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Dynamic Model of Reactive Electromotor with Full Phase Functioning Regime

BIYA MOTTO Frederic[1k], TCHUIDJAN Roger[2], NDZANA Benoît[2], ATANGANA Jacques[3].

[1]*Faculty of Science, University of Yaounde I, PO. Box 812 Yaoundé, Cameroun;*
[2]*National Advanced School of Engineering of Yaounde;*
[3]*Higher Teacher Training College Yaounde, University of Yaounde I, PO Box 47 Yaounde, Cameroon.*

Abstract: *In this paper, we study voltages equations in stator windings for longitudinal and transversal rotor symmetry d,q axis, the conditions of electromagnetic torque appearance, and also is given an evaluation of energetic efficiency for reactive electromotor functioning. We assume that along all the reactive electromotor windings, the currents circulating have a continuous character.*

Keywords: *Dynamic Model; Reactive Electromotor; Full Phase Regime*

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I. Introduction

Artificial intelligence (AI) as a field of research and development emerged and developed in parallel with the development of the theory of automatic control, starting around 50-th years, with the first major applications in computing and information science, and later in automatic control[1]. The first commercial and industrial applications of AI belong to the 80-th years of the last century[2]. During this period, AI has reached some level of stability and maturity.

An important factor that can lead to a rethinking of today's achievements and make new ups of the theory and practice of AI is the sharp increase in possibilities of computer technology, including hardware implementation of logical and other means of AI.

The term "intellectual control system" refers to any combination of hardware and software, which is joined by general information process, operating autonomously or in man-machine mode, and capable to synthesize the control goal and to find rational ways to achieve the control goal (in the presence of motivation and knowledge including information about the environment and its internal status)[1,3]. Today the capacity to synthesize the control goal is realized by human-machine interaction, and the autonomous control systems capable only to find rational ways to achieve the control goal are called as "intelligent control systems".

Currently, the science and practice of control retains a keen interest in the integration of classical methods of automatic control with methods of AI and in AI applications in the field of control for complex weakly-formalized objects and processes. In particular, when the information, system status, control criteria, and control goals change over time and are fuzzy and sometimes contradictory.

The successful solving of the problems to ensure the technological independence of the state in the field of civil and military purpose complex technical objects development and application significantly depends on the effectiveness of control systems and technologies being developed. Adequate theory and control technologies are necessary, taking into account possible deficiency of certain (depending on application) required resources: information, timing, energy, financial, material, personnel, etc.

Known accidents and disasters in transport, industry, energy etc., are often associated with the so-called "human factor" (HF), including the overwork of operators. HF often occurs as a result of quality problems with design of control system, in particular as emergency situations in controllability. Human errors, as well as the exhaustion of the technical resource of objects and control systems are common for present world circumstances. They urgently require guaranteed reliability and quality of control, including upgrades of project, operational and modernization control capacities.

One needs methods and technologies for evaluation of control systems and to ensure their optimality, functional and operational reliability, efficiency, fault tolerance and survivability are necessary under the following conditions:

- lack of a priori information about the control object and external environment of its functioning, including in opposition conditions;
- A big number of unstationarity factors to be difficult to take into account and their subjective character;

- degradation (from failures, accidents) or necessity of targeted reconfiguration (revitalizing or developmental control).

With expansion of the functional loading the control systems substantially become complicated. Among the numbers of complexity factors of modern and advanced control systems appear:

- multilevel controls, heterogeneity of description of subsystems by quantitative and qualitative models, different scales of processes in space and time, multimodality, multilink, decentralization and ramified nature and general structural complexity of modern control systems and their control objects,
- presence of uncontrolled coordinate-parametrical, structural, regular and singular impacts, including active counteraction in a conflict environment,
- the use of the deterministic and probabilistic models for description of uncertainties of information about the vector of the state and parameters of the system, about properties of errors of measuring and environment,
- non-linearity, distributed parameters, delay in control or object dynamics and impulsive impacts, high dimension of models and others.

