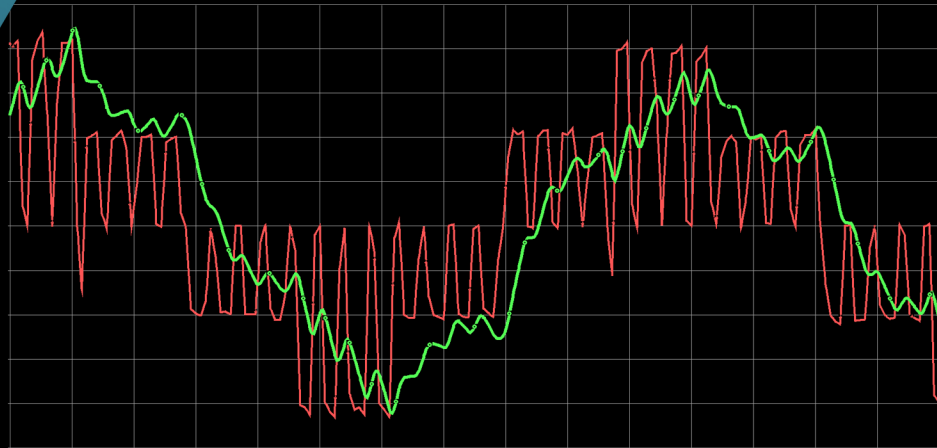


INDUCTION MOTOR COMPUTER MODELS IN THREE-PHASE STATOR REFERENCE FRAMES: A TECHNICAL HANDBOOK



Editors:

Mikhail Pustovetov

Konstantin Shukhmin

Sergey Goolak, Jonas Matijošius

Kateryna Kravchenko

Bentham Books

Induction Motor Computer Models in Three-Phase Stator Reference Frames: A Technical Handbook

Edited by

Mikhail Pustovetov

RIF Shipyard, Rostov-on-Don, Russia

Konstantin Shukhmin

EIM Training Pty Ltd, Cairns, Australia

Sergey Goolak

*State University of Infrastructure and Technologies, Kyiv,
Ukraine*

Jonas Matijošius

Vilnius Gediminas Technical University, Vilnius, Lithuania

&

Kateryna Kravchenko

University of Zilina, Zilina, Slovakia

Induction Motor Computer Models in Three-Phase Stator Reference Frames: A Technical Handbook

Editors: Mikhail Pustovetov, Konstantin Shukhmin, Sergey Goolak,
Jonas Matijošius & Kateryna Kravchenko

ISBN (Online): 978-981-5124-30-9

ISBN (Print): 978-981-5124-31-6

ISBN (Paperback): 978-981-5124-32-3

© 2023, Bentham Books imprint.

Published by Bentham Science Publishers Pte. Ltd. Singapore. All Rights Reserved.

First published in 2023.

BENTHAM SCIENCE PUBLISHERS LTD.

End User License Agreement (for non-institutional, personal use)

This is an agreement between you and Bentham Science Publishers Ltd. Please read this License Agreement carefully before using the book/echapter/ejournal (“**Work**”). Your use of the Work constitutes your agreement to the terms and conditions set forth in this License Agreement. If you do not agree to these terms and conditions then you should not use the Work.

Bentham Science Publishers agrees to grant you a non-exclusive, non-transferable limited license to use the Work subject to and in accordance with the following terms and conditions. This License Agreement is for non-library, personal use only. For a library / institutional / multi user license in respect of the Work, please contact: permission@benthamscience.net.

Usage Rules:

1. All rights reserved: The Work is the subject of copyright and Bentham Science Publishers either owns the Work (and the copyright in it) or is licensed to distribute the Work. You shall not copy, reproduce, modify, remove, delete, augment, add to, publish, transmit, sell, resell, create derivative works from, or in any way exploit the Work or make the Work available for others to do any of the same, in any form or by any means, in whole or in part, in each case without the prior written permission of Bentham Science Publishers, unless stated otherwise in this License Agreement.
2. You may download a copy of the Work on one occasion to one personal computer (including tablet, laptop, desktop, or other such devices). You may make one back-up copy of the Work to avoid losing it.
3. The unauthorised use or distribution of copyrighted or other proprietary content is illegal and could subject you to liability for substantial money damages. You will be liable for any damage resulting from your misuse of the Work or any violation of this License Agreement, including any infringement by you of copyrights or proprietary rights.

Disclaimer:

Bentham Science Publishers does not guarantee that the information in the Work is error-free, or warrant that it will meet your requirements or that access to the Work will be uninterrupted or error-free. The Work is provided "as is" without warranty of any kind, either express or implied or statutory, including, without limitation, implied warranties of merchantability and fitness for a particular purpose. The entire risk as to the results and performance of the Work is assumed by you. No responsibility is assumed by Bentham Science Publishers, its staff, editors and/or authors for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products instruction, advertisements or ideas contained in the Work.

Limitation of Liability:

In no event will Bentham Science Publishers, its staff, editors and/or authors, be liable for any damages, including, without limitation, special, incidental and/or consequential damages and/or damages for lost data and/or profits arising out of (whether directly or indirectly) the use or inability to use the Work. The entire liability of Bentham Science Publishers shall be limited to the amount actually paid by you for the Work.

General:

1. Any dispute or claim arising out of or in connection with this License Agreement or the Work (including non-contractual disputes or claims) will be governed by and construed in accordance with the laws of Singapore. Each party agrees that the courts of the state of Singapore shall have exclusive jurisdiction to settle any dispute or claim arising out of or in connection with this License Agreement or the Work (including non-contractual disputes or claims).
2. Your rights under this License Agreement will automatically terminate without notice and without the

need for a court order if at any point you breach any terms of this License Agreement. In no event will any delay or failure by Bentham Science Publishers in enforcing your compliance with this License Agreement constitute a waiver of any of its rights.

3. You acknowledge that you have read this License Agreement, and agree to be bound by its terms and conditions. To the extent that any other terms and conditions presented on any website of Bentham Science Publishers conflict with, or are inconsistent with, the terms and conditions set out in this License Agreement, you acknowledge that the terms and conditions set out in this License Agreement shall prevail.

Bentham Science Publishers Pte. Ltd.

80 Robinson Road #02-00

Singapore 068898

Singapore

Email: subscriptions@benthamscience.net



CONTENTS

FOREWORD	i
PREFACE	ii
LIST OF CONTRIBUTORS	iii
CHAPTER 1 A USE OF NONLINEAR COEFFICIENTS IN ORDINARY DIFFERENTIAL EQUATIONS OF MATHEMATICAL MODELS OF ELECTRICAL DEVICES DESCRIBING INDUCTANCE VS CURRENT OR MAGNETIC FLUX LINKAGE RELATIONSHIPS	1
<i>Mikhail Pustovetov and Konstantin Shukhmin</i>	
INTRODUCTION	1
COMMON CASE	2
SPECIAL CASE	4
CONCLUDING REMARKS	7
CONSENT FOR PUBLICATION	8
CONFLICT OF INTEREST	8
ACKNOWLEDGEMENT	8
REFERENCES	8
CHAPTER 2 APPROXIMATE CALCULATIONS OF INDUCTION MOTOR EQUIVALENT T-SHAPED CIRCUIT PARAMETERS WITH THE USE OF CATALOGUE DATA	10
<i>Mikhail Pustovetov, Konstantin Shukhmin, Sergey Goolak, Jonas Matijošius and Kateryna Kravchenko</i>	
INTRODUCTION	10
INITIAL DATA	11
CALCULATIONS OF PARAMETERS OF THE SIMPLIFIED T-SHAPED EQUIVALENT CIRCUIT OF IM	13
SETTING THE VALUE	19
CONCLUDING REMARKS	21
CONSENT FOR PUBLICATION	21
CONFLICT OF INTEREST	21
ACKNOWLEDGEMENT	22
REFERENCES	22
CHAPTER 3 THE SHAFT LOAD SIMULATIONS AND CALCULATIONS OF THE IM EFFICIENCY USING ORCAD PSPICE DESIGNER SOFTWARE: OBTAINING STATIC CHARACTERISTICS DATA BASED ON DYNAMIC MODEL MODIFICATIONS OF ELECTRICAL MACHINES	24
<i>Mikhail Pustovetov, Konstantin Shukhmin, Sergey Goolak, Jonas Matijošius and Kateryna Kravchenko</i>	
INTRODUCTION	24
LOAD TORQUE GENERATION DIAGRAMS	26
EFFICIENCY CALCULATION CIRCUIT	29
ELECTRICAL MACHINE DYNAMIC MODEL MODIFICATIONS FOR OBTAINING STATIC CHARACTERISTICS DATA	31
CONCLUDING REMARKS	33
CONSENT FOR PUBLICATION	33
CONFLICT OF INTEREST	33
ACKNOWLEDGEMENT	34
REFERENCES	34

