TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE – 2015, Vol. 15, No.2, 25-32

Using of object-oriented analysis in electric machines mathematic modeling

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Received July 01.2015: accepted July 20. 2015

Summary. The paper discusses the application of the object-oriented analysis principles, such as a hierarchy, inheritance, polymorphism in the structural synthesis of mathematical models of rotating electrical machines. The results allow to dynamically synthesize arbitrary mathematical models of electric machines on the stage of its design and carry out an analysis of electromagnetic transients.

Key words. Object-oriented, analysis, class, synthesis, mathematical model, transient, electric machine.

INTRODUCTION

The level of human society material culture development is primarily determined by the creation and using of energy sources. Now the most volume of energy is produced by electromechanical energy converters. With its high energy performance and smaller, in comparison with other energy converters, material consumption per unit of power, environmentally friendly electromechanical converters are playing a great value in human society [1].

One of the main trends in the development of electrical engineering is improving the of electrical machines design methods. That helps to reduce weight and dimensions of machines, improving their technical and economic performance [2].

One of the modern methods of electrical machines (EM) research is a mathematical modeling to predict the character of electromagnetic, thermal, mechanical, ventilation and other processes at the design stage without making prototypes. In this paper the example of mathematical modeling of electromagnetic transients is considered. The methodological approach of non considered processes modeling is similar and, if necessary, may be made by the proposed methodology.

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

Mathematical modeling includes a description of electromagnetic processes and solving the system of equations describing the electromagnetic processes based on assumptions and variations of the model parameters. Methods of mathematical modeling can be divided into several categories. Thus, methods based on the analysis of EM electrical circuits are equivalent to machine circuits and described by the system of differential equations. The basis of mathematical models incorporated a thesis's on the nature of the known distribution of the magnetic field in the air gap, determines the distribution of the stator current load.

To solve the problems of transients using the equations of Park and Gorev [3], which are magnetically coupled EM circuits by Kirchhoff equations written in matrix form. In this form the equation system (1) used in the theory of generalized electromechanical converter [4] based on nonsinusoidal voltage, saturation, asymmetry:

$$\begin{bmatrix} u_1 \\ u_2 \\ \dots \\ u_i \\ \dots \\ u_n \end{bmatrix} = \begin{bmatrix} r_1+\frac{d}{dt}L_1 & \frac{d}{dt}M_{12} & \dots & \frac{d}{dt}M_{1i} & \dots & \frac{d}{dt}M_{1n} \\ \frac{d}{dt}M_{21} & r_2+\frac{d}{dt}L_2 & \dots & \frac{d}{dt}M_{2i} & \dots & \frac{d}{dt}M_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{d}{dt}M_{i1} & \frac{d}{dt}M_{i2} & \dots & r_i+\frac{d}{dt}L_i & \dots & \frac{d}{dt}M_{in} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{d}{dt}M_{n1} & \frac{d}{dt}M_{n2} & \dots & \frac{d}{dt}M_{ni} & \dots & r_n+\frac{d}{dt}L_n \end{bmatrix} \times \begin{bmatrix} i_1 \\ i_2 \\ \dots \\ i_i \\ \dots \\ i_n \end{bmatrix}, \quad (1)$$

where: $u_1, u_2,..,u_n$ – winding voltage of the appropriate model axis, $i_1, i_2,.., i_n$ – winding current, $r_1, r_2,.., r_n$ – winding active resistance, $L_1, L_2,.., L_n$ – winding inductive reactance, $M_{12}, M_{1i},.., M_{in}$ – winding mutual inductive reactance.

Mathematical models are based on EM equivalent circuits where machine parameters are determined by the formulas of the calculation forms or empirically. The disadvantage of these models is the need to know the parameters of the equivalent circuit and the impossibility of getting during of modeling such differential parameters as magnetic induction of the magnetic elements in the EM, the density distribution of the electromagnetic losses, defining the heating of certain parts of the machine, etc. Instead, the model uses the integral value of the magnetic fluxes, currents, electro motive force, etc.

Types diversity of EM spawned countless models and attempt to classify them is becoming more complicated.

Thus, the EM divided by the nature of supply, the ratio between the angular speed of the stator and rotor fields, the number of equations in the mathematical model with the accumulation of the calculation routines. In the work [5] was considered the theory of electromechanical systems evolution, according to which all electric machines are grouped according to the primary characteristic features of an electromagnetic charge and the geometric shape of the electromagnetic field. This was tasked with the development of knowledge in the field of ordering EM.

Meanwhile, there was not found such a scientific approach, which would allow to connect the classification database of EM and mathematical representation. Solving the problem of matching the mathematical modeling of EM their branched types hierarchy can enable automatically after the completion of the design, synthesize the variety of EM mathematical model.

In modern conditions, when the EM does not end by terminal box, and is inextricable link with an electric drive, one should consider an integrated approach to design, which includes not only the determination of the parameters and characteristics of EM but also evaluation synthesis of its transient dynamics.

OBJECTIVES

Objectives of the paper are to consider the benefits of applying of object-oriented analysis in the synthesis of mathematical models of electric machines and its connection with electric machines types' variety.

