}\\ \frac{d\psi_{2\beta 1}}{d\tau} &= -R_2 \cdot i_{2\beta 1} + \omega_1 \psi_{2\alpha 1}\end{aligned}\right\}, \quad (3.2)$$

$$\frac{d\omega_1}{d\tau} = (M_{em} - M_l)/T_M . \quad (3.3)$$

On Fig.3.1. there is shown IM residual voltage hodograph at switching off time point.

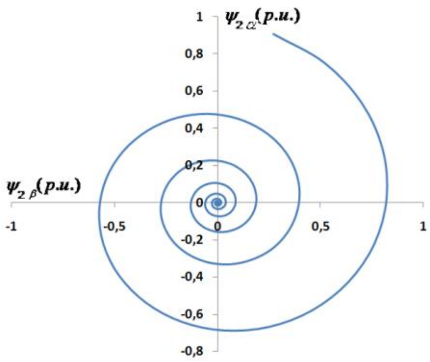


Fig.3.1. Rotor voltage hodograph

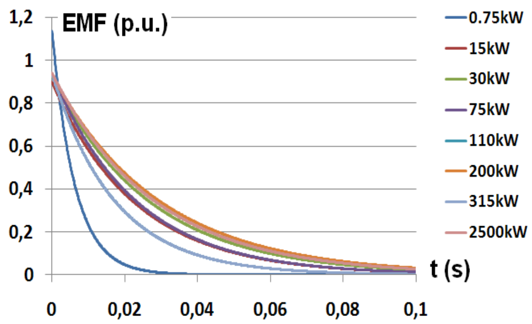


Fig.3.2. Residual voltages characteristics for induction motors with capacity 0.75 – 2500 kW

Using IM mathematical model ***model I***, was modeled rundown regime for eight IM with capacities from 0.75 kW up to 2500 kW. On Fig.3.2. is presented residual voltage damping values for all these motors.

Modeling showed that residual voltage damping process in stator windings is directly dependent on IM capacity and also the fact that at time point 0.005 s residual voltage value is close to network voltage value. This residual voltage presence at full network voltage reclosing could cause essential motor defects and respectively affect considerable windings thermal stress, which might lead to insulation premature aging, its damage and resulting turn-to-turn short circuit.

3.1.2. ROTATION FREQUENCY AT INDUCTION MOTOR RUNDOWN

Mathematically to model IM rotation frequency values at free rundown regime used to apply equations from previous part, i.e. equations (3.2)-(3.3), but IM start-up regime should be modeled using IM model ***model I***. Made modeling gave as result IM rotation frequency values for rundown regime: with static torque and different load factors, with static torque proportional to rotation frequency squared and different load factors and also rotation frequency changes values for different IM capacities, which have same static torque.

3.1.3. OTHER PROCESSES OCCURING AT INDUCTION MOTOR RUNDOWN

Using IM mathematical model ***model I*** and equations (3.2) –(3.3) was modeled IM start-up, rundown and reclosing regimes with following parameters (relative units): $X_1 = 5{,}799$, $X_2 = 5{,}84$, $X_{ad} = 5{,}7$, $R_1 = 0{,}012$, $R_2 = 0{,}027$.

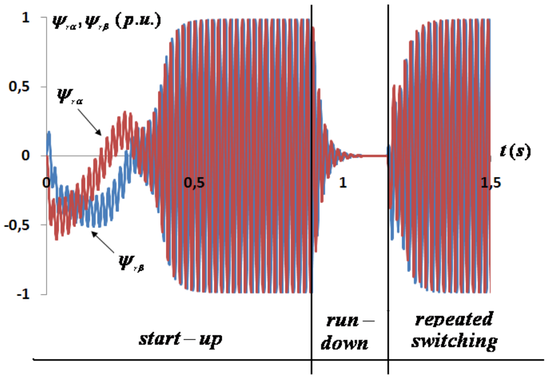


Fig.3.3. Rotor flux linkages variations for start-up, rundown and repeated switching of IM

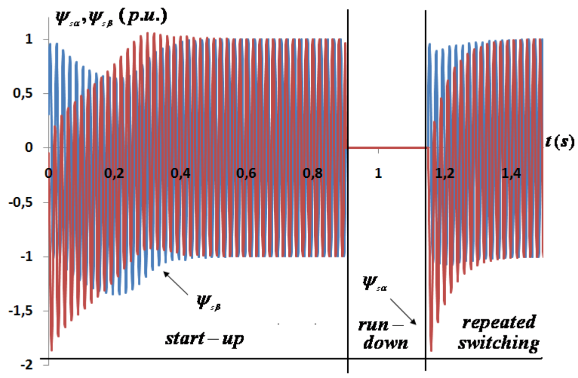


Fig.3.4. Stator flux linkages variations at start-up, rundown and repeated switching of IM

