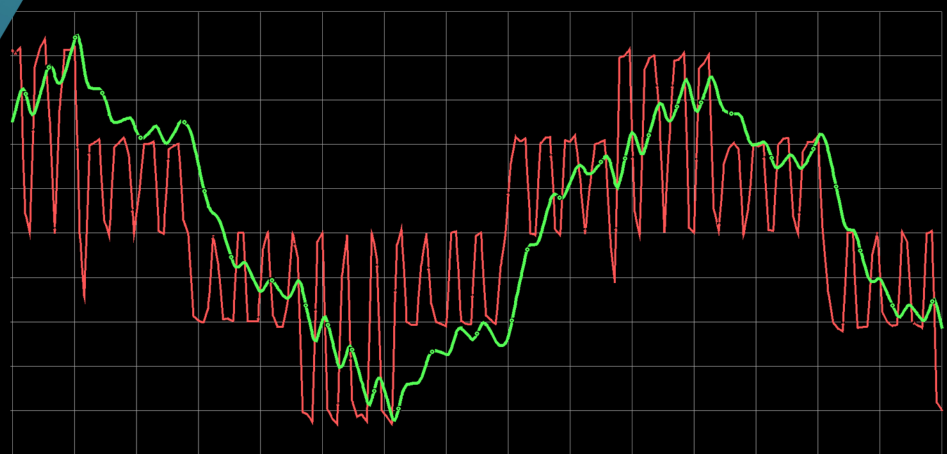
INDUCTION MOTOR COMPUTER MODELS IN THREE-PHASE STATOR REFERENCE FRAMES:

A TECHNICAL HANDBOOK



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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.

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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.

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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

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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.

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Mikhail Pustovetov, Konstantin Shukhmin, Sergey Goolak, Jonas Matijošius and Kateryna Kravchenko (Eds.)

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:

$$\frac{d\Psi}{dt} = \frac{d\left(L(i(t)) \cdot i(t) \right)}{dt} \qquad \textbf{(1.1)}$$

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:

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

therefore

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

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

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

CHAPTER 2

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

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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.

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INITIAL DATA

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

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

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

$$I_{1\text{phase rated}} = \frac{P_{2\text{ rated}}}{3 \cdot V_{1\text{phase rated}} \cdot Efficiency_{\text{rated}} \cdot \cos\varphi_{\text{rated}}}. \qquad \textbf{(2.2)}$$

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.	$Effyciency_{\text{rated}}$
4	Power factor at rated mode, p.u.	$\cos\theta_{\text{rated}}$
5	Rated line voltage RMS, V	$V_{\text{1ph-ph rated}}$
6	Ratio of starting current to rated current, p.u.	$I_{1\text{phase start}} / I_{1\text{phase start}}$

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]: $r_{1*} \approx r'_{2*} = 0.02...0.03$, $x_{\sigma 1*} = 0.08...0.14$, $x'_{2*} = 0.1...0.16$, $x_{\mu *} = 2...4$ as well as $x_{\sigma 1} / x'_2 \approx 0.7...1.0$ - in [15].

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

$$k_{cl} = \frac{p_{\text{cl rated}}}{P_{2\text{ rated}}\left(\dfrac{1}{Efficiency_{\text{rated}}} - 1\right)} \approx 0.5...0.8\,. \qquad \textbf{(2.3)}$$

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 $I_{1phase\ start} / I_{1phase\ rated}$ 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 $I_{1phase\ start} / I_{1phase\ rated}$ 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:

$$k_I = \left(\frac{I_{\text{1phase start}}}{I_{\text{1phase rated}}}\right)_{calculated} \Bigg/ \left(\frac{I_{\text{1phase start}}}{I_{\text{1phase rated}}}\right)_{measured} = 0.9\,. \qquad \textbf{(2.4)}$$

and for IM type AZHV250M2RUKHL2 k_I = 0.64...0.68.

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

Mikhail Pustovetov[*, 1], **Konstantin Shukhmin**[2], **Sergey Goolak**[3], **Jonas Matijošius**[4] and **Kateryna Kravchenko**[5]

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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.