CHAPTER 4 COMPUTER SIMULATION OF ELECTRIC DRIVE WITH INDUCTION MOTOR AND FLUID COUPLING	36
<i>Mikhail Pustovetov, Konstantin Shukhmin, Sergey Goolak, Jonas Matijošius and Kateryna Kravchenko</i>	
INTRODUCTION	36
THE EQUATION OF MOTION OF ELECTROHYDRODYNAMIC DRIVE WITH INDUCTION MOTOR AND FLUID COUPLING WITH CONSTANT FILLING	37
COMPUTER SIMULATION MODEL OF THE SELF-EMPTYING FLUID COUPLING	40
CONCLUDING REMARKS	44
CONSENT FOR PUBLICATION	44
CONFLICT OF INTEREST	44
ACKNOWLEDGEMENT	45
REFERENCES	45
CHAPTER 5 AN IMPROVEMENT OF THE INDUCTION TRACTION MOTOR'S MATHEMATICAL MODEL AT ASYMMETRY OF STATOR WINDINGS	46
<i>Sergey Goolak</i>	
INTRODUCTION	46
LITERATURE REVIEW AND PROBLEM STATEMENT	47
THE AIM AND OBJECTIVES OF THE STUDY	49
COMPONENTS AND METHODS OF THE STUDY	50
A MATHEMATICAL MODEL OF THE INDUCTION TRACTION MOTOR	51
Magnetization Branch Resistance Value Calculations Taking into Account the Magnetic Saturation Caused by the Main Magnetic Flux	57
Analytical Method to Account for Variations in Geometrical Sizes of the ITM Windings which Affect Parameters of the ITM	59
THE SIMULATION MODEL OF ITM	63
SIMULATION RESULTS	65
ANALYSIS OF THE ITM'S SIMULATION RESULTS	70
CONCLUDING REMARKS	72
DISCLOSURE	74
CONSENT FOR PUBLICATION	74
CONFLICT OF INTEREST	74
ACKNOWLEDGEMENT	74
REFERENCES	74
CHAPTER 6 SELECTED INFORMATION OF THE AUXILIARY ELECTRIC DRIVE OF AN AC ELECTRIC LOCOMOTIVE, COMPRISING THREE-PHASE INDUCTION MOTORS, A CAPACITIVE PHASE SPLITTER AND A THYRISTOR FREQUENCY AND NUMBER OF PHASE CONVERTER	78
<i>Mikhail Pustovetov, Konstantin Shukhmin, Sergey Goolak, Jonas Matijošius and Kateryna Kravchenko</i>	
INTRODUCTION	78
THE CAPACITIVE PHASE SPLITTER ONBOARD OF LOCOMOTIVE	80
STATISTICS OF FAILURES OF AUXILIARY INDUCTION MOTORS	83
FAILURE CAUSES OF AUXILIARY INDUCTION MOTORS	88
CONCLUDING REMARKS	89
CONSENT FOR PUBLICATION	89
CONFLICT OF INTEREST	89
ACKNOWLEDGEMENT	89
REFERENCES	89

CHAPTER 7 STARTING MODE COMPUTER SIMULATION OF AUXILIARY INDUCTION MOTOR ONBOARD OF AN AC ELECTRICAL LOCOMOTIVE EQUIPPED WITH A CAPACITIVE PHASE SPLITTER	92
<i>Mikhail Pustovetov and Konstantin Shukhmin</i>	
INTRODUCTION	92
MOTOR-COMPRESSOR STARTING MODE SIMULATIONS	93
SIMULATION OF THE SIMULTANEOUS START-UPS OF A MOTOR-FAN AND A MOTOR-COMPRESSOR SUPPLIED BY THE SAME SYSTEM	106
CONCLUDING REMARKS	109
CONSENT FOR PUBLICATION	114
CONFLICT OF INTEREST	114
ACKNOWLEDGEMENT	114
REFERENCES	114
CHAPTER 8 MATHEMATICAL MODELING OF THERMAL PROCESSES IN AN AUXILIARY THREE-PHASE INDUCTION MOTOR OF AN ELECTRIC LOCOMOTIVE WITH UNBALANCED SUPPLY VOLTAGES AND SQUIRREL-CAGE DEFECTS	115
<i>Mikhail Pustovetov and Konstantin Shukhmin</i>	
INTRODUCTION	115
FEATURES OF THE DEVELOPED THERMAL MATHEMATICAL MODEL OF A THREE-PHASE INDUCTION MOTOR	116
CAPABILITY VALIDATION OF THE THERMAL MATHEMATICAL MODEL OF A THREE-PHASE INDUCTION MOTOR	141
REFINEMENT OF THE MATHEMATICAL MODEL OF AN AUXILIARY ELECTRICAL DRIVE OF AN ELECTRICAL LOCOMOTIVE WHEN THE INDUCTION MOTORS ARE SUPPLIED BY A CAPACITIVE PHASE SPLITTER	145
CONCLUDING REMARKS	150
APPENDIX	150
CONSENT FOR PUBLICATION	176
CONFLICT OF INTEREST	176
ACKNOWLEDGEMENT	176
REFERENCES	176
SUBJECT INDEX	39:

FOREWORD

Dear reader!

The book you are holding in your hands is devoted to computer simulation of three-phase induction electric motors. This type of electrical machine is the most popular and numerous in the world. The authors propose original approaches to the preparation of initial data for simulation, techniques for using building blocks from CAD, methods for building models of widely used mechanisms, and numerical characteristics of some induction motors. The book focuses on the use of a mathematical model of an induction electric machine in the three-phase stator reference frame. Much attention is paid to induction motors operated onboard of the electric rolling stock of railways, including those powered by a three-phase unbalanced voltage system. The book provides a detailed description of a computer model developed to study non-stationary thermal processes in a three-phase induction motor with a squirrel-cage rotor. This thermal model is developed as an addition or extension to the previously published computer model for the study of electromechanical processes. Both models function simultaneously and jointly within the same project within the same CAD system. It is necessary to note the intelligibility of the presentation of the material, a large number of illustrations and explanations, and comparisons of simulation results and experimental data, which make the book a convenient reference tool for an engineer to solve problems of analysis or to conduct synthesis of electrical systems using computer simulating tools. The book is based on the results of scientific and technical research carried out by the authors over a considerable period of time. It is worth stating the fact that the book can rightfully be classified as high-quality technical literature. I'm sure that this book will be useful to a wide range of specialists, as well as students of electrical engineering specialties.

Dr. Sc., Professor Neyman Vladimir
Department "Theoretical Basis of Electrical Engineering"
Novosibirsk State Technical University (NETI)
Novosibirsk
Russia

PREFACE

According to the outcomes of modern research in the field of electromechanics, approaches to the design of induction motors, their drives, and control systems have changed significantly due to some dedicated simulation software packages which enable engineers and researchers to apply and enhance new calculation algorithms of electrical, electromagnetic, thermal and other associated processes. Nowadays such engineering software packages for example, MatLab, Electronics Workbench, Micro-Cap, OrCAD, JMAG, ANSYS, EMWorks and others are commonly used for the design, analysis, and debugging of various electrical applications including induction machines and drives. Their tool and component libraries as well as the features of combining electrical schematic diagrams and circuits with operational block diagrams have opened up a wide range of possibilities for engineers and researchers. Examples of virtual models described in this book were designed and analysed with the aid of OrCAD and MathLab. The equations of the mathematical model of a three-phase induction motor in a three-phase reference frame are useful for comparison of the calculated and experimental curves of currents and phase voltages. These equations are suitable, without additional transformations, for consideration of induction motor operation models at asymmetrical characteristics of supply and/or equivalent circuit parameters of the said motors. The authors of this book hope that the principles and specific examples described herein will have value for engineers, researchers, graduate and post-graduate students, and academics dealing with the design and analysis of electromechanical systems.

Mikhail Pustovetov

RIF Shipyard, Rostov-on-Don, Russia

Konstantin Shukhmin

EIM Training Pty Ltd, Cairns, Australia

Sergey Goolak

State University of Infrastructure and Technologies, Kyiv, Ukraine

Jonas Matijošius

Vilnius Gediminas Technical University, Vilnius, Lithuania

&

Kateryna Kravchenko

University of Zilina, Zilina, Slovakia

List of Contributors

Jonas Matijošius	Vilnius Gediminas Technical University, Vilnius, Lithuania
Kateryna Kravchenko	University of Zilina, Zilina, Slovakia
Konstantin Shukhmin	EIM Training Pty Ltd, Cairns, Australia
Mikhail Pustovetov	RIF Shipyard, Rostov-on-Don, Russia
Sergey Goolak	State University of Infrastructure and Technologies, Kyiv, Ukraine

CHAPTER 1

A Use of Nonlinear Coefficients in Ordinary Differential Equations of Mathematical Models of Electrical Devices Describing Inductance vs Current or Magnetic Flux Linkage Relationships**Mikhail Pustovetov^{1,*} and Konstantin Shukhmin²**¹ *RIF Shipyard, Rostov-on-Don, Russia*² *EIM Training Pty Ltd, Cairns, Australia*

Abstract: When mathematical models of electromagnetic devices are described by ordinary differential equations, then the magnetization curves of their cores are often expressed with a help of nonlinear coefficients. Sometimes such an approach is considered questionable, and therefore, the purpose of this chapter is to prove its admissibility.

Keywords: Choke, Induction motor, Magnetization curve, Mathematical model, Nonlinearity, Ordinary differential equations, Transformer.

INTRODUCTION

Some or even all parameters in the equations of an induction motor (IM)/drive mathematical model (MM) can vary over time or other characteristics of the system. In the equations of electromechanical energy conversion, it is common to describe coefficients in front of the independent variables as parameters [1]. Herein the term “parameters” is used for the inductances and resistances of the equivalent circuit and combined moment of inertia of the rotating parts on the motor’s shaft. Depending on the degree of precision or abstraction of the MM, the values of some and even all coefficients could be set as constants. Some of the IM practical problems were described and solved in [2] and [3] with a help of MM where all of the parameters were constants or allowed for the curvature of magnetic saturation along the main magnetic flux path.

* **Corresponding author Mikhail Pustovetov:** RIF Shipyard, Rostov-on-Don, Russia; Tel: +79885651027, E-mail: mgsn2006@rambler.ru

Often used in ordinary differential equations (ODE), nonlinear coefficients describe inductance in electromagnetic devices (electrical machines [4, 5], transformers [6, 7], and chokes [3] vs current or magnetic flux linkage.