THE MAIN RESULTS OF THE RESEARCHES

The principles of object-oriented design (OOD) provide an opportunity not only to synthesize the electromagnetic design techniques, but also consider their mathematical models of hereditary succession in the base class and descendant classes [6]. This will resume the mathematic modeling as a complex problem and obtain the parameters and characteristics of EM in steady-state and transient operating modes. It performs automated generation of mathematical model of any type of EM at the design stage [7, 8]. The main idea is to form a mathematical model (MM), a specific type of electromagnetic component of the components of the basic model, using the principles of inheritance, hierarchy and polymorphism. The advantage of this method is the close connection of design (in which the parameters and coefficients for MM calculated) and mathematical modeling in the optimization of EM in dynamic modes. Thus, any changes in the project immediately go to the input of MM that is essential in the optimization of EM CAD systems. The need for such way has been described in [4], but the problem was limited to the accumulation of various types of MM for EM. For machines not included in this database, obviously, the proposed approach is not acceptable and is not working. Object-oriented MM can solve this problem.

Complex object-oriented design that includes both the design and the associated mathematical modeling of transients allows to perform optimization of arbitrary form EM, which is the main objective of CAD - getting optimal EM satisfies the given constraints and having the best technical and economic indicators. Consideration of models of electric machines is repelled by an idealized electrical machines - symmetric electric machine having a smooth air gap, steel sections with zero resistance and sine magnetic winding. The ultimate goal is to create the principles of synthesis of MM for the most common types of EM: induction motor with squirrel cage rotor (IM with SQR), induction motor with phase rotor (IM with PhR), induction motor with ferromagnetic rotor (IM with FR), synchronous motor (SM), DC motor, transformer. The implementation of such a synthesis is feasible given by inheriting the basic properties of MM, having common characteristics for all of the EM. Embrace the diversity of EM in one work is impossible, however, the resulting MM does not require consideration of all examples. The above types of EM possible to find a universal way to the modification of the MM, which in turn would allow for disseminating results of similarity to other signs are not considered EM.

This formulation of the problem allows to work out the principles of inheritance not only for known machines, but also to create conditions for development of the concept of object-oriented modeling of EM special designs (for example, machines with two-cage slot, linear motors, motors with rolling rotor), as well as undiscovered machines. There is no need to create a database of EM and MM accumulation of computer programs. Typical solutions will be getting by generating EM models with adding or cutting off specific characters with simultaneous generation of MM [7]. The advantage of OO modeling is in contrast to the known methods of classification EM is not only a reflection pattern of EM types diversity, but also to support a classification of mathematical description. When designing EM differs from known methods, the inheritance help in getting their MM by defining new attributes generated from the already known from the base class. So it is similar to nature inheritance when the parents pass on their specific characters to descendants, and the descendants, in turn, bring their own to the formation of a species or refuse parent.

When the model was obtained for an idealized electric machine that will perform the work for the purpose of clarifying its approach to a real EM [10].

Processes in a multi pole EM can be reduced to a two-pole processes. Therefore, in order to simplify the presentation, we accept as MM generalized model of the electric machine - the two-phase and two-pole symmetrical idealized electric machine having two pairs of windings on the rotor and stator. In such machine an air gap is smooth, winding represented in the form of current layers with sinusoidal distribution of the magnetic motive force.

The EM is unsaturated and has no nonlinear resistance, so the power winding sinusoidal voltage field in the air gap is sinusoidal.

Under such conditions all EM with a circular field in the air gap can be obtained from the generalized EM. The system of equations of base machine electromechanical energy conversion, describes the energy conversion process consists of four Kirchhoff's equations of the electromagnetic torque and motion. For a generalized EM known equations [4] like:

$$\begin{bmatrix} u_{su} \\ u_{ru} \\ u_{rv} \\ u_{sv} \end{bmatrix} = \begin{bmatrix} r_{su} + \frac{d}{dt}L_{su} & \frac{d}{dt}M & M\omega_c & L_{sv}\omega_c \\ \frac{d}{dt}M & r_{ru} + \frac{d}{dt}L_{ru} & L_{rv}(\omega_c - \omega_r) & M(\omega_c - \omega_r) \\ -M(\omega_c - \omega_r) & -L_{ru}(\omega_c - \omega_r) & r_{ru} + \frac{d}{dt}L_{ru} & \frac{d}{dt}M \\ -L_{su}\omega_c & -M\omega_c & \frac{d}{dt}M & r_{su} + \frac{d}{dt}L_{su} \end{bmatrix} \times \begin{bmatrix} i_{su} \\ i_{ru} \\ i_{rv} \\ i_{sv} \end{bmatrix}, \quad (2)$$

equation of electromagnetic torque:

$$M_e = pM(i_{sv} \cdot i_{ru} - i_{su} \cdot i_{rv}), \quad (3)$$

and equation of motion:

$$J\frac{d\omega_r}{dt} \pm M_L = M_e, \quad (4)$$

where: M_L – loading torque, J – torque of inertia, ω_c – an angular speed of coordinate system; ω_r – rotor angular speed.

Equations (2) - (4) of basic generalized machine in the selected coordinate system u, v rotating with arbitrary angular speed ω_c are the most common.

If $\omega_c = 0$ we can get equations in the inhibited coordinate system α, β.

If $\omega_c = \omega_r$ we can get equations in the coordinate system d, q, associated with the rotor.