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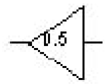
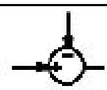
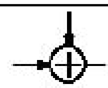
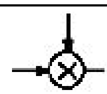
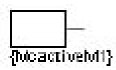
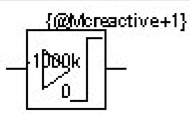
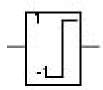
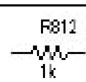
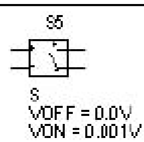
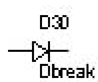
Table 3.1. OrCAD [1, 2] analogue components (blocks) used for the model building.

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		BREAKOUT.SLB	Voltage controlled switch
Dbreak		BREAKOUT.SLB	Diode
VDC		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:

a. The active load torque McactiveM2;
b. The reactive load torque of constant magnitude McreactiveM2;
c. The reactive load torque such as viscous friction McventM2;
d. The torque caused by mechanical (ventilation) losses McventlossesM2.

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.

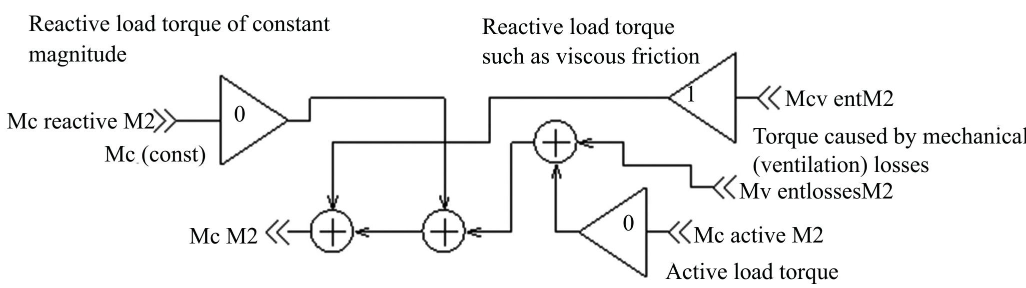


Fig. (3.1). A segment of the simulation model used for generation the electrical machine shaft load torque.

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_O, 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_O and its output is connected in series to the block ABS. Another PWRS block has its power value set to 0.

CHAPTER 4

Computer Simulation of Electric Drive with Induction Motor and Fluid Coupling

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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 veriety 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:

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- 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**).

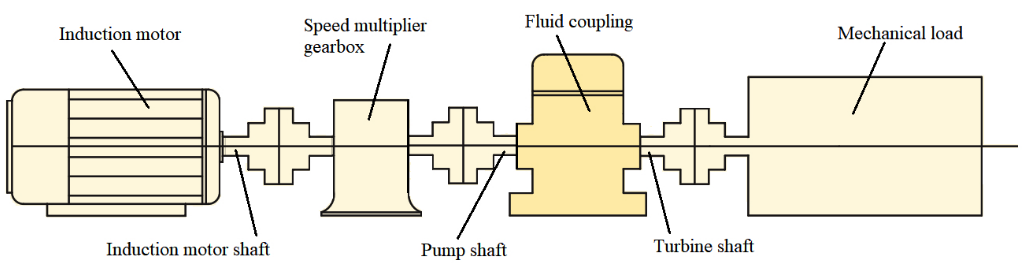

Fig. (4.1). Structure diagram of induction motor drive system.

The equation of motion for the IM shaft is:

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

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:

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

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

$\left(p_{mech0} / \omega_{r0}\right) \cdot \left(\omega_r / \omega_{r0}\right)^{1.7}$ 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:

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

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:

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

where Q, m^3/s is the flow rate of the working fluid in the FC:

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

CHAPTER 5

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

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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].

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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

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

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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

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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].

