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Study of the Characteristics and Computation Analysis Results of Electromechanical Systems Models

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***Abstract*—Today, simulation of electrical drives with asynchronous motors based on systems of differential equations is regarded as one of the principal means of their research study. The difficulty of the simulation is determined by the need for accuracy of the results obtained and the complexity of the mathematical model's differential equations. In this article, we present a study of the particularities of the simulation of electrical drives systems with asynchronous motors. We have studied models composed of three-phase and orthogonal coordinates systems and we have shown that qualitative and quantitative differences exist in the process of changing the angular speed of the rotor and electromagnetic torque. The result obtained is above all influenced by the non-linear character of the load opposing a fan-type or "dry friction"-type resistant torque. For dual-earthed electromagnetic actuation with the moments of the resistant torques indicated, integration of differential equation systems was carried out with various digital methods used in professional mathematical software for simulation.**

***Index Terms*—electromechanical system model, differential equations, discontinuous functions**

1. Introduction.

Simulation and research into electromechanical systems (EMS) and apparatus on computers is a firmly established research practice [1,2], sometimes even replacing theoretical research or analysis based on analytically obtained expressions. Researchers are gradually moving away from simplified mathematical models, and considering models based on differential or integral equations taking account of the electrical circuit as a whole and the various forms of magnetic or electromagnetic interaction. Understanding of the physical nature of equipment and the possibilities of computer programs for simulation is therefore limited. But with increasing complexity of the model, a new problem appears - to effectively and efficiently correct systems of differential equations (SDE) resolution we have to set the nature of the computational problem and choose the best method.

2. Analysis of previous studies.

With the possibilities of expansion of computer equipment, the study of electromechanical systems is carried out by mathematical and object-oriented software packages (tab.1).

As a rule, Simulation Software Packages contain a set of methods enabling problems of various types to be solved [3]. Real electromagnetic and electromechanical processes in the EMS, as inculcated, are described by rigid systems of differential equations (SDE). However, we often meet enough fast oscillating systems which describe the high-frequency fluctuations and locally unstable system, in the choice of zones with divergent processes alternating with more stable zones.

With integration of stiff systems, it is necessary to provide fast attenuation of rigid components. To do this, we can use implicit A- or L stable methods [4, 6]. The character of the problem can be changed during the resolution process or when passing from one variable to another. For solving such problems we have to use effective adaptive methods [7] whose settlement formulas are adjusted on systems that integrate.

Tab.1 Some mathematical and object-oriented software packages to study electromecanical systems EMS.

Mathematica, MatLab, Maple	Interactive system for performing engineering and scientific calculations
Mathcad	Environment for execution on a computer of a variety of mathematical and engineering calculations
Model Vision Studium	Computer lab to simulate and study complex dynamic systems
WorkBench	Package design and simulation of electrical circuits
TCAD	Universal package for the simulation of electric machines and semiconductor converters
VisSim	Software package for the simulation of complex electrical systems and their analysis.

Difficulties appear during the integration of systems with discontinuous right hand sides [9]. For correct resolution of such problems, it is necessary to reduce the integration step in the vicinity of break points, which adds further requirements to the procedure of controlling the value of the step; besides this, there are possible even pseudo hang solution due to the significant reduction step.

New mathematical software uses a series of methods for numerical solution of differential equation systems. For example, in Matlab-simulink seven methods are implemented with automatic choice of integration fixed steps :

– Methods with constant step integration: ode5 – is the fixed-step version of ode45 (Dormand-Prince formula); ode4 is RK4, the fourth-order Runge-Kutta formula; ode3 – is the fixed-step version of ode23, the Bogacki-Shampine formula; ode2 – is Heun's method, also known as the improved Euler formula; ode1 – is Euler's method.