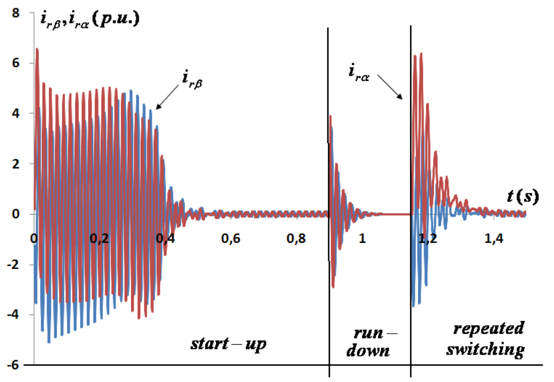


Fig.3.5. Rotor currents variations for start-up, rundown and repeated switching of IM

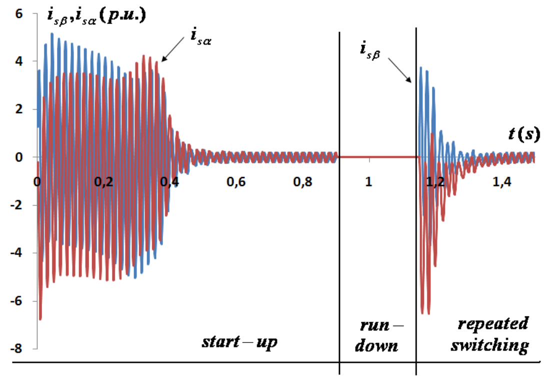


Fig.3.6. Stator currents variations for start-up, rundown and repeated switching of IM

It is found out researching rundown regime that IM rotor circuit at switching off (power source) moment rotor current change at jump mode (Fig.3.5) comparing to current in stator circuit, where it drops to zero (Fig.3.6). Rotor flux linkage at IM switching off (power source) moment inherent damping (in time) nature, but stator flux linkage drops to zero value (Fig.3.3 and 3.4) at the moment.

As far at rundown process at IM switching off (power source) moment rotor current in rotor circuit steeply rise, this inrush current induce EMF with phase and value together with network voltage might negatively impact IM if it is rapidly repeatedly closed.

3.1.4. EFFECT OF ROTOR ELECTROMAGNETIC TIME CONSTANT ON RESIDUAL VOLTAGE DAMP CHARACTERISTIC

On Fig.3.2 there are presented IM residual voltage damping values for different rotor windings electromagnetic time constants. Modeling showed that residual voltage damping process in stator windings depends on IM capacity. At Fig.3.7. designed curve showing rotor windings electromagnetic time constant as a function of IM capacity.

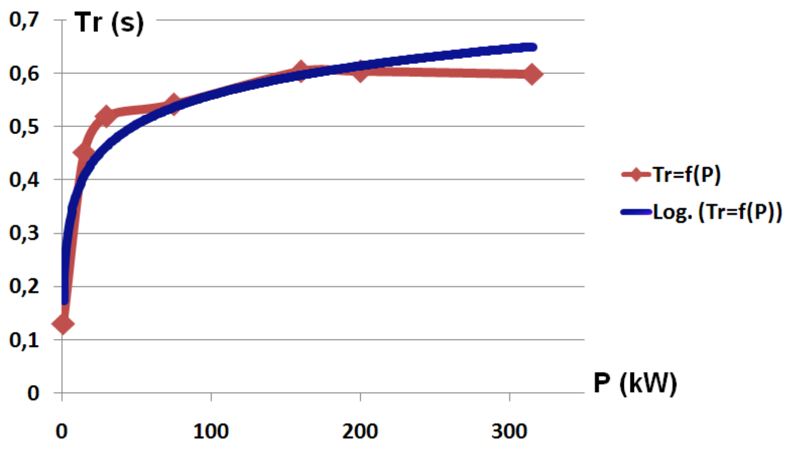


Fig.3.7. Rotor windings electromagnetic time constant dependence on IM capacity

For instance IM with 0.75 kW capacity rotor windings electromagnetic time constant is $T_r = 0{,}131$ s, but motor 2500 kW capacity rotor time constant is $T_r = 0{,}688$ s. From received residual voltage values (Fig.3.2) we see that IM EMF damping proceeds rather fast and exceeds time 0,1 s, residual voltage actually is equal to zero.

Below in thesis is shown that IM EMF values depends on rotor windings electromagnetic time constant. Examined two versions. At the first function *EMF = f(Tr)* if reclosing in $t = 0{,}005$ s (Fig.3.8.a). At the second function *EMF = f(Tr)* if reclosing in $t = 0{,}05$ s (Fig.3.8. *b*).