Generalized MM takes the group level in the structural organization of the EM. Thus, solving the problem of the formation of the object MM at the types level of structural organization to bringing the respective calculation models.

Mathematical model of generalized EM (2) is written in a universal form, and the coordinate system of the stator (u) and the rotor (v) rotates each with its own speed. There are countless number of coordinate systems in electromechanics, but for the most common types of EM accepted certain assumptions to be able to compare the new results with the existing ones.

For IM with SQR using the traditional way of MM forming and take a fixed coordinate system α, β associated with the stator.

IM with SQR is derived from the basic EM model with the following types of mutations [8]:

a) in a coordinate system α, β the speed of coordinate system rotation $\omega_c = 0$;

b) sinusoidal voltage $u_{s\alpha}$, $u_{s\beta}$ with frequency f_1 is assign to stator windings, windings are shifted on 90 deg.;

c) because the rotor is short circuited $u_{r\alpha} = u_{r\beta} = 0$;

d) because EM is cylindrical and symmetrical, active and inductive resistance of stator and rotor of the same axes are $r_{s\alpha} = r_{s\beta} = r_s$; $r_{r\alpha} = r_{r\beta} = r_r$.

So the system of equations (2) degenerates to the following form:

$$\begin{bmatrix} u_{s\alpha} \\ 0 \\ 0 \\ u_{s\beta} \end{bmatrix} = \begin{bmatrix} r_s + \frac{d}{dt}L_s & \frac{d}{dt}M & 0 & 0 \\ \frac{d}{dt}M & r_r + \frac{d}{dt}L_r & -L_r\omega_r & -M\omega_r \\ M\omega_r & L_r\omega_r & r_r + \frac{d}{dt}L_r & \frac{d}{dt}M \\ 0 & 0 & \frac{d}{dt}M & r_s + \frac{d}{dt}L_s \end{bmatrix} \times \begin{bmatrix} i_{s\alpha} \\ i_{r\alpha} \\ i_{r\alpha} \\ i_{s\alpha} \end{bmatrix}. \quad (5)$$

The system of differential equations (5) is not a discovery in the theory of mathematical modeling of EM, but this important factor to its preparation. Fundamental is the allocation of mutational symptoms (modifiers) that led to a change the basic equations of the machine. Later, when the accumulated material from other species of EM will be visible to the general picture of the modifications, which can be contacted by design changes to the synthesis of EM MM.

Then we proceed to the further accumulation of databases of engineering modifications models. For IM with SQR refined inheritance tree is shown on (Fig. 1). The presence of the cage in the IM with SQR counted by zero reference voltage u_{ru} and u_{rv} in a generalized model. Adoption of a fixed coordinate system ($\omega_c = 0$) changes the corresponding elements in the matrix of parameters. All modifications of matrix parameters shown in table modifiers (Table. 1). Those parameters of the original matrix that are not changed, is represented as "1" in the table of modifiers. Resetting the missing elements of the matrix, respectively, received "0" as a parameter. Those elements, which may be different from 0 or 1 (perspective for other types of EM) are indicated with modifier «m». Table of modifiers yet only matches the conditions for creating a model of IM with SQR. Further this table will become a universal form with such modifiers, which will enable to change the form of the original MM in accordance with the conditions of the synthesis of the target MM.

Using this way the inheritance of descends can be got from the generalized EM and all the main types of machines are provided to the generalized. In particular, the generation of machines, the descendants of the machines, the parents performed by adding or cutting off the functional features. And these signs are both constructive and mathematical in nature. Made classification can not only consider the diversity of EM, but also to simultaneously receive their MM. Synthesis of EM MM accompanied by the formation of the table of modifiers, which are coefficients and conditions that change the parameters of the base MM matrix. In order to be able to get the MM of backlog EM, it is need to transit from a particular form of the table modifiers to a generalized, as shown on (Fig. 2.) As can be seen from (Fig. 2), summary table modifier is not bound, i.e. invariant to the specific type of EM and allows to change the basic parameters of the MM matrix for target MM using the rules of the algorithm modifications listed in Table. 1.

As known, all EM with a circular field in the air gap This position raises the OOD ideology to a scientific discovery tool. When there is the idea of a new machine, the algorithm of its development can be represented by the following rules of the modifications algorithm:

1) identifying the basic classification features;

2) finding a place in the of the machine structure in EM types classification;

3) defining the primary supply sources;

4) defining the technological functions;

5) defining the possible interaction with the environment taking into account the physical conditions of existence of the machine;

6) compile a list of the main functional features;

7) getting a new type of structural composition and, importantly, MM of EM using inheritance.

As an example of inheritance in the composition of MM consider a model of IM with FR and short-circuit winding embedded in the slots of the rotor body [11, 12]:

$$\begin{aligned} \frac{d\Psi_{s\alpha}}{dt} &= u_{s\alpha} - r_1 i_{s\alpha} + \omega_e \Psi_{s\beta}; \\ \frac{d\Psi_{s\beta}}{dt} &= u_{s\beta} - r_1 i_{s\beta} - \omega_e \Psi_{s\alpha}; \\ \frac{d\Psi_{r\alpha}}{dt} &= -r_r i_{r\alpha} - \frac{d}{dt} i_{r\alpha} L_{r\sigma}\omega_s - \Psi_{r\beta}\left(\omega_e - \omega_0\omega_s\right); \\ \frac{d\Psi_{r\beta}}{dt} &= -r_r i_{r\beta} - \frac{d}{dt} i_{r\beta} L_{r\sigma}\omega_s + \Psi_{r\alpha}\left(\omega_e - \omega_0\omega_s\right), \end{aligned} \quad (6)$$

where: $\Psi_{s\alpha}$, $\Psi_{s\beta}$ – total flux on the stator axis α and β, $\Psi_{r\alpha}$, $\Psi_{r\beta}$ – total flux on the rotor axis α and β,

ω_0 – synchronous speed, ω_e – speed of coordinate system, ω_s – slippery speed, $L_{r\sigma}$ – rotor leakage reactance.