Sometimes the validity of such approximation of the magnetization curves is questioned by researchers dealing with MM of electromagnetic devices. A simple answer to these doubts is just an absence of data required for precise equations of the magnetic curves.

COMMON CASE

A time derivative of the magnetic flux linkage is:

$$\frac{d\Psi}{dt} = \frac{d(L(i(t)) \cdot i(t))}{dt} \quad (1.1)$$

Quite often the equation is solely influenced by the magnetic saturation of cores upon their permeability.

And for this particular reason in MMs:

- Magnetically symmetric structures are used for 3-phase IM and transformers;
- In IMs, smooth airgap surfaces are considered, neglecting any effects of magnetic field serration;
- Adopted coordinate systems in IM are stationary which ensures the absence of the periodic coefficients [1, 4, 8, 9]. Those coefficients would allow for periodic changes in the mutual inductance of the phases during the rotation of the rotor.
- Choke's core and other parts are assumed as stationary.

The inductance below depends on the absolute value of current or magnetic flux linkage and can be expressed as the sum of constant and variable components:

$$L(i(t)) = L_{\text{const}} + L_{\text{var}}(i(t)), \quad (1.2)$$

therefore

$$\begin{aligned}
\frac{d\Psi}{dt} &= \frac{d(L(i(t)) \cdot i(t))}{dt} = \frac{d((L_{\text{const}} + L_{\text{var}}(i(t))) \cdot i(t))}{dt} = \\
&= L_{\text{const}} \frac{di(t)}{dt} + \frac{d(L_{\text{var}}(i(t)) \cdot i(t))}{dt} = \\
&= L_{\text{const}} \frac{di(t)}{dt} + L_{\text{var}}(i(t)) \frac{di(t)}{dt} + i(t) \frac{dL_{\text{var}}(i(t))}{dt} = \\
&= L_{\text{const}} \frac{di(t)}{dt} + L_{\text{var}}(i(t)) \frac{di(t)}{dt} + i(t) \frac{dL_{\text{var}}(i(t))}{di(t)} \cdot \frac{di(t)}{dt}.
\end{aligned} \tag{1.3}$$

Due to the inverted symmetry of the magnetization curve we can conclude that in a steady-state period of alternating current, its instantaneous value has double the number of the sine wave periods in the variable component of the inductance corresponding to the magnetization symmetry.

Oscillations of the magnetization current of IMs and transformers due to the filtering properties of inductors in general and a large value of the main inductance are basically sinusoidal even when supplied with a rectangular form of PWM voltage.

Fig. (1.1) [3] shows an example of transient changes in current and inductance of a choke with a magnetic core after the moment when its AC voltage supply is turned ON.

Assuming that the oscillations of the current have similar frequency and shape as the variable component of the inductance, then

$$\frac{dL_{\text{var}}(i(t))}{di(t)} = \text{const} = C_1 \tag{1.4}$$

Then

$$\begin{aligned}
\frac{d\Psi}{dt} &= L_{\text{const}} \frac{di(t)}{dt} + L_{\text{var}}(i(t)) \frac{di(t)}{dt} + i(t) \frac{dL_{\text{var}}(i(t))}{di(t)} \cdot \frac{di(t)}{dt} = \\
&= L_{\text{const}} \frac{di(t)}{dt} + L_{\text{var}}(i(t)) \frac{di(t)}{dt} + i(t) \cdot C_1 \cdot \frac{di(t)}{dt} = \\
&= (L_{\text{const}} + L_{\text{var}}(i(t)) + i(t) \cdot C_1) \frac{di(t)}{dt}.
\end{aligned} \tag{1.5}$$

Approximate Calculations of Induction Motor Equivalent T-Shaped Circuit Parameters with the Use of Catalogue Data

Mikhail Pustovetov^{1,*}, Konstantin Shukhmin², Sergey Goolak³, Jonas Matijošius⁴ and Kateryna Kravchenko⁵

¹ RIF Shipyard, Rostov-on-Don, Russia

² EIM Training Pty Ltd, Cairns, Australia

³ State University of Infrastructure and Technologies, Kyiv, Ukraine

⁴ Vilniaus Gedimino Technikos Universitetas, Vilnius, Lithuania

⁵ University of Zilina, Zilina, Slovakia

Abstract: This chapter is dedicated to an algorithm of approximate calculations of three-phase induction motor equivalent T-shaped circuit parameters such as resistances and inductances. These calculations are conducted with the use of catalog or reference book data containing information related to rated shaft power, angular speed or slip, efficiency, power factor, line RMS voltage and the ratio of starting to rated currents.

Keywords: Parameters of induction motor, Per phase T-shaped equivalent circuit.

INTRODUCTION

It is an essential task to determine the parameters of a T-shaped equivalent circuit prior to the simulation processes in applications driven by three-phase, squirrel-cage IMs. Often these parameters are not readily available for engineers and researchers who are involved in the modeling of electromechanical systems with induction motors, therefore, there are a number of publications [1 – 10] dedicated to derivation of such parameters from induction machines' catalog data. Accurate and efficient derivation of the equivalent circuit parameters is a current and in-demand issue which is addressed in this chapter.

It is necessary to obtain the physical values of r_1 , r'_2 , $L_{\sigma 1}$, L'_2 , and L_{μ} of the IM T-shaped equivalent circuit for conducting computer simulation studies.

* Corresponding author Mikhail Pustovetov: RIF Shipyard, Rostov-on-Don, Russia; Tel: +79885651027; E-mail: mgsn2006@rambler.ru

INITIAL DATA

First we need to convert the relative (p.u.) values of the resistances and reactances into their physical values in Ohms.

$$r = r_* \frac{V_{1\text{phase rated}}}{I_{1\text{phase rated}}}; x = x_* \frac{V_{1\text{phase rated}}}{I_{1\text{phase rated}}}, \quad (2.1)$$

where the motor's rated phase current can be easily found in catalogs or calculated from other parameters:

$$I_{1\text{phase rated}} = \frac{P_{2\text{ rated}}}{3 \cdot V_{1\text{phase rated}} \cdot \text{Efficiency}_{\text{rated}} \cdot \cos \phi_{\text{rated}}}. \quad (2.2)$$

An overwhelming majority of IM reference literature such as [11 - 13] and others provide data similar to Table 2.1, which can be successfully utilized to derive the necessary parameters of the T-shaped equivalent circuit.

Table 2.1. IM data given in reference books.

#	Performance Data	Designation
1	Rated shaft power, W	$P_{2\text{rated}}$
2	Rated speed, rpm or rated slip, %	n_{rated} or $S_{\text{rated}\%}$
3	Efficiency at rated mode, p.u.	$\text{Efficiency}_{\text{rated}}$
4	Power factor at rated mode, p.u.	$\cos \theta_{\text{rated}}$
5	Rated line voltage RMS, V	$V_{1\text{ph-ph rated}}$
6	Ratio of starting current to rated current, p.u.	$I_{1\text{phase start}} / I_{1\text{phase rated}}$

From theory, practice, design and testing of IMs, one could recall several p.u. values of a general purpose machine with a power rating from units to hundreds of kilowatts. The following ranges of typical values of resistances and reactances are given in [14]: $r_{1*} \approx r_{2*}' = 0.02 \dots 0.03$, $x_{\sigma 1*} = 0.08 \dots 0.14$, $x_{2*}' = 0.1 \dots 0.16$, $x_{\mu*} = 2 \dots 4$ as well as $x_{\sigma 1} / x_{2}' \approx 0.7 \dots 1.0$ - in [15].

At the rated load IM ratio of the total to copper losses is:

$$k_{cl} = \frac{P_{cl \text{ rated}}}{P_{2 \text{ rated}} \left(\frac{1}{\text{Efficiency}_{\text{rated}}} - 1 \right)} \approx 0.5 \dots 0.8 \quad (2.3)$$

For example, for a 55 kW four-pole IM with increased slip (NEMA Design D [16]) such as NVA-55, this ratio is $k_{cl} = 0.68$; or for a 110 kW two-pole general purpose IM (NEMA Design A) AZHV250M2RUKHL2, the ratio is $k_{cl} = 0.75$.

Row six in Table 2.1 is the inrush or starting current (p.u. or %) and usually manufacturer's catalogs or other references give the $I_{1\text{phase start}} / I_{1\text{phase rated}}$ based on the test results.

To reduce the starting current and, at the same time, increase the starting torque of squirrel – cage IMs, it is common to utilize the skin effect phenomenon which increases resistance of the rotor winding during the start. Therefore to account for the skin effect, the value of $I_{1\text{phase start}} / I_{1\text{phase rated}}$ has to be measured.

One can assume that the skin effect causes the r_2 to increase reducing the starting current and increasing the starting torque. However, this is a known fact that the experimental value of the starting current is always higher than that calculated by the designers. The reason for such discrepancy is the Eddy current loops created by the imperfection of lamination. These loops can appear along the squirrel – cage bars as well as across them. Therefore this phenomenon reduces equivalent resistance of the rotor winding due to the additional parallel branch in the equivalent circuit which in its turn increases the motor's current more noticeably at the start and low speed conditions.

The question of the size of this difference for different types of IM requires additional research.

The discrepancy between calculated and measured values of the starting current needs to be accounted for with the formula (2.4) and perhaps could be a subject of further studies.

For example, for IM of type NVA-55:

$$k_I = \left(\frac{I_{1\text{phase start}}}{I_{1\text{phase rated}}} \right)_{\text{calculated}} // \left(\frac{I_{1\text{phase start}}}{I_{1\text{phase rated}}} \right)_{\text{measured}} = 0.9 \quad (2.4)$$

and for IM type AZHV250M2RUKHL2 $k_I = 0.64 \dots 0.68$.