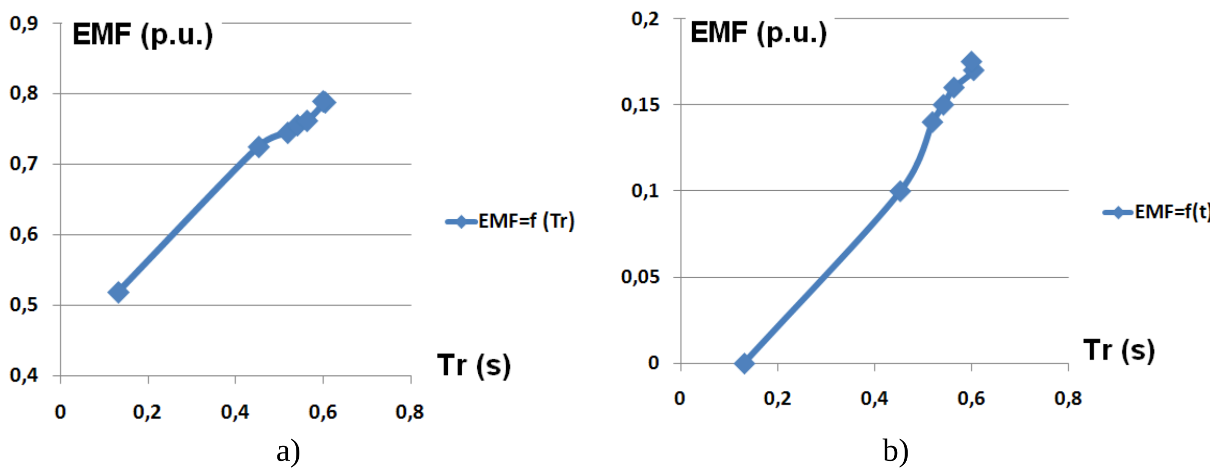


Fig.3.8. Residual voltage dependence on rotor windings electromagnetic time constant: a) at 0.005s; b) at 0.05s

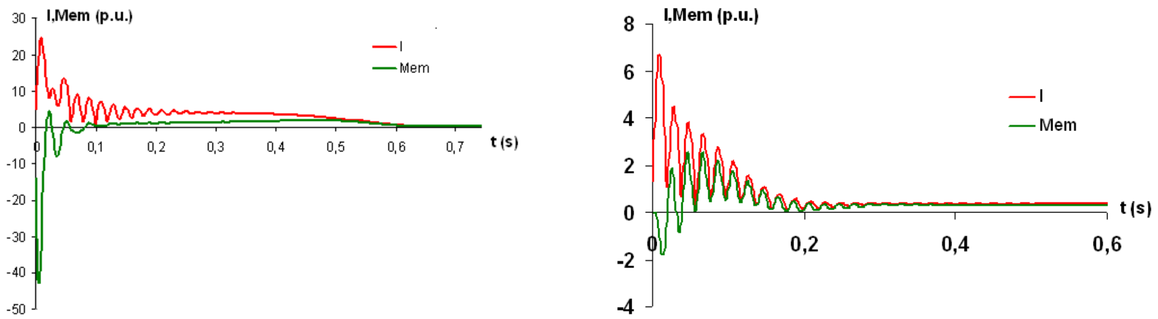
Making analysis of received curves (Fig.3.8.a and 3.8.b) we consider that in IM with small rotor windings electromagnetic time constant residual voltage damping proceeds than in motors with large rotor windings electromagnetic time constant. These curves knowing IM rotor windings electromagnetic time constant give opportunity to define residual EMF value for the exact reclosing time point. To avoid numerous calculations such *EMF = f(Tr)* curves is possible to create for every reclosing time point.

3.2. INDUCTION MOTOR SWITCHING REGIME MODELING

3.2.1. INDUCTION MOTOR WYE-DELTA START UP

To model and search IM wye-delta regime used IM mathematical model–***model II***.

IM wye-delta start up regime appears power supply switching off for the short time resulting due to load torque affect decreases motor rotation frequency as motor switched off power supply rundown creates residual EMF in stator windings. Implemented analyze showed that rapid switching from wye to delta in case of unfavorable phase closing (antiphase) might cause inrush current several times larger then nominal. For instance switching on stator winding in unfavorable conditions of phase (Fig.3.9.a) inrush current exceeded nominal 25 times, but in favorable phase condition (Fig.3.9.b) inrush current didn’t exceeded IM starting current.



a) b)

Fig.3.9. *Current and electromagnetic torque curves:*
a) unfavorable switching phase; b) favorable switching phase

Thus is possible to make save IM wye-delta starting analysis, using fast response automation devices.