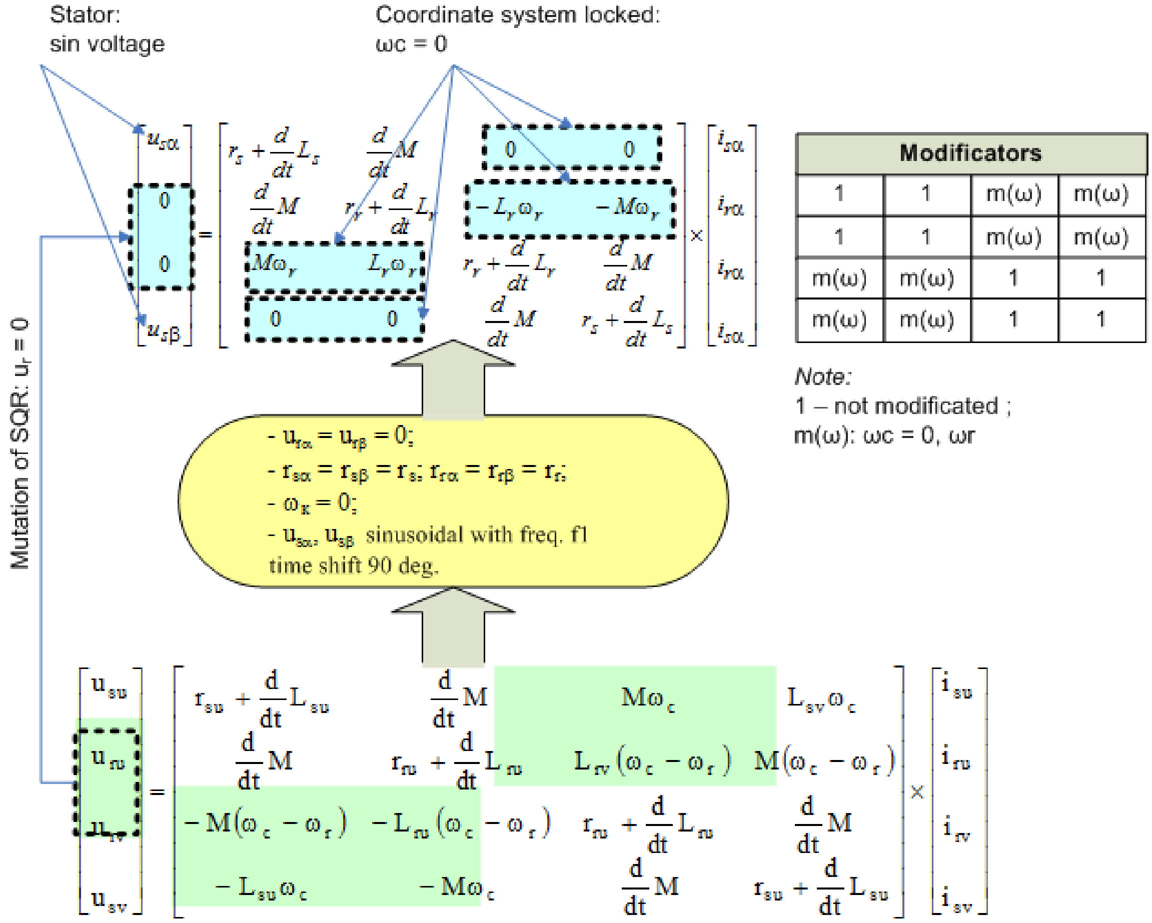

Fig. 1. Refined inheritance tree of IM with SQR

Table 1. The matrix of EM modification parameters

EM type	Speed modification	Parameters modification	Additional winding modification	Parameters of additional winding
IM with SQR	m(ω): $\omega_\kappa = 0$, ω_r	dm = 0	$dm_i = 0$	$p_i = 0$
IM with PhR	m(ω): $\omega_\kappa = 0$, ω_r	dm = 0	$dm_i = 0$	$p_i = 0$
IM with FR	m(ω): $\omega_\kappa = 0$, $\omega_r = \omega_0 \cdot \omega_s$	dm= $d/dt(L_{r\sigma})\omega_s$	$dm_i = 0$	$p_i = 0$
Transformer	m(ω):$\omega_\kappa = 0, \omega_r = 0$	dm = 0	$dm_i = 0$	$p_i = 0$
SM	m(ω): $\omega_\kappa = \omega_r$, ω_r	dm = 0	$dm_f = d/dt(M)$	$p_f = r_f$, $d/dt(L_f)$
DC motor	m(ω): $\omega_\kappa = \omega_r$, ω_r	dm = 0	$dm_i = 0$	$p_i = 0$
Additional factor	-	-	$dm_i = d/dt(M_i)$	$p_i = r_i$, $d/dt(L_i)$
New type of EM	m(ω): $\omega_\kappa = 0$ (ω_r), $\omega_r = 0$ ($f(\omega_r)$)	dm = $f(r_n, L_n)$	$dm_n = d/dt(M_n)$	$p_n = r_n$, $d/dt(L_n)$

Considered EM mathematic model is the descendant of IM with SQR model and IM with FR model.