The Shaft Load Simulations and Calculations of the IM Efficiency Using OrCAD PSpice Designer Software: Obtaining Static Characteristics Data Based on Dynamic Model Modifications of Electrical Machines

Mikhail Pustovetov^{*},¹, Konstantin Shukhmin², Sergey Goolak³, Jonas Matijošius⁴ and Kateryna Kravchenko⁵

¹ RIF Shipyard, Rostov-on-Don, Russia

² EIM Training Pty Ltd, Cairns, Australia

³ State University of Infrastructure and Technologies, Kyiv, Ukraine

⁴ Vilniaus Gedimino Technikos Universitetas, Vilnius, Lithuania

⁵ University of Zilina, Zilina, Slovakia

Abstract: In this chapter, authors suggest an approach to the shaft load simulations and calculations of the electrical machine efficiency with the use of OrCAD PSpice Designer Software, and in particular, visual programming of analogue component blocks. Also, a method for modifying the EM dynamic model is put forward. This method enables researchers and designers to acquire data for plotting static mechanical, electromechanical and performance curves vs the angular speed of the rotor. These data are obtained by modifications to the block-diagram of the motion equation of the drive where the instantaneous values of the electromagnetic torque of the motor and the load torque are equal by absolute values and opposite to each direction.

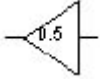




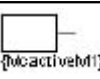
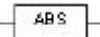
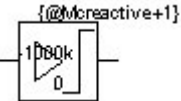



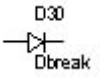
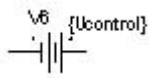
Keywords: Analog component, Dynamic Model, Efficiency, Electrical Machine, Equation of Motion, load Torque, PSpice, Simulation, Static Curve.

INTRODUCTION

Table 3.1 shows typical analogue components (blocks) of the OrCAD software [1, 2]. These blocks are used to build the models of information nodes of the load torque and efficiency. For the power function, X^y the block PWRS is used with the X value signal at its input.

^{*} Corresponding author Mikhail Pustovetov: RIF Shipyard, Rostov-on-Don, Russia; Tel: +79885651027, E-mail: mgns2006@rambler.r

Table 3.1. OrCAD [1, 2] analogue components (blocks) used for the model building.

Block name	Graphic symbol	Name of the library	Block description
1	2	3	4
GAIN		ABM.SLB	Proportional amplifier
DIFF		ABM.SLB	Subtraction of voltages
SUM		ABM.SLB	Summation of voltages
MULT		ABM.SLB	Multiplication of voltages
PWRS		ABM.SLB	Power function
CONST		ABM.SLB	Constant DC voltage source
ABS		ABM.SLB	Absolute value
GLIMIT		ABM.SLB	Amplifier - hard limiter
LIMIT		ABM.SLB	Hard limiter
R		ANALOG.SLB	Resistor
Sbreak	 S V _{OFF} = 0.0V V _{ON} = 0.001V	BREAKOUT.SLB	Voltage controlled switch
Dbreak	 D30 Dbreak	BREAKOUT.SLB	Diode
VDC	 V6 {Ucontrol}	SOURCE.SLB	Constant DC voltage source

The PWRS block is the preferred option over the PWR due to their difference of processing negative input signals. The PWR block, regardless of its power, outputs the positive signal only. Whereas the PWRS block applies sign (whether “+” or “-“) of the input signal to the output signal regardless of the block’s power. Instances of the Dbreak block are used because they ideally execute the function of one-sided conduction (no breakdown voltage and no reverse conduction).

LOAD TORQUE GENERATION DIAGRAMS

The segment of the model shown in Fig. (3.1) represents generation of the shaft load torque by taking into account its following components:

- The active load torque M_{activeM2} ;
- The reactive load torque of constant magnitude $M_{\text{reactiveM2}}$;
- The reactive load torque such as viscous friction M_{ventM2} ;
- The torque caused by mechanical (ventilation) losses $M_{\text{ventlossesM2}}$.

The designation “M2” in the end of torque indexes means that the simulation study is for the motor identified as M2 and distinguishing it from other motors.

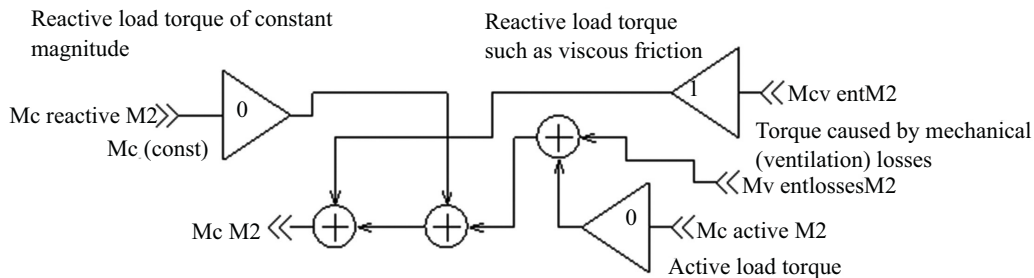


Fig. (3.1). A segment of the simulation model used for generation the electrical machine shaft load torque.

The balancing and tuning of the load torque components are performed by changing the individual gain values of the corresponding blocks shown in Fig. (3.1). The proposed diagram of the shaft load torque enables simulations of invertible operation models of the electrical machine. In case of a viscous friction type load on the motor shaft and the torque-speed characteristic is at the power X_0 , it is recommended to program the model as shown in Fig. (3.2). The shaft rpm signal depending on its direction (forward or reverse) is inputted into two PWRS blocks connected in parallel. One of these parallel PWRS blocks has its power value set at X_0 and its output is connected in series to the block ABS. Another PWRS block has its power value set to 0.

Computer Simulation of Electric Drive with Induction Motor and Fluid Coupling

Mikhail Pustovetov^{1,*}, Konstantin Shukhmin², Sergey Goolak³, Jonas Matijošius⁴ and Kateryna Kravchenko⁵

¹ RIF Shipyard, Rostov-on-Don, Russia

² EIM Training Pty Ltd, Cairns, Australia

³ State University of Infrastructure and Technologies, Kyiv, Ukraine

⁴ Vilniaus Gedimino Technikos Universitetas, Vilnius, Lithuania

⁵ University of Zilina, Zilina, Slovakia

Abstract: A new approach to the shaft load simulation with the different types of fluid coupling is introduced herein. The presented simulation results are obtained for an electrohydrodynamic drive at different load modes and types of fluid coupling such as: with constant filling; static self-emptying (traction fluid coupling) and dynamic self-emptying (limiting fluid coupling). The chapter also provides an example of fluid coupling parameters and characteristics as well as depicts the following operation modes of the system: acceleration; no-load; load and overload on the turbine shaft.

Keywords: Analog component, A Relative Slip Of Impellers, Equation of motion, Fluid coupling, Induction motor, PSpice.

INTRODUCTION

Fluid couplings (FC) are widely used in a variety of electrical power drives such as belts; chain scrapers and plate conveyors; elevators; axial fans and smoke exhausters; feed pumps and gas turbines; mills and crushers; bucket wheel excavators; road rollers; concrete mixers; drum dryers and centrifuges; hydromechanical transmissions of diesel locomotives, cars and tractors. The use of FC as part of an electrical power drive has the following advantages:

* Corresponding author Mikhail Pustovetov: RIF Shipyard, Rostov-on-Don, Russia; Tel: +79885651027, E-mail: mgsn2006@rambler.ru

- Improved static and starting characteristics of the electrical drives;
- Protection of the drives against dynamic overloads such as sudden stops causing excessive vibrations and jolts of the electrical machines and driven mechanisms;
- Limiting the torque to safe values during starts and braking thereby protecting the driving and driven components from undue stresses;
- Damping and reducing the amplitude of prolonged torsional vibrations arose from the drive's normal operation.

In some cases, the FC is a link between the power shaft of the induction motor (IM) and the driven mechanism. FC provides for a smooth acceleration of the drive and enables the direct start of IMs with or without the coupled load. IM shaft load mathematical models of electrical drives with FCs are more complex compared to the models described in Chapter 3. More information about the design, principle of operation, and characteristics of the FCs can be found, for example, in [1 - 4].

THE EQUATION OF MOTION OF ELECTROHYDRODYNAMIC DRIVE WITH INDUCTION MOTOR AND FLUID COUPLING WITH CONSTANT FILLING

The three-phase IM MM equations are provided in [5 - 7].

The following structure diagram of the drive's mechanical part was adopted from examples considered in [8, 9]. This diagram includes: the IM shaft, the speed multiplier gearbox, the pump shaft, FC and the turbine shaft to which the mechanical load is applied (Fig. 4.1).

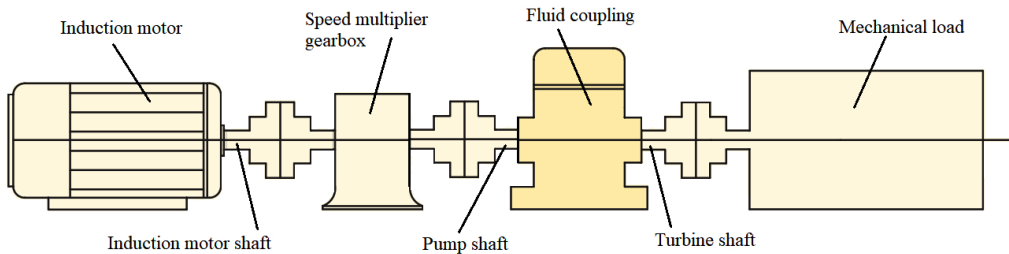


Fig. (4.1). Structure diagram of induction motor drive system.