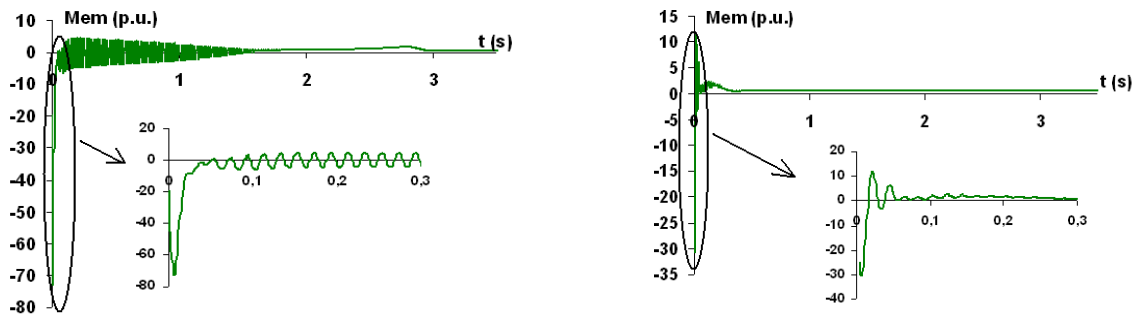
3.2.2. INVESTIGATION OF THE UNDAMPED FIELD EFFECT TO THE ELECTROMAGNETIC PROCESSES IN INDUCTION MACHINE

To model electromagnetic residual processes used IM mathematical model ***model II.***

Researches showed that after IM switching off power supply rotor continue to rotate. Therefore damping field inducts on stator terminal electromotive force also damping in time.

To estimate undamped field impact it was analyzed electromotive forces impact on electromagnetic transient processes. Therefore it was looked over network voltage impact on electromagnetic transient processes.

After IM switching off network voltage vector continue to rotate with constant synchronous speed. So, depending on commutation interval duration (no current pause) network and residual voltage (on IM terminal) vectors at reclosing moment may take various mutual positions in space, but after motor switching on they always take positions responding to steady-state regime with fixed rotation speed. The less there positions defer stationary position at closing moment, the smaller is motor magnetic flux change and therefore the smaller is electromagnetic torque value.



a) b)

Fig.3.10. Electromagnetic torque curve at IM reclosing a) after 0.005s, b) after 0.01s.

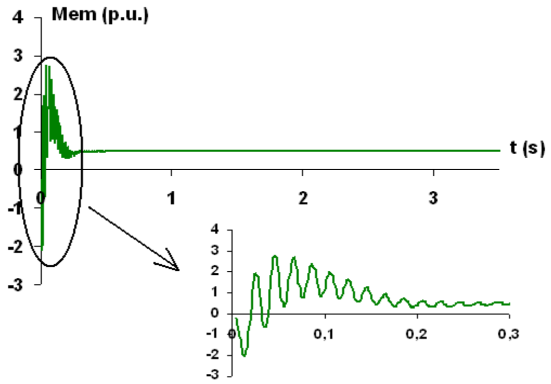


Fig.3.11. Electromagnetic torque curve at IM reclosing after 0.1 s

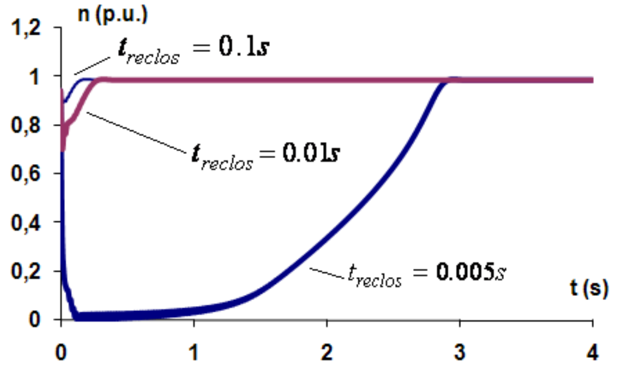


Fig.3.12. IM rotor rotation curve at reclosing

Presented curves (Fig.3.10. and 3.11.) reflect torque change nature at motor reclosing. Research shows that rotor rotation speed changes at reclosing (Fig.3.12) affect first transient moment surge only. That we can clearly see on Fig.3.10.a. The less drive inertia and larger acceleration at reclosing process, the smaller the first and following maximums transient process amplitudes and there quantity.

Negative transient torque arising might be described by fact that during connector switching time rotor damping field vectors and network voltage get considerably to change there mutual position. Under impact of breaking torque motor speed considerably decreases, but torque sign change appears similar transient process as at starting stage.