When we merge two models (Fig. 3), the resulting MM is derivative of (1), (4), (5) with considering the modifiers of Fig. 2 and Table. 1.

On (Fig. 3) for simplify purpose the matrix of intermediate machines is not fully shown. In resulting system of equations $L_r = l_{\sigma 20} + l^{//}_{\sigma 20} + M$, where $l^{//}_{\sigma 20}$ is a leakage inductance of the short circuited cage and $l_{\sigma 20}$ is a leakage inductance of ferromagnetic rotor core.

As shown on (Fig. 3) an inheritance tree can be traced to modify the directions of development of various EM. This modification design at the same time is accompanied by mathematical representation.

The methodology of object-oriented analysis and design became widespread with the advent of object modeling language of the new generation - the Unified Modeling Language (UML), intended for visual modeling and design of information systems [13, 14].

The use of modern simulation systems allows realized such methods of system analysis as establishment of a hierarchy concepts, compilation of concepts, property inheritance, variety of models, describing domain visualization of the processes occurring in the subject area.

In this mean, the UML significant increases substantially as it increasingly acquiring the features of a knowledge representation language.

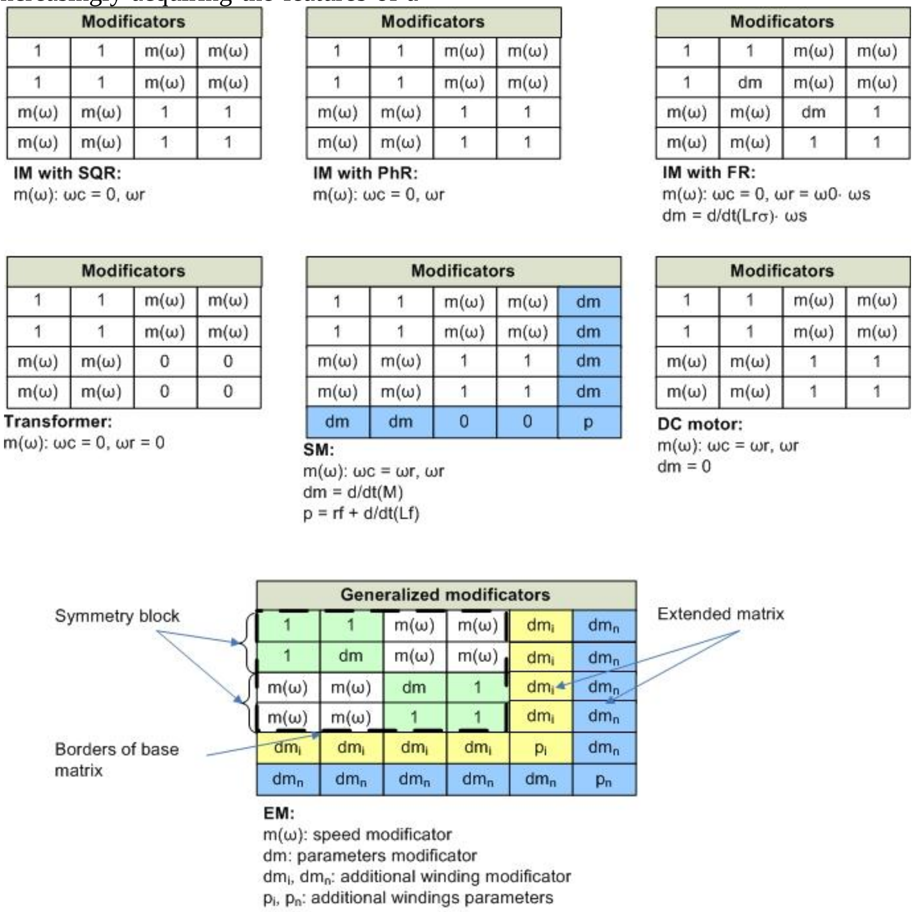

Fig. 2. Generalized table of EM model modifiers

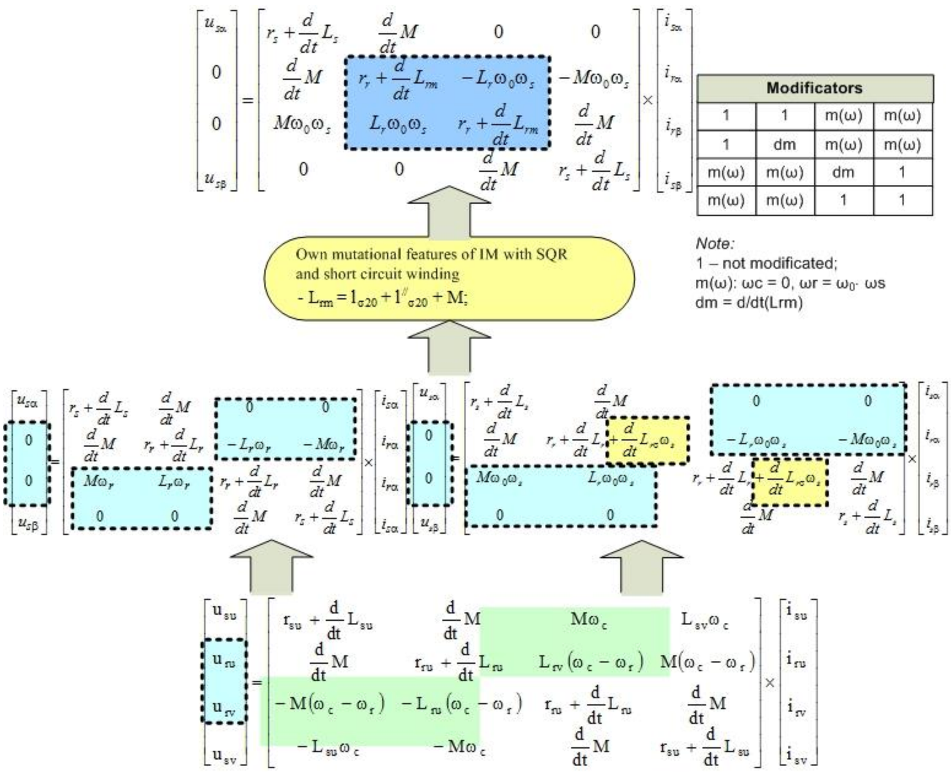

Fig. 3. Refined inheritance tree of EM with ferromagnetic rotor (FR) and squirrel cage winding

At the same time, the presence of visual means in the UML, represent the structure and behavior of the model allows for adequate representation of declarative and procedural knowledge and, not least, to establish between these two forms of knowledge semantic matching [15,16].

These features of the UML lead to the conclusion that it has future as a means of developing models of knowledge representation. The class structure of the generalized EM MM presented in the form of UML-model on (Fig. 4).