The equation of motion for the IM shaft is:

$$\frac{d\omega_r}{dt} = \frac{1}{J} \left(T_{em} - \frac{T_{pumpFC}}{j_G} - \frac{P_{mech0}}{\omega_{r0}} \left(\frac{\omega_r}{\omega_{r0}} \right)^{1.7} - k_{load_pump} \cdot \omega_r \right). \quad (4.1)$$

Where: J is the moment of inertia of the rotating parts: IM rotor, gearbox and pump with the working fluid;

J_G -gear ratio of the gearbox is the ratio of the IM rotor rotation frequency to the rotation frequency of the FC pump.

J_G is the gearbox ratio between the rotational frequencies of the IM rotor and the FC pump:

$$j_G = \omega_r / \omega_{pump} ; \quad (4.2)$$

T_{pumpFC} / j_G is the torque on the drive shaft of the FC pump, reduced to the shaft of the IM rotor;

$(p_{mech0} / \omega_{r0}) \cdot (\omega_r / \omega_{r0})^{1.7}$ is the torque losses for the IM's self-cooling;

p_{mech0} is the IM mechanical losses at the ideal no load conditions;

ω_{r0} is IM rotation frequency at the ideal no load conditions;

$k_{load_pump} \cdot \omega_r$ is the combined FC pbox rotation resistance torque is reduced to the IM shaft.

Instantaneous value of the shaft power of IM:

$$P_2 = \omega_r \cdot M_{pumpFC} / j_G . \quad (4.3)$$

The physical and mathematical models of the FC with constant filling are described in [10] and were taken as the base. Torque on the FC pump shaft:

$$T_{pumpFC} = \rho(\omega_{pump} r_2^2 - \omega_{turbine} r_1^2) Q , \quad (4.4)$$

where Q , m³/s is the flow rate of the working fluid in the FC:

$$Q = \frac{900 g b_2 D^4 \omega_{pump} \lambda(\varepsilon)}{\pi^2 r_1^2 \left[1 - \frac{r_1^2}{r_2^2} (1 - \varepsilon) \right]} ; \quad (4.5)$$

An Improvement of the Induction Traction Motor's Mathematical Model at Asymmetry of Stator Windings

Sergey Goolak^{1,*}

¹ State University of Infrastructure and Technologies, Kyiv, Ukraine

Abstract: The author proposes an improved version of the mathematical and computer model of a three-phase induction motor in the three-phase braked coordinates (in the three-phase stator reference frame), which proves the correctness of the starter winding asymmetry considerations in electrical machines. The chapter presents the parameters and characteristics of an induction traction motor type STA-1200 manufactured in Ukraine. A comparative analysis of the simulation results for intact and damaged motors has been carried out.

Keywords: Asymmetric Stator Windings, Induction Traction Motor, MATLAB, Non-Symmetric.

INTRODUCTION

It is impossible to manage railroad electrical rolling stock efficiently without optimal control over all of its components [1, 2]. The rolling stock operation is associated with high electricity consumption, which renders relevance to the task of reducing the losses within its systems and primarily in the traction electrical drive [3, 4]. In order to find ways to reduce losses in the traction electrical drive, electrodynamic processes and their components should be investigated. Studying electrodynamic processes of the rolling stock traction electrical drives requires the aid of a simulation model for accurate calculation of the required parameters of the drive [5]. The modern rolling stock commonly utilizes induction traction electrical motors (ITM) as the main traction motors due to their advantages over the commutator traction electric motors. These advantages are: greater power at the same mass and size, simplicity of design, high reliability, low maintenance, and greater efficiency [6].

* Corresponding author **Sergey Goolak**: State University of Infrastructure and Technologies, Kyiv, Ukraine; Tel: +380965631253, E-mail: sgoolak@gmail.com

There are several approaches to the modeling of induction electric motors. They are primarily associated with the choice of a coordinate system for implementing the model algorithms. The simplest approach is to build a mathematical model of an induction motor using a single-phase coordinate system [7, 8]. Such models have proven to be effective under the condition of symmetry of all motor windings. Otherwise, the use of single-phase coordinates is invalid.

For one reason or another, asymmetric modes [9] may occur during the induction motor operation in the stator windings. Therefore a three-phase coordinate system [10, 11] is used for modeling such asymmetric modes.

In three-phase induction electric motors, the stator and rotor magnetic circuits are permeated with a rotating magnetic flux of corresponding poles [12, 13]. The saturation of the main magnetic flux is created by all phases throughout the entire magnetic system. Thus, when building a model of the induction motor (IM), one should take into consideration the saturation effect on the value of the IM's main inductance.

When modeling induction electrical motors, the correct selection of the resistance of the magnetic circuit is essential in terms of losses in this circuit [14]. These losses directly affect such performance characteristics of the IM as the power factor and efficiency. A mathematical model of an ITM which takes into account the stator asymmetry and saturation and losses of the magnetic circuit would provide for high calculation accuracy of the IM's electrodynamic processes. These models enable accurate determination of the energy characteristics of the ITMs and their drives.

LITERATURE REVIEW AND PROBLEM STATEMENT

The choice of the ITM mathematical model is influenced by the possibility to consider a series of assumptions [15, 16]. The first assumption is about the ITM power supply system. Several authors recommend that the power supply system of the induction motor should be considered symmetrical and sinusoidal while the stator and rotor windings are symmetrical. Another assumption is that the air gap between the IM's stator and rotor is smooth neglecting its serrated quality.

When controlling a traction drive with induction motors, there are several methods for adjusting the motor shaft rotation frequency. These are the current control [17], the vector control [18] and the direct torque control [19]. All these methods utilize an autonomous voltage inverter (AVI) as a power supply for the ITMs. The choice of optimal operation (control) mode vs movement modes of the vehicle was considered in the publication [20] alongside the basic modes of operation of the traction induction drive. It is impossible for an AVI to have all its

elements with completely identical parameters and therefore the voltage system on the inverter output terminals is asymmetrical [21]. A study [22] considers the modes of operation of the induction traction drive on a rolling stock with energy storage. However, the selection of the motor parameters is carried out on the basis of a mathematical model with many assumptions. Additionally, the underlying control algorithm of the AVI valves is the pulse-width modulation (PWM). When an AVI with PWM is used to power an ITM, there is a dilemma associated with the following factors. On one hand, the higher the modulation frequency of the PWM, the closer the shape of phase voltage to the sine wave providing for the significant component of the fundamental harmonic. On the other hand, the power transistors which are used as the modulating “valves” in the AVI are low-frequency devices and increase the modulating frequency, even within the operating range, causing an increase in the transistor’s temperature and consequently their resistance which in turn reduces inverter’s efficiency. Therefore it is impossible for an AVI to supply an ITM with a perfect sine wave voltage [23] and when ITM drives, it is incorrect to assume that the voltage supply system is symmetrical and sinusoidal.

A solution to this issue is suggested in publications [24] and [25]. Wherein the author proposes for computer modeling and simulations of electrical drives to use a three-phase coordinate system and represent IM’s electrical part as a circuit with resistances and inductances. This method has enabled researchers to simulate the operation of IM supplied from an asymmetrical non-sinusoidal voltage system. Additionally, the author of some studies ([24] and [25]) has offered selection algorithms for resistance of the IM’s magnetic circuit and for consideration of the saturation of this circuit. Despite the proper approach to modeling of the IM electromechanical processes, the cited studies do cover the asymmetric modes specific to the ITM during its operation. In case of such modes, not only the resistances and inductances of the damaged phases are changed but also the mutual inductance of phases and the complete (main) inductance of the magnetization branch. A procedure for determining the mutual inductance when changing the dimensions of its windings is reported [26]. However, the cited study provides only the algorithm for the mathematical model and does not describe the implementation of the algorithm.

An implementation of the algorithm proposed in a study [26] is illustrated [16]. However, the cited work [16] considers only changes in the local mutual inductances of the stator and the rotor *vs* changes in the windings’ geometric dimensions. The local mutual inductances between the stator and rotor windings were not taken into consideration in this study [16]. An IM model presented in the study [16] is compiled in the form of structural schemes; and it cannot account for

Selected Information of the Auxiliary Electric Drive of an AC Electric Locomotive, Comprising Three-Phase Induction Motors, a Capacitive Phase Splitter and a Thyristor Frequency and Number of Phase Converter

Mikhail Pustovetov^{1,*}, Konstantin Shukhmin², Sergey Goolak³, Jonas Matijošius⁴ and Kateryna Kravchenko⁵

¹ RIF Shipyard, Rostov-on-Don, Russia

² EIM Training Pty Ltd, Cairns, Australia

³ State University of Infrastructure and Technologies, Kyiv, Ukraine

⁴ Vilniaus Gedimino Technikos Universitetas, Vilnius, Lithuania

⁵ University of Zilina, Zilina, Slovakia

Abstract: This chapter provides an electrical schematic diagram of the power circuits of an auxiliary electric drive with a capacitive phase splitter and 3-phase induction motors onboard of an AC electric locomotive and the statistics and root causes of typical failures of the induction motors operating as part of such a circuit. A conclusion is made about the expediency of simulating thermal processes in the auxiliary induction motors.

Keywords: AC electrical locomotive, Auxiliary Electric Drive, Phase Splitter, 3-Phase Induction Motor.