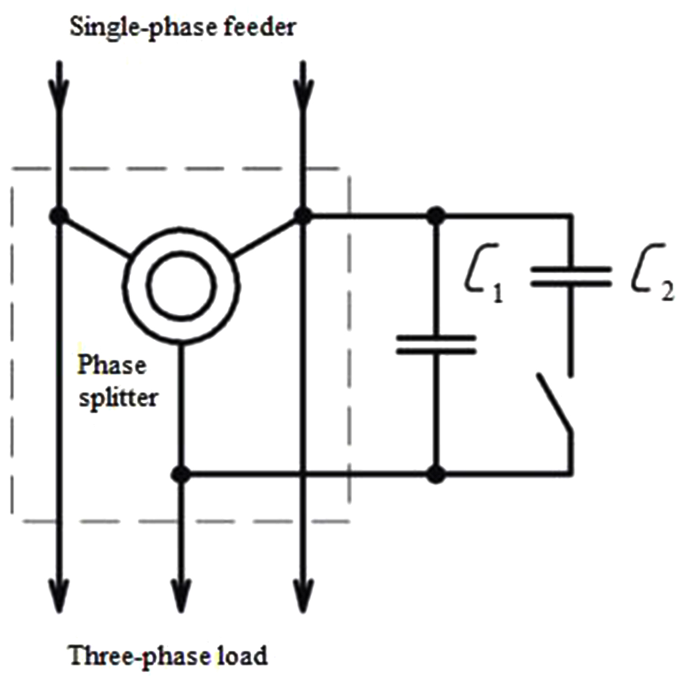

Fig. (6.1). Electrical diagram of the rotary phase splitter.

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 3Ø IM supplied by the single-phase supply with the capacitors connected to its terminals, the power factor value of the 3Ø 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

CHAPTER 7

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

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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.

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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**).

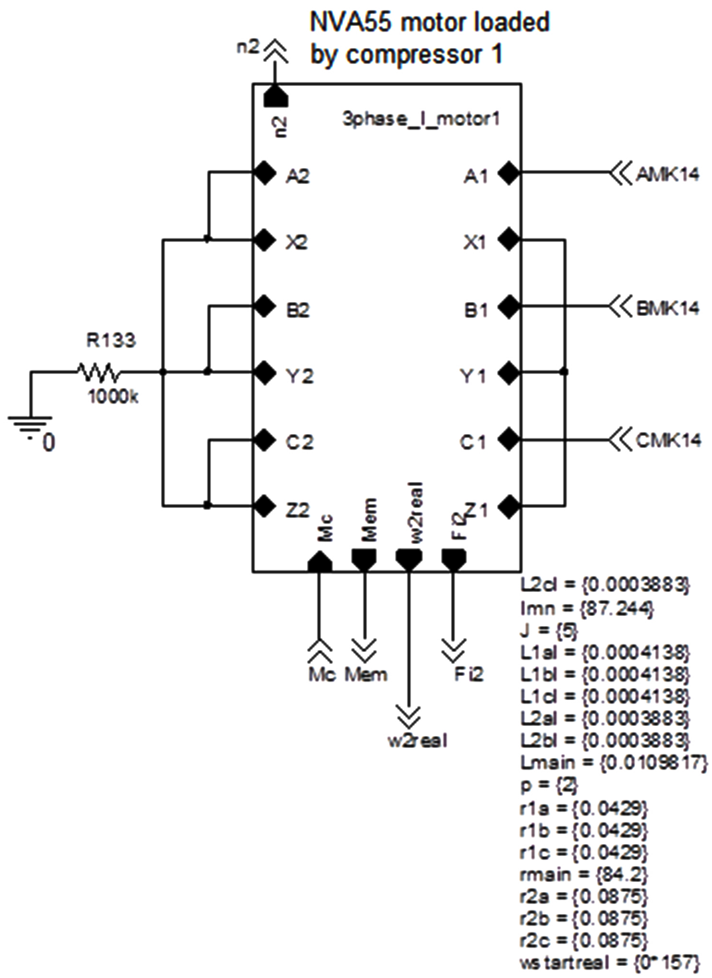

Fig. (7.1). The IM type NVA-55 motor-compressor hierarchical block with the terminals and symbols of the computer model.