Examples of critically important technological processes and intellectual control objects are the large-scale infrastructural systems of electric power industry. In this case:

- an inefficient structure of electro-network grids and generating capacity,
- lack of energy saving in electricity consumption,
- technological and commercial losses in electric networks,
- a technological backwardness and high degree of wear of equipment,
- a high level of monopolization of power markets,
- vulnerability of electric power systems to terrorist and cyber threats and others require developing the models of the complex infrastructural dynamic systems and creation of efficient and highly reliable intellectual control systems for smart-grids)[4-6].

Control based on logical-reactive (production) knowledge model in the so-called expert, recommender or decision-making support systems which require to be enhanced with new features:

- co-operating with other means of control systems intellectualization (artificial neural networks, genetic algorithms) and algorithms of adaptive, robust and predictive control,
- reduction of interface complexity of logical control systems with the external physical world by combining methods of symbolic and multimedia presentation and knowledge processing,
- operating with partially formalized and natural language texts,
- abductive and inductive updating of knowledge,
- integration of quantitative and qualitative models with ontologies of different subject domains that characterize the problem situation.

There are different ways of combining different AI means. For example, the neuron-reactive and logical-reactive (productional) AI means can be integrated with the 1-st order logical methods of intellectual control from[1,7]. The latter methods can treat wider stratum of knowledge, while the first two means support "reasonable" behavior on the basis of providing the simplest heuristic reactions of control system for changes in an environment or in controlled object. Logical-reactive level (sometimes with its numerous "if-then" rules) especially needs verification of knowledge presentation. In the case of productional rules of Boolean type with constructive semantics the verification of knowledge base can be reduced to the dynamic analysis of automata networks. This analysis is additionally simplified in the class of automata monotonous w.r.t. the state by application of method of mathematical models properties transfer [8].

The important problem in AI is the problem of automatic estimation of irrelevance of knowledge, because not only a deficit but also a surplus of information causes degradation of intellectual control systems.

Recent advances in the field of intellectual control include the automation of searching for ways to achieve the control goal given externally, while the automation of goal-setting and revision of control quality criteria is not sufficient yet. It is now also recognized that improvement of only "machine components" in developed human-machine systems is not enough for the desired essential increase in their efficiency. This goal in creating anthropocentric systems can be achieved by directing the efforts of engineers and scientists on improving the intellectual component of the "system-core" in anthropocentric system as built-in set of algorithms for embedded computers together with algorithms of operator activity, referred to as "on-board intelligence"[8,9].

First and foremost the on-board intelligence is required in aviation, especially in combat situations, typical for fighters, i.e. in the circumstances of the most aggressive external environment and tight timing constraints for the crew. On-board intelligence is a functionally integral complex, aimed at the fulfillment of all aircraft tasks9.

Scientific and technological advances in this field will be useful also in other applications of AI in the conditions of a multicriteriality, uncertainty and risk to improve control quality in a situation of information overloading the operator, limited time or stress.

Development of practically useful on-board decision-making support expert systems, including those based on fuzzy logic and case-based reasoning by analogy, has reached the practical stage of building the models and prototypes. They are intensively developed in the world in favor of the creation of the manned combat aircraft of the 4++ and 5th generations, as well as combat UAVs. Their fragments already appear on the modernized fighters of 4++ generation. In foreign developments, they are planned to be used, first of all, on board of the new USA fighters F-22, F-35, modernized F-16, F-15, F/A-18 and helicopters, which have a number of on-board intellectual systems of tactical decision making [9]. The results of the research, the improvement of on-board computers, cockpit displays and controls as well as other avionics give the constructors of next generation aircraft / helicopter an opportunity to design and realize a-board computer systems of a new type. These systems will be capable to support tactical decisions making (the prompt appointment of the current purpose of flight and choice of a rational way of achieving the goal). Solving such tasks on past generations aircraft could be only completed by the efforts of the crew.