INTRODUCTION

Electromechanical phase splitters are used in Russia and India [1 - 3] onboard of electric trains and electrical locomotives to transform the single-phase AC voltage into the three-phase voltage to feed auxiliary electric drives with IM driving the fans and the air compressors. Fig. (6.1) shows the schematic diagram of the rotary phase splitter, where C_1 is the run and C_2 is the start-up capacitors. The phase splitters are the IMs with a symmetrical or asymmetrical stator winding and with

* Corresponding author Mikhail Pustovetov: RIF Shipyard, Rostov-on-Don, Russia; Tel: +79885651027, E-mail: mgsn2006@rambler.ru

no or low load on the shaft. The phase splitter can be considered as the combined single-phase IM and the three-phase synchronous generator.

In accordance with the terminology, adopted in India, the phase splitter is called the Arno converter [3].

After completion of the starting process [1, 2], the rotor of the electromechanical phase splitter is continuously rotating. This ensures reliable start of the three-phase auxiliary IMs driving compressors, fans and pumps. As the rotational speed of the phase splitter increases, the reverse field is significantly reduced by the rotor, and at the operating modes, the rotational field becomes almost circular with an asymmetry coefficient of 2...10%. Part of the energy consumed by the auxiliary machines is obtained directly from the single-phase supply network and the other part – from the phase splitter [4].

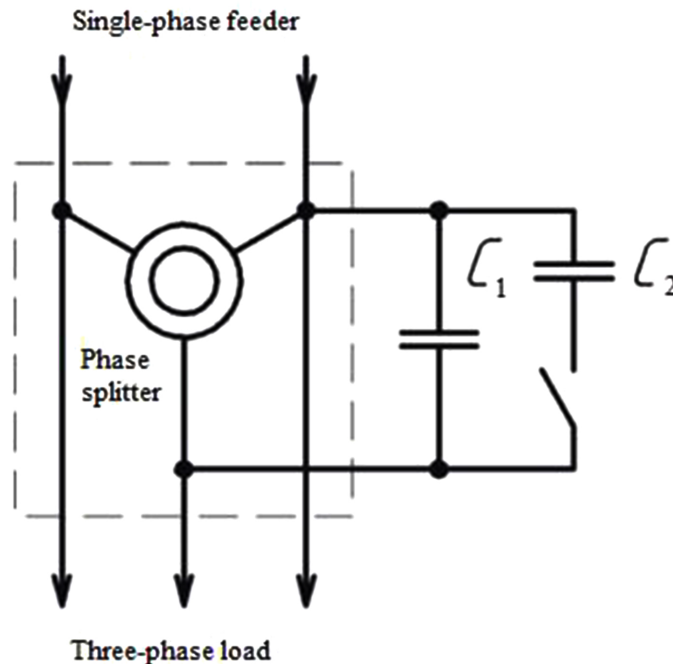


Fig. (6.1). Electrical diagram of the rotary phase splitter.

At present, the conventional IMs with the three-phase stator winding and the squirrel-cage rotor are used on AC electric locomotives: IM ANE225L4UHL2 on the VL85 and IM NVA-55S on the 2,3ES5K electric locomotives. Under the steady-state operation of the auxiliary electric drives, the role of the phase splitter is insignificant [5]. According to the measurement data presented in the source [4]

the share of the energy received by the IM from the electromechanical phase splitter in relation to its total energy consumption is between 5 and 10%. This means that 90...95% of the total energy is consumed by the auxiliary IM directly from the single-phase power grid through the capacitors. As indicated in the source [6], the phase splitter predominantly functions as a phase compensator, with an almost fully loaded auxiliary 3 \emptyset IM supplied by the single-phase supply with the capacitors connected to its terminals, the power factor value of the 3 \emptyset system has to be at 0.5 providing for the single-phase supply power factor value of 0.9...1.0.

In spite of predominantly acting as the phase compensator during the continuous operation of the system, the phase splitter also plays an important role in the initiation of auxiliary IM and the short-term supply voltage fluctuations [4]. In these modes, the phase splitter automatically converts the kinetic energy stored by its rotating parts into electromagnetic energy which is supplied through the system to where its deficiency occurs. In this case, all three phases of the winding serve as a generator and the large moment of inertia of the phase splitter rotor becomes an advantage. Thus, the performance of the phase splitter is more significant in dynamic rather than static modes of operation of the auxiliary electric drive of the locomotive.

The functional insignificance of the rotational electromechanical phase splitter in the power supply systems of auxiliary IMs at the steady-state operating modes stands as the main historical premise to explore available options of the auxiliary AC systems without the rotational electromechanical phase splitters [5, 7].

Another reason for avoiding the circuits with rotational phase splitters is the constant increase of power of the locomotive's auxiliary equipment and therefore the inevitable increase in weight and dimensions of the phase splitter.

The compatibility problem of a single-phase power grid and three-phase electrical loads still remains and causes unbalanced supply voltages which in turn lead to a large number of auxiliary IMs failures. Analysis of these failures, in 2005 onboard of ED9 electric trains with the electromechanical phase splitter, revealed the auxiliary motors failure rate of one per 106 km (0.93 failures per 100 km). These figures are more than double (the similar rate of 0.44 failures per 100 km) for the traction electric motors with a commutator supplied by the pulsating current despite their severe operating conditions [8].

THE CAPACITIVE PHASE SPLITTER ONBOARD OF LOCOMOTIVE

The closest technical alternative to the systems of an auxiliary electric drive with an electromechanical phase splitter is the electric drive, where the IM is powered

Starting Mode Computer Simulation of Auxiliary Induction Motor Onboard of an AC Electrical Locomotive Equipped with a Capacitive Phase Splitter

Mikhail Pustovetov^{1,*} and Konstantin Shukhmin²

¹ RIF Shipyard, Rostov-on-Don, Russia

² EIM Training Pty Ltd, Cairns, Australia

Abstract: This chapter discusses the start-up simulation results of auxiliary drives of fan and piston-type air-compressor driven by three-phase induction motors. The computer model described in this chapter simulates a relay-contactor type system of auxiliary machines powered from the secondary winding of the traction transformer through the capacitive phase-splitter. The authors make an analytical comparison of the start-up process at different values of the grid voltages. Comparative assessments of the simulation-based and experimental oscillograms of voltages, currents and the rotational speed of the motor-fan and motor compressor during the start-up process are described.

Keywords: AC Electric Locomotive, Air Compressor, Auxiliary Induction Motor, Capacitor Phase Splitter, Motor-Fan, Simulation.

INTRODUCTION

A computer model of the electromechanical processes of starting a motor-compressor or a motor-fan driven by an induction motor (IM) powered from a single-phase 50 Hz grid with a capacitive phase splitter is part of a more complex computer model that enables simulation of the dynamics of thermal processes [1 - 3] taking place in the IM of the auxiliary electrical drive of the electrical locomotive 2ES5K. The development of the computer model and the processes studies are based on the diagram shown in Fig. (6.2). Further this chapter describes the OrCAD [4] computer model of the motor-compressor start-up mode simulations [5]. Also, the results of the start-up mode computer simulations of the motor-compressors and motor-fans are assessed and compared with the experimental data.

* Corresponding author Mikhail Pustovetov: RIF Shipyard, Rostov-on-Don, Russia; Tel: +79885651027, E-mail: mgsn2006@rambler.ru

MOTOR-COMPRESSOR STARTING MODE SIMULATIONS

A starting mode computer model of a motor-compressor driven by an IM type NVA-55 powered by a single-phase 50 Hz grid with a capacitive phase splitter is shown in Figs. (7.1 , 7.2 and 7.3).

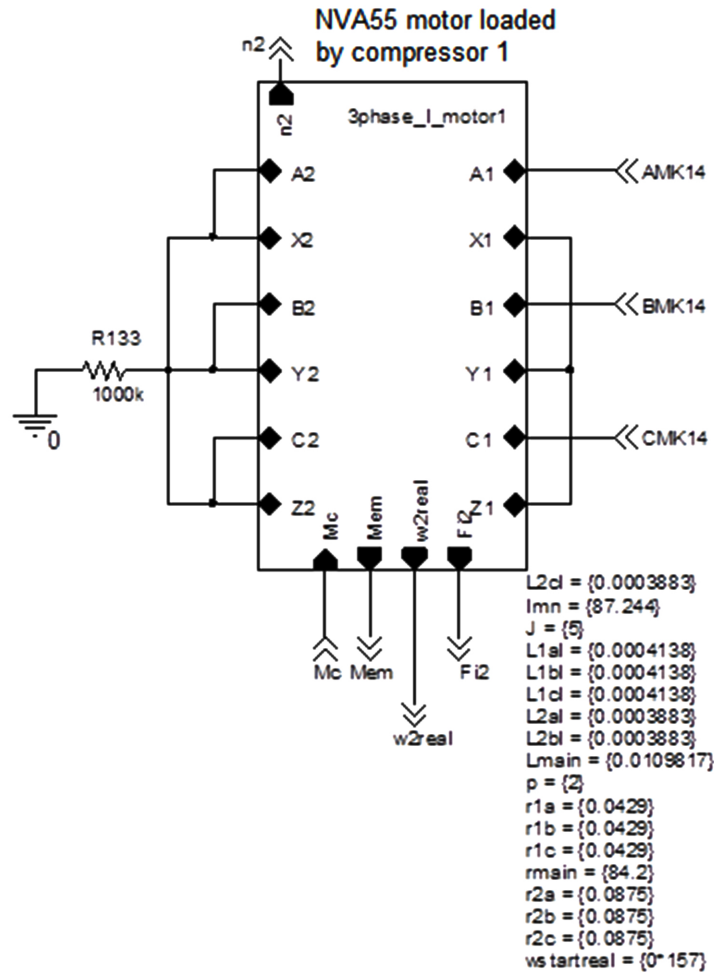


Fig. (7.1). The IM type NVA-55 motor-compressor hierarchical block with the terminals and symbols of the computer model.