3.3. INDUCTION MOTOR SELF START REGIME MODELING

3.3.1. SELF START AT VOLTAGE DEEP DECREASE

Usually self start is understood as electric drive normal operation renewal without human participation if there was short time power supply interruption or deep voltage decrease. It is assumed that self start is successful if machine after power supply renewal accelerated up to normal angular speed and continuously operates at normal efficiency and motor load.

To model process start-up – voltage drop – IM self start used IM model ***model II***. Thus was estimated process during which permanent electric motors after power supply renewal are able to gather speed up to rated rotation frequency.

Making analysis of after number of mathematical modeling received curve it was cleared up that the voltage decrease time interval affects IM rotation speed decrease depending on load torque with which motor operates.

As we know at short circuit motor feed short circuit place. Feeding current creates breaking torque and thus motor rotation frequency at short circuit promptly changes.

Got results analyzing in details we may make following conclusions:

- voltage decrease duration does not affect electromagnetic torque value at voltage decrease time;
- voltage decrease duration does not affect current value at voltage decrease time;
- voltage decrease duration affects current value at voltage renewal time, i.e. the shorter is voltage decrease interval, the smaller is current value at voltage renewal and opposite, the longer is voltage decrease interval, the larger is current value at voltage renewal;
- looking over variant when IM operates with static torque proportional to rotation frequency squared ($M_l =$ var) and with static torque independent on rotation frequency ($M_l =$ const) we could conclude that IM working with $M_l =$ const comes to generator regime at voltage deepest decrease value in contrast to IM operating with $M_l =$var;
- IM operating with $M_l =$ var current value at voltage renewal is larger than in motor operating with $M_l =$ const.

3.3.2. SELF START AT POWER SUPPLY LOSS

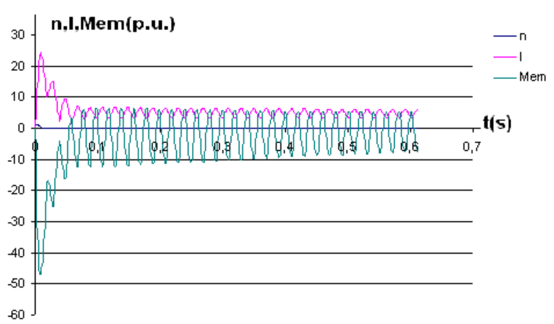
Another story is self start after short time power supply interruption acting changeover or automatic reclosing devise. In such case motor, which losing power supply switches off and switched on by automation devices, takes part in self start.

To research IM fed by one power supply source self start regime at power supply loss used IM model ***model II***.

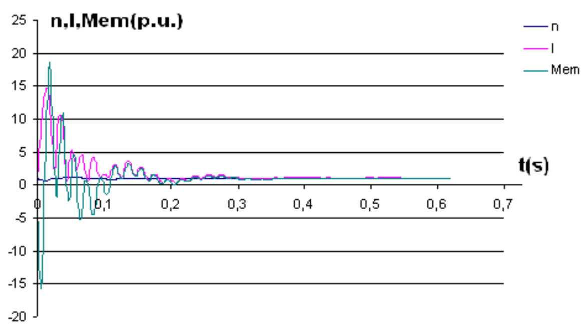
At mathematical modeling result we've got current, rotation frequency and electromagnetic torque values at IM starting process, which from we get steady-state regime parameters. Then it was modeled IM rundown process and received rotation frequency, residual voltage values and IM voltage and current hodographs.

After that it was modeled two variants of reclosing. At the first case stator voltage in antiphase network voltage (Fig.3.13.a). This modeling variant showed that the self start process is unsuccessful, current at automatic reclosing multiple larger then starting current and electromagnetic torque initiate considerable IM vibrations. Such conditions in practice lead to considerable motor damage.

In the second case, when stator voltage concur in phase with network voltage reclosing is successful (Fig.3.13.b). In such conditions transient processes are similar to IM start-up conditions.



a)



b)

Fig.3.13. IM reclosing: a) unsuccessful; b) successful

So, self start regime research analysis showed that in case of short time power supply interruption and reclosing to reserve power source or power on bus bars renewal, self start process if present rotor field might be dangerous if power supply renewal acts too fast without network voltage phase control or IM residual voltage in stator.

4. EXPERIMENT

To make IM any operation regime mathematical modeling you should know IM equivalent circuit parameters values: stator, rotor and magnetic circuit active and inductive resistances. It is a known fact that due to technological processes inobservance, differences in manufacturing processes used by different producers the motor parameters meant in technical documentation might defer to reference data up to 10 – 20 %. So, to design the high quality drive designers need to know the motor parameters authentic values.