Further we consider in details some questions of intellectualization of automatic control systems in the form of fuzzy regulators and combining them with other AI means. Note that the first regulators developed in Greece in the 3rd century BC partly can be considered as the fuzzy controllers described linguistically with logical operations. Today, a huge number of practical applications of fuzzy control systems in the industry, transport, energy, oil and gas, metallurgy, medicine and other industries and household appliances can be observed in Japan, China, USA, Germany, France, Britain, Russia and other countries.

We consider four basic types of regulators: logical-linguistic, analytical, learned and proportional-integral-differential (PID) fuzzy controllers [1], [7],[11-17].

II. Voltages Equations Of Reactive Electromotor With Full Phase Functioning Regime

Electromagnetic processes in reactive electromotor are determined by voltages equations in stator windings:

$$U_S = R_1 I_S + L_1 . PI_S + P\{L_{SS} . I_S\}, \qquad (1)$$

With U_S – voltages vector in stator windings

I_S – Currents vector in stator windings

The equation (1) is written in real coordinates system and it has periodical coefficients matrix that makes the analysis very complicated.

If we make the following variables change, assuming

$I = 2/m . \nabla(\gamma)^T . D_S . I_S ; U = 2/m \nabla(\gamma)^T . D_S U_S$, then

$U = R_1 . I + \omega . E . L_{01} . I + L_{01} . pI, \qquad (2)$

With $L_{01} = L_0 + L_1 .1; L_0 = w^2 . D_S . D_S^T \Delta d_q = diag\left(L_{dd} , L_{qq}\right);$

$$E = \nabla(\pi/2)$$

The vectors I and U in equation (2) are the dimension and are characterized in a plane by two coordinates

$$I^T = \left[i_d , i_q\right]; U^T = \left[u_d , u_q\right].$$

The equation (2) is called the “equation of reaction machine in d,q coordinate axis.”

In a developed form the equations system that describes the electromagnetic processes dynamics will be:

$$u_d = R_1 i_d - \omega . L_q . i_q + L_d P i_d \qquad (3)$$

$$u_q = R_1 i_q + \omega . L_d . i_d + L_q P i_q \qquad (4)$$

With $L_d = L_{dd} + L_1 ; L_q = L_{qq} + L_1 ; L_q = L_{qq} + L_1 .$

The characteristic polynom of equation (2) $Y(P) = L_d . L_q P^2 + \omega R_1 \left(L_d + L_q\right) . P + (R_1^2 + \omega^2 . L_d . L_q)$

The roots of characteristic equation Y(P)=0

$$P_{1,2} = \frac{R}{2}\left[-\frac{L_d + L_q}{L_d L_q} \pm \sqrt{\left(\frac{L_d - L_q}{L_d L_q}\right)^2 - \frac{4\omega^2}{R_1^2}}\right]$$

For little rotor rotation speed

$\omega < R_1 . (1/L_q - 1/L_d)/2$are negative and real numbers

For high rotation speed, the roots are complex numbers. In that case, the imaginary part of the root is approximately equal to ω, while the real part is equal to $(R_1/L_d - R_1/L_q)/2$.

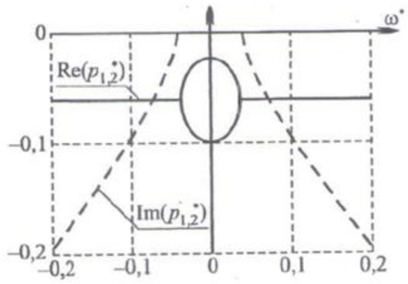

Figure 1: Dependences of real and imaginary parts of roots for characteristic equation on speed

The dependences of real and imaginary parts of roots for characteristic equation on speed are shown in figure 1.