A feature of the model shown on (Fig. 4) is that it acts as a template (pattern), and speaking in terms of OOD, a class of generalized EM. The block of attributes on model (Fig. 4) is an EM matrix generalized model parameters and two-phase coordinate system. Generalized model characteristic of all types of machines to be confirmed by the blocks below.

Block of additional attributes is a set of modifiers parameters of stator and rotor circuits in the system of differential equations.

The voltage block is responsible for the power supply of primary and secondary circuits of the machine.

Related blocks of the rotation function and events are modifiers of rotation of the secondary machine part.

A set of attributes to a subset of the associations forming requirements to the secondary part of the machine. In other words, there is no division of EM initially on any features.

In addition, the key words are "class" and "generalized". UML-blocks are not the essence, the real machine replacement – it is a tool for generating a plurality of objects provided by the machine tool inheritance and selection.

Using a template class of generalized EM (Fig. 4) and selecting certain features, we can go to a specific object of EM. Thus, on (Fig. 5) is no longer the class, but the object model of IM with SQR generated by the class of the model (Fig. 4).

On (Fig. 6) UML-model for IM with SQR, similar to (Fig. 5) is shown but with the notation of peculiar to MM written in differential form.

The algorithm for generating of the object MM on even diagram (Fig. 6) is shown too.

Table of modifiers shown on (Fig. 6) contains is a matrix of parameters in a system of differential equations of the generalized EM.

The event model (Fig. 6) describes the sequence of operations that occur in the system in response to external effects (as opposed to the content, subject matter, and the implementation of the operations described by the model classes).

The diagrams on (Fig. 5), (Fig. 6) are the direct implementation of an IM with SQR in the form of an abstract model which can perform calculations. Similarly, it is possible to represent the object model of known types of EM, and of such EM that has not yet created, giving them a new features.