Therefore it was IM catalogue presented parameters compared with experimentally and calculation way received parameters for 4A series 4A90L2Y3 type motor.

4.1. INDUCTION MOTOR PARAMETERS DEFINITION BY CALCULATION WAY

To determine IM T-type equivalent circuit parameters in calculation way (Fig.4.1) it was used 3 methods.

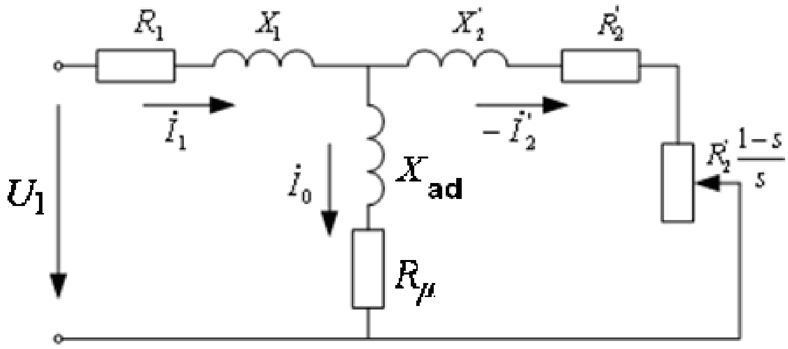


Fig.4.1. IM T-type equivalent circuit

Start-up process modeling with first calculation method got parameters [*Герман-Галкин С.Г., Кардонов Г.А. Электрические машины: Лабораторные работы на ПК.-СПб.: КОРОНА принт, 2003.*] showed that IM is successfully started and succeeded steady-state regime. But start delayed.

Parameters got by second calculation method [*Фираго Б.И., Павлячик Л.Б. Регулируемые электроприводы переменного тока.- Мн.: Техноперспектива, 2006.*] unfit for IM dynamical operation regimes modeling. They are fit for steady-state regime only. In this case IM does not start.

The third induction motor parameters dfinition calculation method [*И.П. Крючков, Б.Н. Неклепаев, В.А. Старшинов и др. Расчет коротких замыканий и выбор электрооборудования. – Уч. Пособие для студ. Высш.учеб.заведений. – М.: Издательский центр «Академия», 2005.*] showed that IM successfully starts and succeed steady-state regime.

Received by three methods IM parameters for T-type equivalent circuit combined in Table 4.1.

Table 4.1.

IM parameters determined in calculation way

Number of method	$X_\mu(\Omega)$	$X_1(\Omega)$	$X_2(\Omega)$	$R_1(\Omega)$	$R_2(\Omega)$
1	103,903	19,651	5,542	1,547	1,141
2	74,391	75,579	1,332	3,243	1,213
3	121,596	6,478	6,478	1,209	1,629

IM equivalent scheme parameters calculation by different methods showed that different type empiric equations usage does not provide confident searched parameters values. This way received parameters are suitable for steady-state regimes analysis and static values only.

4.2. INDUCTION MOTOR CREDIBLE PARAMETERS DEFINITION BY EXPERIMENTAL WAY

To determine IM equivalent scheme parameters in experimental way it was mounted the facilities, presented in Fig.4.2.

Fig.4.2. Facilities for induction motor parameters definition

The diagram of facilities for induction motor parameters definition is presented in Fig.4.3.