The equation (2) can be represented corresponding to reactive electromotor two pairs of poles in stator and single pair of poles in rotor (figure 2).
Two dimensional vectors I and U in d,q coordinates system correspond to two dimensional vectors current and voltage in stator windings:

$$I_S = \nabla(\gamma).I; U_S = \nabla(\gamma).U$$

III. Voltages And Currents Harmonical Analysis

We use the equation (2). We consider U_S in real coordinates system as approximated series of rotation matrix.

$$U_S = U_S(0) + \nabla(\gamma).U_S(1) + \nabla(\gamma)^2.U_{S(2)} + \nabla(\gamma)^3.U_{S(03)} + \cdots$$

With $U_{S(K)} -$ the amplitude of vector with harmonic k=0,1…
In d,q coordinates system, the decomposition of voltages vector will look like:

$$U = \nabla(\gamma)^{-1}.U_{(0)} + U_{(1)} + \nabla(\gamma).U_{(2)} + \nabla(\gamma)^2.U_{(3)} \ldots (5)$$

With $U_K = 2/m.D_S.U_{S(K)}; K = 0,1, \ldots$
The current vector in d,q coordinates system is:

$$I = \nabla(\gamma)^{-1}.I_{(0)} + I_{(1)} + \nabla(\gamma).I_{(2)} + \nabla(\gamma)^2.I_3 + \cdots (6)$$

We consider$I_{(0)}I_{(1)}I_{(2)}I_{(3)}$ as constant values.
After various replacements and simplifications, $U_{(0)} + \nabla(\gamma).U_{(1)} + \nabla(\gamma)^2.U(2) + \cdots = R_1.I_{(0)} + (R_1 + \omega.E.L_{01}).\nabla(\gamma)I_{(1)} + (R_1 + 2.\omega.L_0.E).\nabla(\gamma)^2.I_{(2)} + 2.\omega.L_m.E_0.\nabla(\gamma).I_{(3)} + \cdots,$
With $E_0 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}; L_m = \frac{L_d - L_q}{2} = \frac{L_{dd} - L_{qq}}{2}; L_0 = \frac{L_d + L_q}{2}$
Thus, $U_{(0)} = R_1.I_{(0)}; U_{(1)} = R_1.I_{(1)} + \omega.E.L_{01}.I_{(1)} + 2.\omega.L_m.E_0.I_{(5)};$

$$U_{(2)} = R_1.I_{(2)} + 2\omega.L_0.E.I_2; U_{(3)} = R_1.I_{(3)} + 2\omega.L_m.E_0.I_{(5)}$$

$$U_{(24)} = R_1.I_{(4)} + 2\omega.L_0.E.I_4; \ldots$$

If we assume that in the composition of $U_{(S)}$, we just have the harmonics 0,1, and 2, then

$$I_{(0)} = R_1^{-1}.U_{(0)}; I_{(1)} = (R_1.1 + 2\omega.E.L_{01})^{-1}.U_{(1)};$$

$$I_{(2)} = (R_1.1 + 2\omega.L_0.E)^{-1}.U_{(2)}. \qquad (7)$$

Finally, each current harmonic is a function of each corresponding voltage harmonic.

IV. Electromagnetic Torque

The electromagnetic torque in one rotor pair of poles is: $M = L_m.I^T.E_0.I = (L_d - L_q).i_d.i_q$ (8)
We assume that stationary stator current I is expressed by series (6). Then we have:

$$M = L_m.\sum_{K=0}^{\infty}\sum_{l=0}^{\infty} I_K^T.\nabla\big((2 - K - l).\gamma\big).E_0.I_{(l)} \qquad (9)$$

From equation (9), the electromagnetic torque has constant components for K=0 and l=2, and also for K=l=1. The interaction of the rest of currents harmonics will load to appearance of periodical components of electromagnetic torque.
The medium value of electromagnetic torque is:

$$M_m = \frac{L_m}{2\pi}\int_0^{2\pi} M.d\gamma = L_m.\{2.[I_{(0)}^T.E_0.I_{(2)}] + [I_{(1)}^T.E_0.I_{(1)}]\}$$

Finally, a constant electromagnetic torque is created by currents of harmonic 0,2,1, or by current harmonic 0,2, or by currents of only harmonic 1. The currents of harmonic whose order is greater than 2 create pulsations of electromagnetic torque.