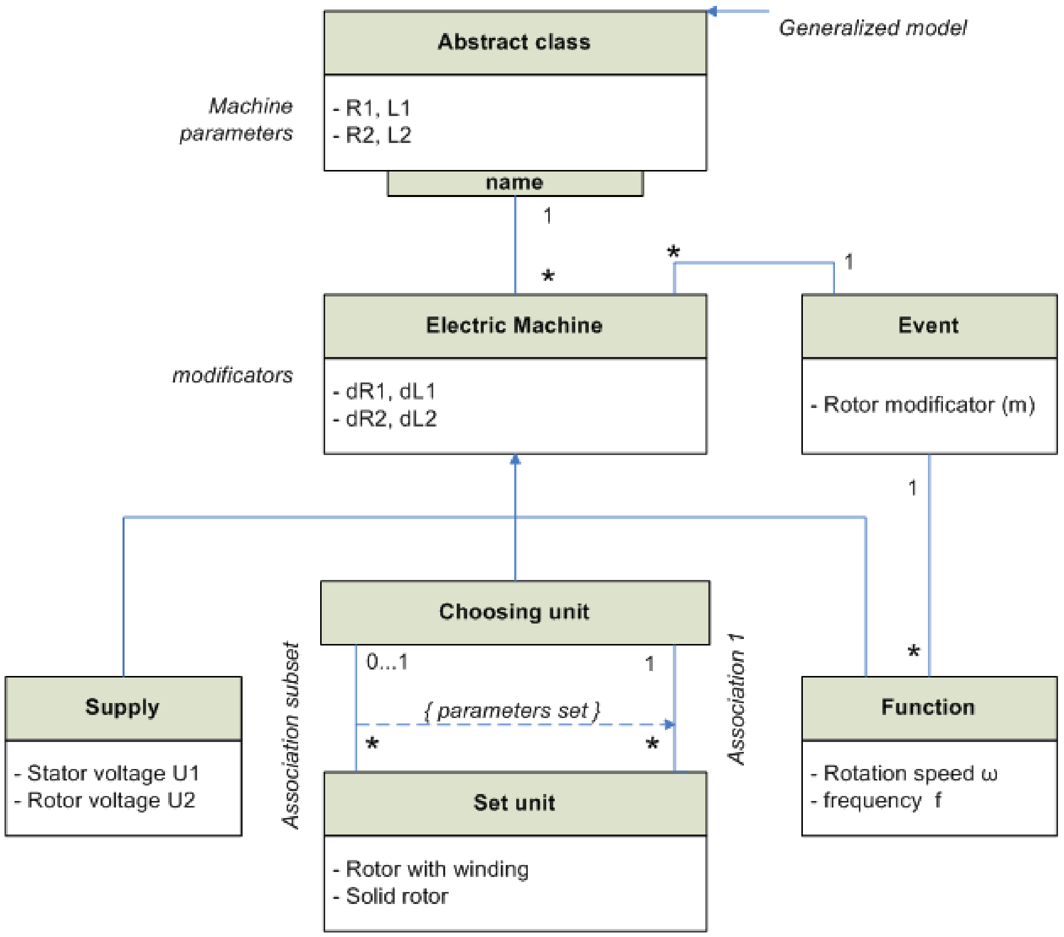

Fig. 4. Class UML diagram of the generalized EM

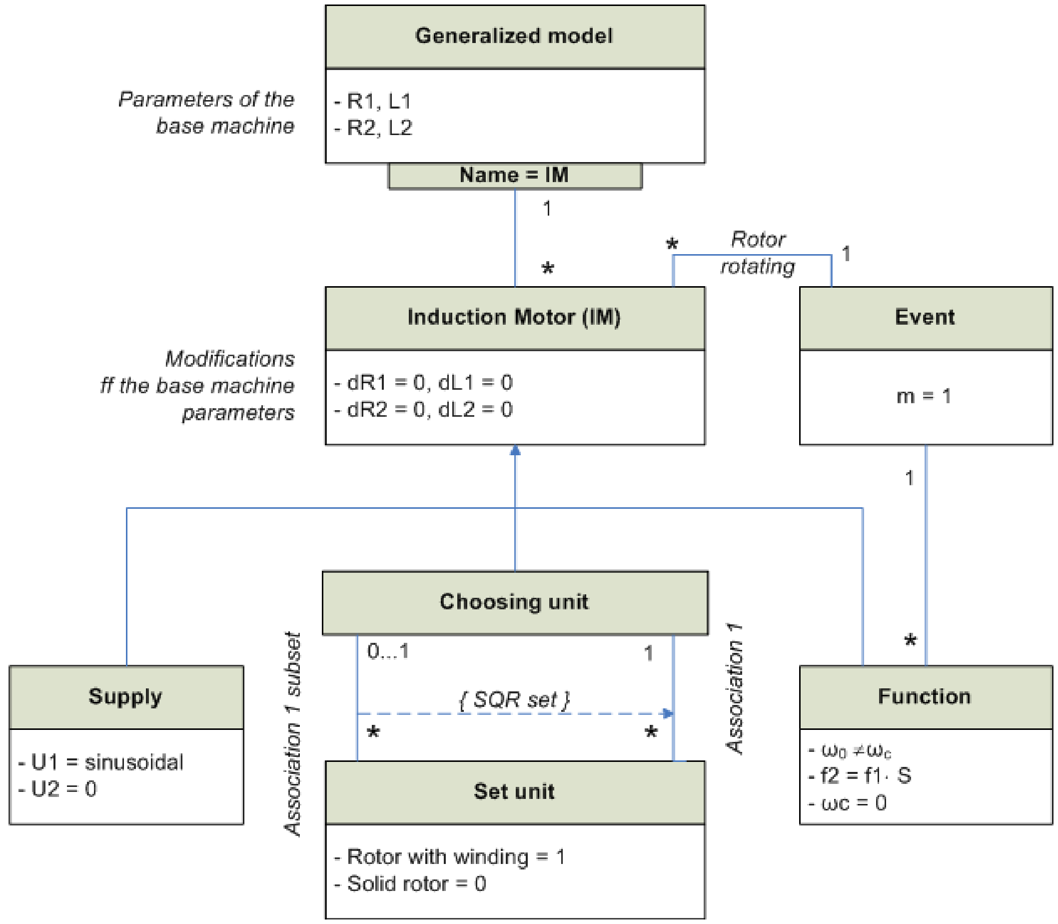

Fig. 5. Object UML diagram of the IM with SQR

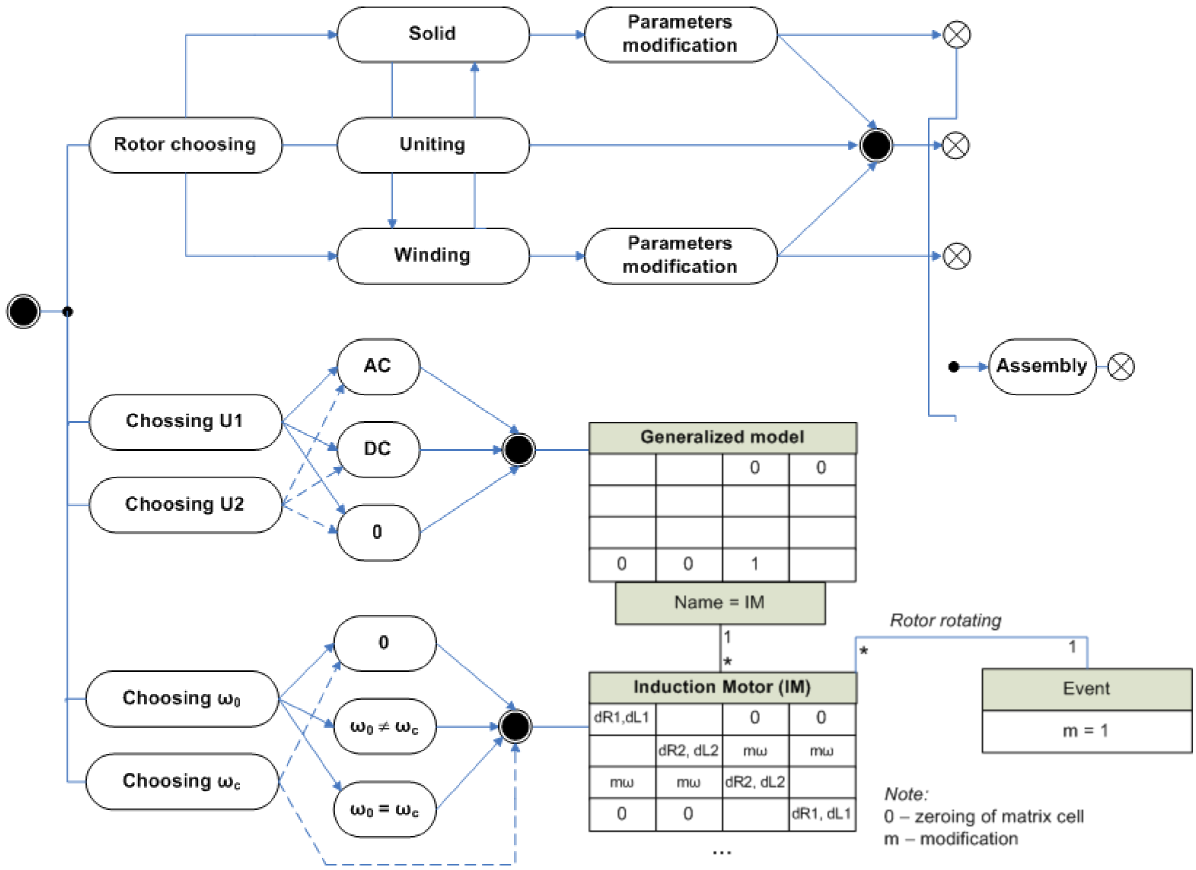

Fig. 6. The part of object diagram of IM with SQR and the event diagram of IM with SQR mathematic model forming

CONCLUSIONS

Considering got results, we can conclude that different types of EM can be obtained from the general equations of the generalized EM by giving additional features. These features do not include classification on design features. They are distinguished by:

a) the properties of the material;

b) the presence of motion;

c) the dependence of the parameters on the properties of the material and moving speed;

d) various forms of supply energy.

Thus, it is possible to organize knowledge on existing machines classification method, different from the known - namely, on the basis of inheritance of characters in the theory of the OOD.

The method of structural and system organization of design and mathematical modeling of EM, based on the inheritance of the derived classes of EM simultaneously with the evolutionary synthesis of mathematical representation.

Creating specific types of EM from the base type, it is possible not only to fulfill their systematization, but also using the principles of OOD, to generate MM and design methods of their calculation.

Using the class template and choosing specific mutational symptoms, it is possible to move an object to a specific EM simultaneously with getting of mathematical model equations.

Using various modifiers it is possible to combine different features of EM and to synthesize EM that is under scientific research work.

Developed principles of evolutionary synthesis EM MM serve as the basis for OOD and modeling of both the external structure of the class of EM and internal organization of a single class of EM.

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ИСПОЛЬЗОВАНИЕ ОБЪЕКТНО-ОРИЕНТИРОВАННОГО АНАЛИЗА В МАТЕМАТИЧЕСКОГО МОДЕЛИРОВАНИЯ ЭЛЕКТРИЧЕСКИХ МАШИН

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Аннотация. В статье рассматривается применение принципов объектно-ориентированного анализа, таких как иерархии, наследования, полиморфизма в структурного синтеза математических моделей вращающихся электрических машин. Полученные результаты позволяют динамически синтезировать произвольные математические модели электрических машин на стадии его проектирования и провести анализ электромагнитных переходных процессов.

Ключевые слова: объектно-ориентированный анализ, класс, синтез, математическая модель, переходные, электрическая машина.