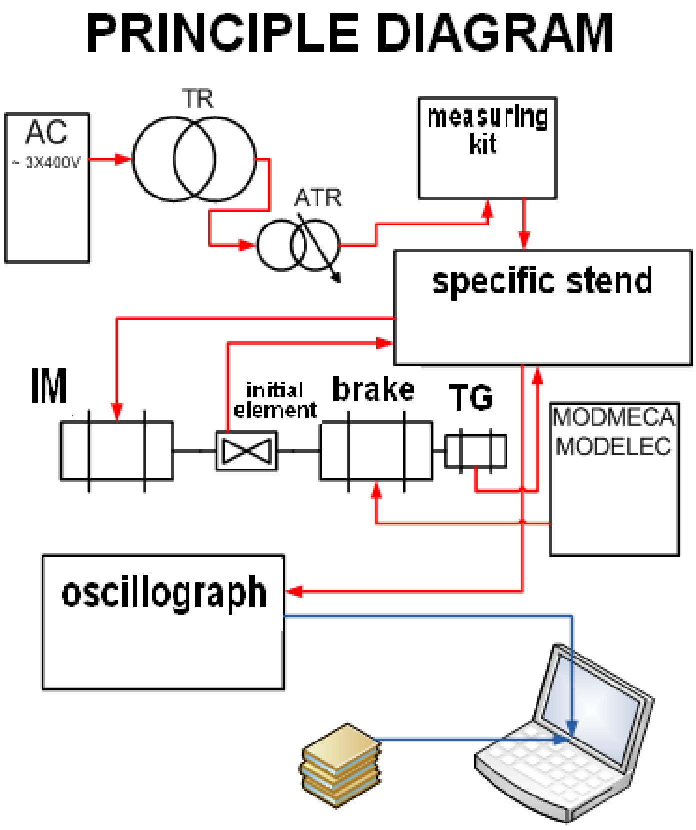


Fig.4.3. The diagram of facilities for induction motor parameters definition

Examined IM technical passport data placed in Table 4.2.

Table 4.2

4A90L2Y3 type IM technical passport data

$P_2\,(kW)$	$U_N\,(V)$	$I\,(A)$	$\cos\varphi$	$\eta(\%)$	$f\,(Hz)$	$n\,(min^{-1})$
3	220/380	6,1/10	0.88	84,5	50	2840

IM additional data:

- category: IP44;
- operation regime: S1 (long-term);
- insulation category: B;
- embodiment: IM 1001.

To determine IM active and inductive resistance values based on test data it was executed three following tests:

- stator winding active resistance metering at DC proceeded by single and double bridge or using just voltmeter and ammeter;
- no-load test, which enables to define stator inductance (approximate value) and power losses for friction and ventilation, including losses in core (magnetic circuit);
- short circuit test, which is executed with fixed rotor. It might be performed using both by reduced voltage and rated voltage. At the same time it is preferable to use voltage close to rated because the motor active and reactive leakage resistance depends on

current intensity. Short circuit test allows to define rotor resistance and rotor and stator windings leakage reactive resistances sum (related to stator).

If motor rotor performed as squirrel cage, disregard of inductance value is not acceptable. Taking into account that the inductance of the stator and rotor is extremely difficult, usually both are expected equal.

So, for the IM equivalent circuit, presented in Fig.4.1, applying the above described methods, for 4A90L2Y3 type IM resulted experimental data and computed its parameters: $R_1 = 2{,}699\,\Omega$, $X_1 = 2{,}951\,\Omega$, $X_{ad} = 77{,}774\,\Omega$, $X_2' = 2{,}951\,\Omega$, $R'_2 = 1{,}079\,\Omega$.

To check 4A90L2Y3 type IM received parameters confidence used IM model ***model I*** and it was modeled direct start-up regime.

4.3. RECEIVED AT MODELING AND EXPERIMENTAL CHARACTERISTICS COMPARATIVE ANALYZE

Modeling start-up regime become clear that values received in accordance with experimental way defined parameters and which were token from catalogue for IM T-type equivalent circuit correspond to real start-up oscillogram. Therefore let us look them over in details.

Superposing together starting curves from catalogue and starting curves got in accordance with test data by mathematical modeling (Fig.4.4 and 4.5) and become clear that the difference between curves does not exceed 10%.

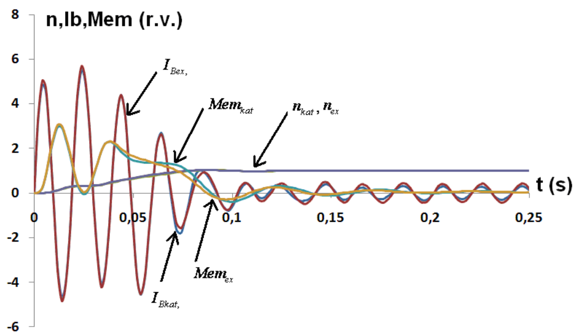


Fig.4.4. 4A90L2Y3 type IM starting curves.($I_{Bkat}, n_{kat}, Mem_{kat}$ - curves in accordance with catalogue parameters; $I_{Bex}, n_{ex}, Mem_{ex}$ -curves in accordance with experimental way received data)

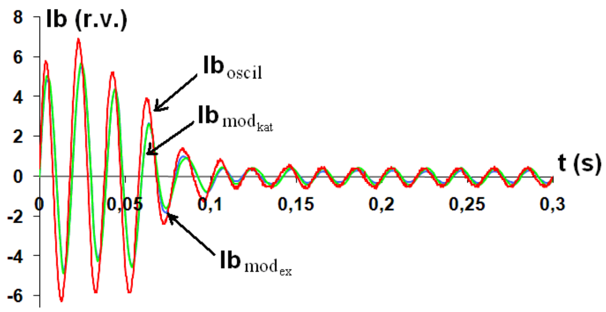


Fig.4.5. Phase current variation curve starting IM (I_{boscil} -starting current got at oscillogram; I_{bkat} - starting current based on catalog parameters; $I_{b\text{mod}}$ - starting current based on parameters got in the experimental way)

Let us compare starting curves got experimentally and catalogue data for 4A90L2Y3 type IM with curves received on oscillogram.