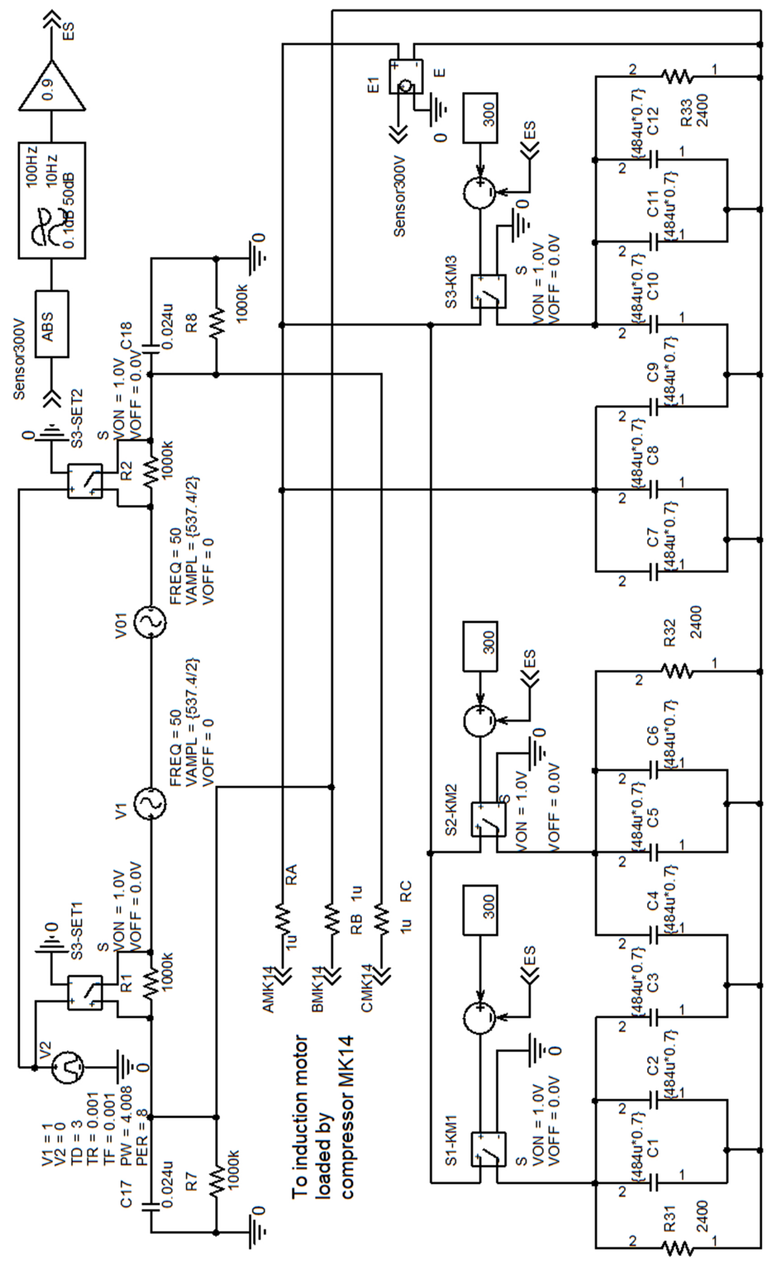

Fig. (7.2). Electrical circuit diagram of the start-up computer model of the IM type NVA-55 motor-compressor supplied by a 50 Hz single-phase grid with the capacitive phase splitter.

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

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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:

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- 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** – **8.4**) 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 osf differential equations of the heat balance in a form similar to the equation (8.1) and is shown in Fig. (**8.3**).