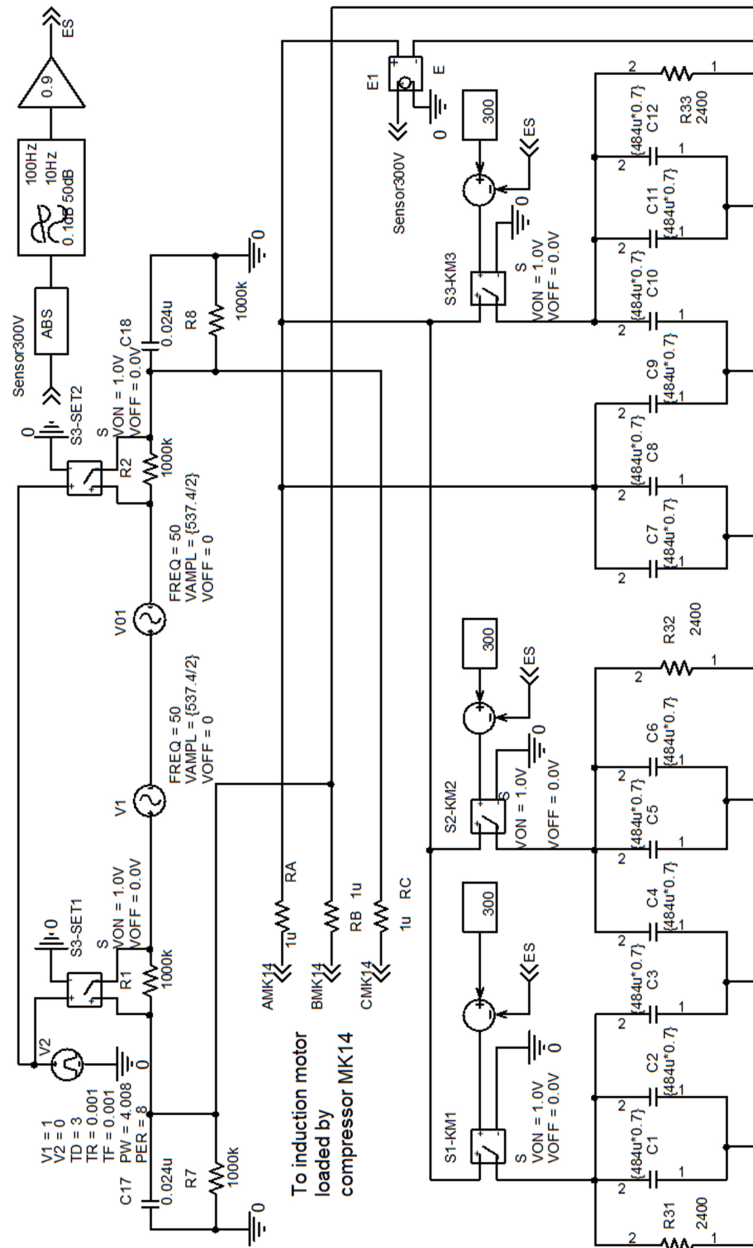


Fig. (7.2). Electrical circuit diagram of the start-up computer model of the IM type NVA-55 motor-compressor supplied by a 50 Hz single-phase grid with the capacitive phase splitter.

CHAPTER 8**Mathematical Modeling of Thermal Processes in an Auxiliary Three-Phase Induction Motor of an Electric Locomotive with Unbalanced Supply Voltages and Squirrel-Cage Defects****Mikhail Pustovetov^{1,*} and Konstantin Shukhmin²**¹ *RIF Shipyard, Rostov-on-Don, Russia*² *EIM Training Pty Ltd, Cairns, Australia*

Abstract: This chapter is dedicated to the consideration of the possibility of building a thermal computer model of an induction electric machine with a squirrel-cage rotor. The thermal model is considered as an add-on to the computer model that describes electrical and mechanical phenomena of the IM. Both models are included in a single OrCAD project. The structure and components of the developed thermal model are described. The thermal processes modeling results in an induction motor type NVA-55 as part of an auxiliary electric drive of a freight electrical locomotive are presented-taking into account the unbalanced supply voltages and squirrel-cage defects.

Keywords: Auxiliary induction motor, Electrical locomotive, Thermal processes, Unbalanced supply voltages, Squirrel-cage defects.

INTRODUCTION

The difficulties of modeling the heating processes in the elements of the induction motor (IM) driving an auxiliary equipment onboard an electrical locomotive are associated with an unbalanced 3-phase supply system.

The initial prerequisites for selection of the design method of IM's thermal model:

1. A necessity to consider the dynamics of the thermal processes.
2. A need to obtain temperature information of the individual elements of the IM structure at the level of average temperatures, for example:

* **Correspondence author Mikhail Pustovetov:** RIF Shipyard, Rostov-on-Don, Russia; Tel: +79885651027; E-mail: mgsn2006@rambler.ru

- Terminal parts and slotted parts of the phases of the stator winding;
- Bars and short-circuiting rings of the rotor winding;
- Teeth and yoke of the stator magnetic circuit for individual phases;
- The IM housing over the individual phases of the slotted part of the stator winding and above the terminal parts;
- The air inside the IM (end cap air), bearings, end shields and etc.

3. A requirement to consider the thermal state differences of the individual phases of the IM and their mutual thermal exchange.

4. A need to calculate the IM operating modes with a different number of breakages in the squirrel-cage bars.

5. Design possibilities of the IM thermal mathematical model (MM) based on the technical data documentation and the test reports of a specific types of IM.

6. A possibility of modeling similar IM systems without making significant changes to the structure of the MM.

7. A possibility to input as the heat sources for the thermal calculations the currents and the losses acquired from the computer simulations of electromechanical processes in the IMs [1 - 3] which MMs were developed in the OrCAD [4], enabling the IM's dynamic mode calculations and taking into account parametrical asymmetry of the phases' windings and an unbalanced power supply.

FEATURES OF THE DEVELOPED THERMAL MATHEMATICAL MODEL OF A THREE-PHASE INDUCTION MOTOR

After taking into account the above initial requirements, the method of thermal diagrams using the principle of the approximate calculation of the two-dimensional field by R. Soderberg was chosen for the construction of the thermal MM [5]. Full information about design of the non-stationary thermal processes in electrical machines is given in the publication [5]. Information on calculation methods of the thermal circuits parameters and reference data of the electrical materials thermal properties are given in [5, 6]. The thermal model comprises about 300 different elements such as heat flows, heat capacities and thermal resistances. Figs. (8.1 – 8.6) help to explain the principle of thermal MM compiling for the IM type NVA-55 when powered by an unbalanced voltage system, A segment of the equivalent thermal circuit of the NVA-55 stator is described by a system of differential equations of the heat balance in a form similar to the equation (8.1) and is shown in Fig. (8.3).

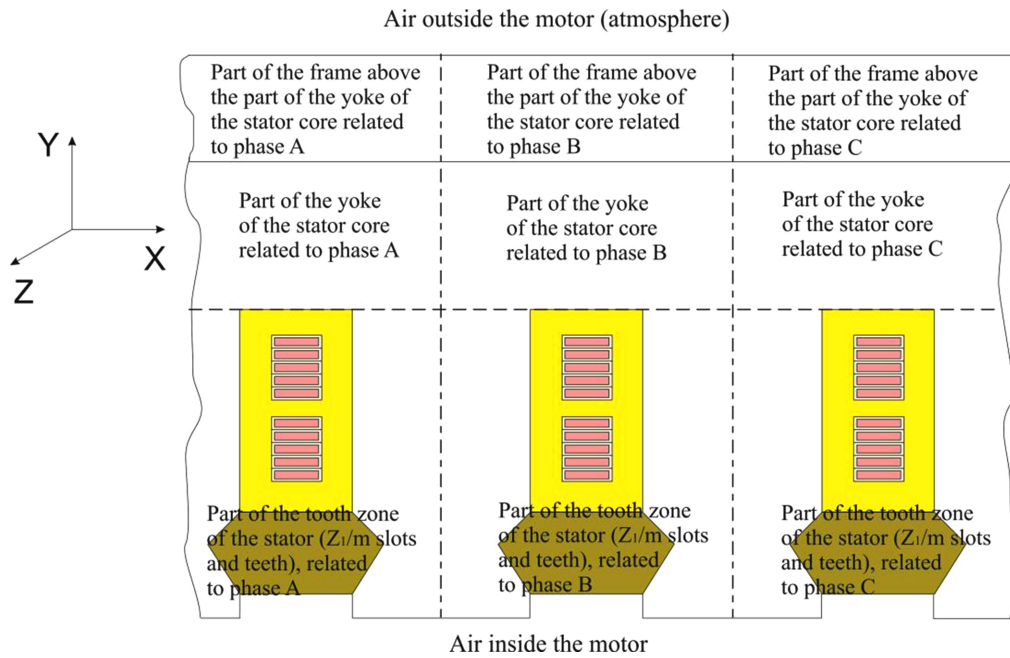


Fig. (8.1). Cross-sectional view of the conditional division of the IM type NVA-55 stator zones of the equivalent thermal diagram.