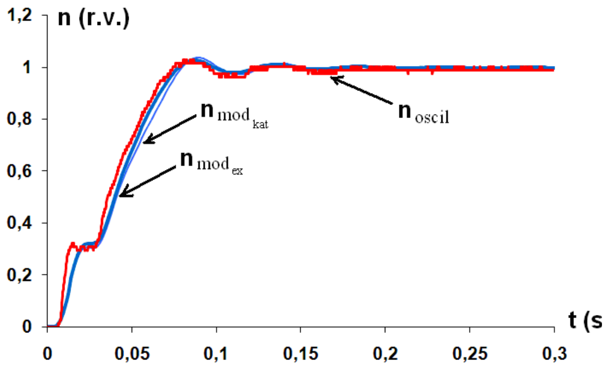


Fig.4.6. Rotation frequency curve starting IM

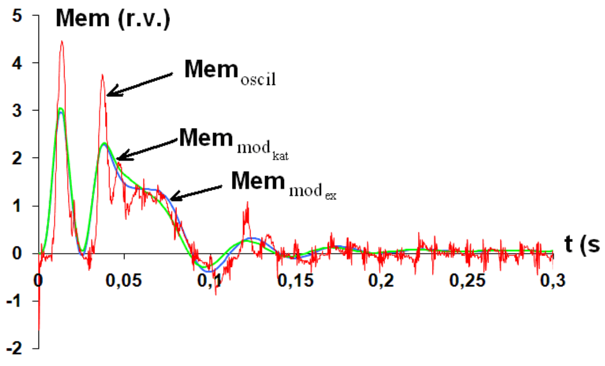


Fig.4.7. Electromagnetic torque curve starting IM

Phase current curves comparison (Fig.4.5) shown that the difference between curve based on catalogue data and received on the oscillogram at the peaks does not exceed 13%. But the difference between curve based on experimental data and curve received on the oscillogram at the peaks does not exceed17%.

Rotation frequency curves comparison (Fig.4.6) shown that the difference between curve based on catalogue data and curve received on the oscillogram did not exceed 4%. But the difference between curve based on experimental data and received on the oscillogram did not exceed 6%.

Electromagnetic torque curve got at modeling concur to real electromagnetic torque curve received on the oscillogram (Fig.4.7).

Thus IM mathematical models provided in the first part of thesis are adequate and are able completely reflect transient processes proceeding in real IM.

CONCLUSIONS

Presented IM mathematical modeling method allowed on the assumption of problem to be solved definition to develop a number of IM mathematical models in two phase d,q and α,β coordinate systems. With the help of developed mathematical models it was researched responsible consumers (actually induction motors) complicated dynamic operation regimes.

The research of short time power supply interruption and further renewal linked operation regimes showed that the successful induction motor switching on affects:

- IM power supply interruption time;
- residual voltage value at IM repeated closing moment;
- probability of repeated closing at antiphase.

Implemented analyze of rotor residual field impact in case of IM repeatedly closed in short time showed that fast response switching automation usage without estimation of residual voltage value may reverse current surge multiple exceeding rated current and may generate large electromagnetic torque value, which could lead to considerable motor damage.

To insure safe and stable IM operation in regimes linked to switching processes it was defined the minimal power supply interruption time ensuring motor residual voltage value decrease to safe value at repeated closing. Therefore it is recommended for IM with capacity from 0.75 to 315 kW to choose repeated closing interval not less than 0.05 seconds.

Provided method allowing to define current, electromagnetic torque, IM rotation frequency values at network voltage unbalance. The specific of this method is that there is used simple symmetrical IM model, but unbalance terms provided using feeder (active-inductive elements) conducting IM with network. Thus to estimate IM operation safety there is opportunity to imitate unbalance variants.

Implemented IM confident parameters receiving methods analysis needed to make mathematical modeling of dynamic regimes showed that:

- different kind of empiric equations usage does not provide confident searched parameters value. This way got parameters are useful only to analyze steady-state regimes and static values;
- usage of mathematical modeling for clear information about IM processes in a complicated dynamic modes receiving gives the best and most credible results if equivalent circuit parameters sourced directly from producer or in experience way.

4A (4A90L 2Y3) series induction motor starting oscillograms and starting regime characteristics received by any of provided mathematical models comparison showed that the best results concur gives the model based on tests way received equivalent circuit parameters.