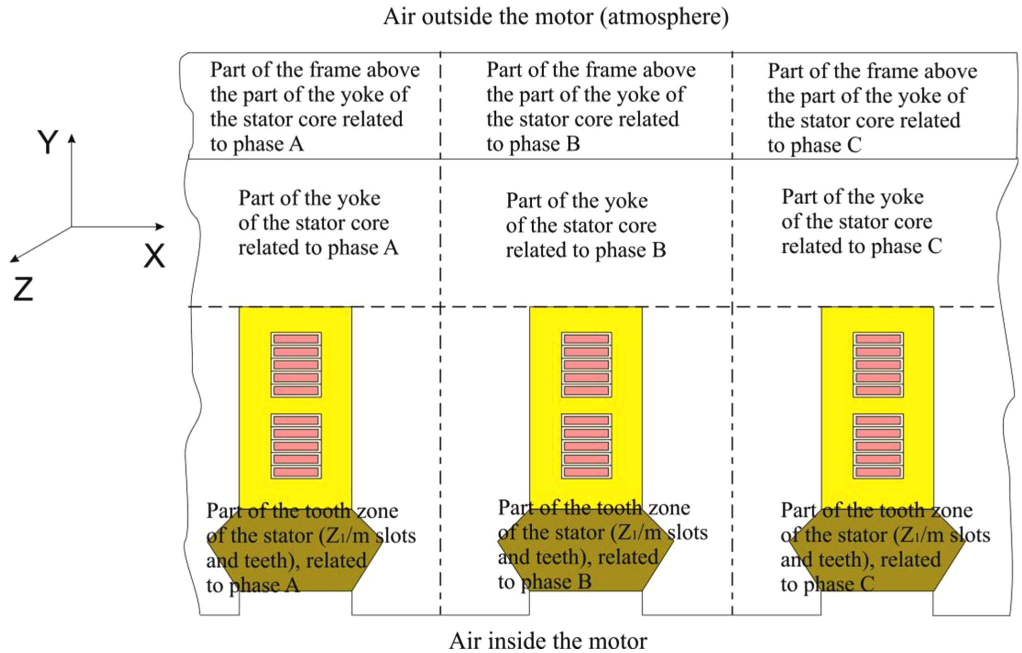

Fig. (8.1). Cross-sectional view of the conditional division of the IM type NVA-55 stator zones of the equivalent thermal diagram.

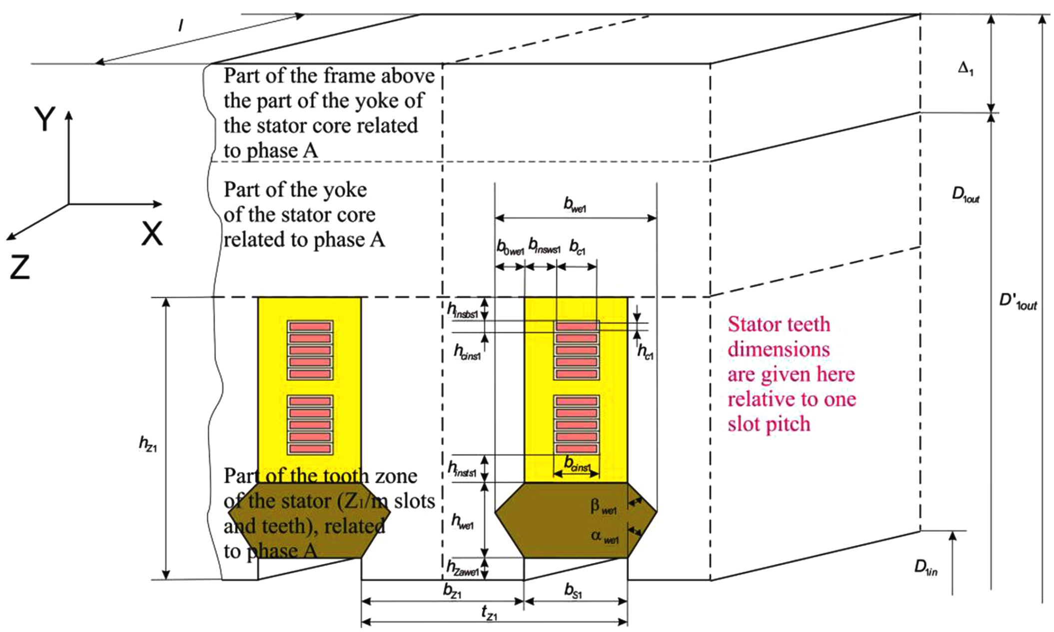

Fig. (8.2). Cross-sectional view of the IMtype NVA-55 stator's geometrical dimensions of the equivalent thermal diagram.

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