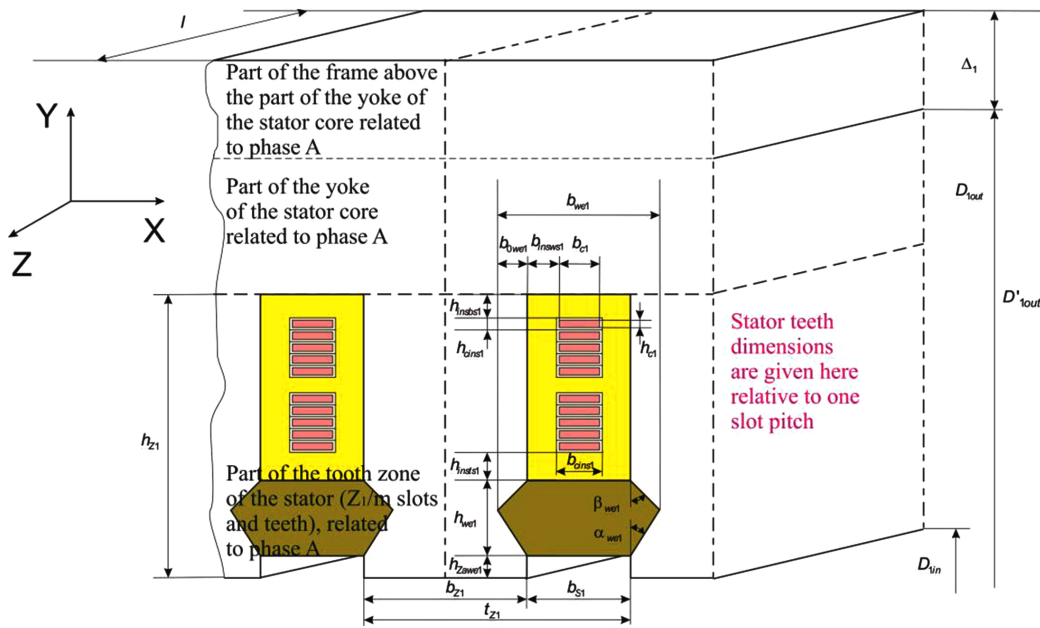


Fig. (8.2). Cross-sectional view of the IMtype NVA-55 stator's geometrical dimensions of the equivalent thermal diagram.

SUBJECT INDEX**A**

Acceleration 36, 37, 39, 40, 41, 43, 149, 150
 fast angular 39
 process 149
 smooth 37
 Accuracy 47, 70
 high calculation 47
 simulation's 70
 AC 3, 72
 locomotives 72
 voltage supply 3
 Adiabatic heating process simulation 141
 Air 47, 60, 78, 92, 109, 126, 143
 compressor 78, 92, 109
 exchange 143
 gap 47, 60
 mixing 126
 Aluminum 87, 88, 142, 176
 alloys 87, 142, 176
 casting technology 88
 Angle 49, 71, 96, 97
 motor shaft rotational 49
 rotor rotational 71
 Angular, synchronous 6
 Applications 10, 57, 58, 72, 85
 real rolling stock 85
 Autonomous voltage inverter (AVI) 47, 48,
 87, 88
 Auxiliary 78, 79, 83, 84, 86, 88, 92, 115
 induction motor 78, 83, 88, 92, 115
 machines 79, 92
 mechanisms 84
 system 86

B

Bar breakages 125

C

Capacitive phase-splitter 92, 141, 142
 Capacitors 78, 80, 81, 96, 146, 148, 149
 Cap air heat capacity 129
 Circuit 47, 83, 84, 119
 capacitor 47, 83, 84, 119
 rotor magnetic 47
 rotor thermal 119

D

Defects 49, 50, 88, 89, 119, 149
 manufacturing 88
 pre-failure 89
 winding 49
 Drive 24, 36, 37, 42, 43, 44, 46, 47, 92, 145,
 146
 electrical 46, 92, 145, 146
 electrohydrodynamic 36, 37
 traction induction 47
 Drum dryers 36

E

Electrical 28, 46, 47, 122, 123, 124, 136, 137
 conductivity 123
 drive theory 28
 losses 122, 123, 124, 136, 137
 motors 46, 47
 Electricity consumption, high 46
 Electric locomotives 17, 50, 79, 84, 89, 115
 Electrification system 85
 Electrodynamics processes 46, 47
 Electromagnetic 1, 2, 7, 8, 49, 88
 devices 1, 2, 7, 8
 forces 88
 processes 49
 Electromechanical 1, 10, 31, 48, 92, 109, 116
 energy conversion 1
 processes 48, 92, 109, 116

Subject Index

systems 10, 31
Encompassing 138, 140
 electrical losses 138
 pulsation losses 140
Energy 79, 80, 81, 87
 electromagnetic 80
 kinetic 80

H

Harmonic spectrum 57
Heat 97, 116
 emission 97
 flows 116
Heating processes, adiabatic 141, 142
Hydromechanical transmissions 36
Hysteresis 146, 147

I

Induction 10, 81
 machines 10
 phase splitter 81
Induction motor 1, 10, 36, 37, 47, 78, 92, 115, 145, 150
 drive system 37
 operation 47
Induction traction 46, 48, 50, 51
 drive 48
 motor 46, 50, 51
Iron losses 16, 19, 20, 21, 49, 119, 122

L

Leakage inductances 56, 59, 63, 67, 72
Linear density 60, 61
Load torque 24, 27, 28, 31, 42, 97

M

Magnetic system 47, 49
Magnetizing circuit 19, 20, 73
MATLAB 50, 63, 73

Induction Motor Computer Models 179

programming environment 50
 software 63, 73
Mechanical stresses 88
Mechanism, piston compressor 97
Meltdowns, winding 88
Momentary quantity 29
Motion equation 24
Motor 26, 47, 56, 141
 shaft 26, 56
 windings 47, 141
Motor compressor(s) 81, 84, 92, 95, 105, 108, 109, 112, 113
 load 95
 rotational 108, 109, 112, 113
 stator 112, 113

O

One-sided conduction 26
OrCAD software 24
Oscillations 3, 146
Oscillograms 83

P

Permeability, magnetic 60
Power 37, 39, 48
 shaft 37, 39
 transistors 48
Power drive 36, 41, 42
 dynamics of 41, 42
 electrical 36
Power supply 43, 44, 47, 84, 116, 118, 122
 balanced 122
 unbalanced 116, 118
 unbalanced three-phase 84
Power supply systems 47, 80, 85
 railway traction 85
Power voltage 51
 frequency 51
Properties 73, 116
 dynamic 73
 electrical materials thermal 116
Protection 37, 89, 146, 150

emergency overload 89
 thermos-electric 146, 150
 Pulse-width modulation (PWM) 48
 Pump shaft 37, 43, 44

R

Rated rotation frequency 51
 Reactive load torque 26, 27, 28, 97
 Reverse 26, 27
 conduction 26
 viscous friction 27
 RMS phase 50
 Rotor 7, 19, 47, 48, 49, 56, 60, 61, 71, 96,
 119, 120, 123, 146
 iron losses 119, 120
 phase 19, 123, 146
 shaft 7
 windings 47, 48, 49, 56, 60, 61, 71, 96
 Rotor squirrel-cage 83, 84, 89, 142, 144
 aluminum alloy 83

S

Saturation, magnetic 1, 2, 7, 8, 57
 Sine wave periods 3
 Single 31, 124
 bar losses 124
 mass system 31
 Software, mathematical modeling computer
 31
 Squirrel-cage 79, 88, 115, 124
 manufacturing technology 88
 phase 124
 rotor 79, 115
 Stator windings 50, 71, 73, 78
 asymmetrical 50, 73, 78
 electric machine's 71
 Supply 80, 144
 circuit 144
 single-phase 80
 Supply system 84, 115
 unbalanced 3-phase 115
 unbalanced power 84

Supply voltage(s) 4, 67, 80, 84, 86, 96, 115
 fluctuates 84
 unbalanced 80, 115
 Switching starting capacitors 98

T

Teeth 116, 119, 120, 123, 131, 134, 139
 rotor core 119
 Thermal 88, 89, 96, 116, 118, 141, 150
 comparison 96
 destruction 88, 89
 stress 150
 transients 141
 Three-phase voltage system 146
 Thyristor frequency and phase number
 converters 83, 84
 Torque 26, 27, 37, 38, 39, 40, 41, 42, 70, 87,
 96
 constant value 41
 gearbox rotation resistance 38, 40
 load rotation resistance 39, 40
 piston-type motor-compressor 96
 Total energy consumption 80
 Traction, commutator 46
 Turbine 40
 shaft angular frequency 40
 wheel 40

U

Unbalanced supply voltage systems 31, 122

V

Vector, flux linkage's 58
 Ventilation, forced 27
 Voltage(s) 26, 48, 71, 74, 78, 81, 85, 97, 107,
 146
 breakdown 26
 frequency 81
 imbalance factor 85
 lower 97
 single-phase AC 78

Subject Index

supply system 48
supplying 71, 74
switching 146
THD 85
Voltage system 5, 6, 48, 116, 143
asymmetrical non-sinusoidal 48
balanced 5
sin-wave 5
unbalanced 5, 6, 116, 143

Induction Motor Computer Models 181



MIKHAIL PUSTOVETOV

Dr. Mikhail Pustovetov is currently working as an Electrical Design Engineer in the RIF Shipyard, Rostov-on-Don, Russian Federation. He obtained Ph.D. in 2000, on "Traction induction motors calculation methods advancement with the aim of motor's energy performance improving and the torque ripples reduction" from Platov South-Russian State Polytechnic University (NPI), Novocherkassk, Russia. He is working on electric traction issues and power management. His research focus is electrical machines and transformers, frequency-controlled electric drives, power converters, EMC filters, SMES interconnection with power systems, and computer simulation. He has published more than 150 peer-reviewed research articles and book chapters on electromechanics and electrical engineering (mainly in Russian). He also serves as a reviewer for the journals: IEEE Access; Technium: Romanian Journal of Applied Sciences and Technology.