V. Energetic Efficiency Of Reactive Electromotor

We evaluate the energetic efficiency factor for reactive machine winding supply by a current of first harmonic$I_{(1)}$.

The electromagnetic torque created by currents of first harmonic is:

$$M_{11} = L_m . I_{(1)}^T . E_0 . I_{(1)} = 2. L_m . I_{d(1)} . I_{q(1)}, \qquad (10)$$

With $I_{(1)}^T = [I_{d(1)} I_{q(1)}]$.

The electrical losses from currents of first harmonic are $\Delta P_{11} = R_1 . I_{(1)}^T . I_{(1)} = R_1 . (I_{d(1)}^2 + I_{q(1)}^2)$.

The energetic efficiency factor

$E_{11} = M_{11} / \Delta P_{11}$ has a maximal $E_{11max} = L_m / R_1$ for $I_{d(1)} = I_{q(1)}$.

Let us evaluate the energetic efficiency of reactive machine windings supply by a current with constant component $I_{(0)}$ and second harmonic $I_{(2)}$.

The electromagnetic torque:

$$M_{02} = 2. L_m . [I_{(0)}^T . E_0 . I_{(2)}] \qquad (11)$$

With $I_{(0)}^T = [I_{d(0)} I_{q(0)}]$; $I_{(2)}^T = [I_{d(2)} I_{q(2)}]$.

The electrical losses:

$$\Delta P_{02} = R_1 . (I_{(0)}^T . I_{(0)} + I_{(2)}^T . I_{(2)}).$$

Thus the energetic efficiency factor

$E_{02} = M_{02} / \Delta P_{02}$ has a maximum $E_{02max} = L_m / R_1$ for $I_{d(2)} = I_{q(0)}$; $I_{q(2)} = I_{d(0)}$.

After comparison, we conclude that $E_{02max} = E_{11max}$

VI. Inductive Machines And The Relationship With Reactive Machines

Inductive machines are synchronous machines with non-symmetrical magnetic rotor system. They have two stator windings but do not have windings in rotor. One of the windings is supplied by direct current, it is the excitation winding. The second winding is supplied by alternative current, it is the armature winding.

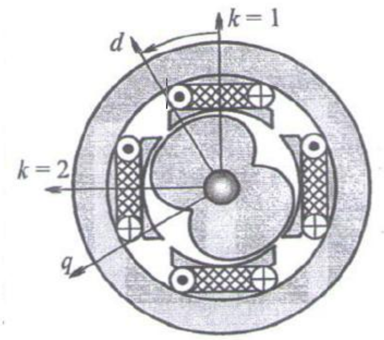

Figure 2: Reactive electromotor with two pairs of poles in rotor

As far as construction is concerned, inductive machine can be represented as shown in figure 2.

The difference with reactive machine is that in stator poles we enroll two windings: excitation and armature.

In inductive machine, the magnetic fluxes will have a constant component and a periodical component, whose pulsations angular frequency will be twice greater than the angular electrical rotation speed.

The reactive machine windings can have polyharmonical supply. We should have currents with harmonics of 0,2 order and (or) 1.

The polyharmonical composition of currents in windings can be designed by rectifier comutators. When we supply rotor windings by polyharmonical voltage, the reactive machines are said to be inductive-rectified.

VII. Conclusions

The electromagnetic processes in reactive electromotor for full phase functioning regime are well characterized by voltages equations in d,q axis.

For polyharmonical supply of windings, in formation of electromagnetic torque constant component, only the harmonics 0,1, and 2 are considered. Harmonical currents whose order is greater than 2 will create electromagnetic torque pulsations. The energetic efficiency of electromagnetic torque formation by harmonical currents of 0,2 and 1 order is the same.

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