– Methods with variable step integration: ode45 – is based on an explicit Runge-Kutta (4,5) formula, the Dormand-Prince pair, for the resolution of non-stiff differential equation systems; ode23 – is an implementation of an explicit Runge-Kutta (2,3) pair of Bogacki and Shampine, for the resolution of non-stiff and moderately stiff differential equation systems; ode113 – is a variable order Adams-Bashforth-Moulton PECE solver. It may be more efficient than ode45 at stringent tolerances and when the ODE file function is particularly expensive to evaluate. ode113 is a multistep solver - it normally needs the solutions at several preceding time points to compute the current solution; ode15s – is a variable order solver based on the numerical differentiation formulas (NDFs). Optionally, it uses the backward differentiation formulas (BDFs, also known as Gear's method) that are usually less efficient. Like ode113, ode15s is a multistep solver. Try ode15s when ode45 fails, or is very inefficient, and you suspect that the problem is stiff, or when solving a differential-algebraic problem; ode23s – is based on a modified Rosenbrock formula of order 2. Because it is a one-step solver, it may be more efficient than ode15s at crude tolerances. It can solve some kinds of stiff problems for which ode15s is not effective; ode23t – is an implementation of the trapezoidal rule using a "free" interpolant. Use this solver if the problem is only moderately stiff and you need a solution without numerical damping. ode23t can solve DAEs; ode23tb – is an implementation of TR-BDF2, an implicit Runge-Kutta formula with a first stage that is a trapezoidal rule step and a second stage that is a backward differentiation formula of order two. By construction, the same iteration matrix is used in evaluating both stages. Like ode23s, this solver may be more efficient than ode15s at crude tolerances. It's used for the resolution of stiff differential equation systems.

This group of methods enables effective resolution of a number of tasks, but, at the same time, the problem of choosing the corresponding method and its parameters became apparent. As a general rule, there are few recommendations put forward in the reference literature [13], and choice of method and its parameters is entirely determined by the researcher's level of knowledge and qualification.

Objective of the work.

Research particularities of calculation models of the electromechanical systems

3. Material and research results

For the resolution of rigid and non-rigid problems, concrete recommendations are given in [2 - 4].

We must take into account that often on the right side of differential equations systems DES of electromecanical systems EMS, models include the output voltage power thyristor converter or power transistor converter; nonlinear characteristics such as a "Dry friction" or "Backlash".etc. These signals are characterized by first-order discontinuities which suggest that the DES of EMS models are discontinuous alignment.

In the first phase of the work, the problems of modelling of Van der Pol oscillator with discontinuous function were studied.

$$\frac{d^2y}{dt^2} = sign(1-|y|)\frac{dy}{dt} - y \qquad (1)$$

The mechanical part of the electric drive system with torque -type "dry friction" was also studied [10].

As a study object, we consider a mathematical model of a two-mass system with reactive torque resistance mechanism and with a gap in the transmission. The system of equations model is of type (2).

$$\begin{aligned} & J_1 \frac{d\omega_1}{dt} M_d - M_y; \\ & J_2 \frac{d\omega_2}{dt} M_y - M_c sign(\omega_2); \\ & \frac{d\Delta\varphi}{dt} \omega_1 - \omega_2; \qquad (2) \\ & M_y = \begin{cases} 0 \;\; npu \;\; |\Delta\varphi| \le \frac{\delta}{2}; \\ c\left(\Delta\varphi - \frac{\delta}{2} sign(\Delta\varphi)\right) \;\; npu \;\; |\Delta\varphi| > \frac{\delta}{2}, \end{cases} \end{aligned}$$

where - $J_1, J_2, \omega_1, \omega_2$ the moments of inertia and rotational speed, respectively, the 1st and 2nd of mass;

M_d, M_y, M_c- Torques respectively motor, elastic and resistant, c - stiffness coefficient,

$\Delta\varphi$- torsion angle of the shaft , 2δ - gap , rad.

the study of system (2) is performed for: $J_1 = 0,1$ $J_2 = 0,5$ кгм^2 , $M_d = 40$ $M_c = 5$ Нм, $c = 5000$.

Figures 2 and 4 show the study results of integration of the systems using the methods with constant step and variable step.

It should be noted that the calculation of systems taking the nonlinearities into account, could only be performed by disabling previously option «Zero crossing control»- position with «Disable All». But in this case, by taking into account precision of 8.10, methods with variable step of integration has not provided the calculation - in fact, they were stuck. The only exception was ode15s and ode23t. Thus, the latter obviously performed the calculation incorrectly. A decrease in Precision down to 10^{-6} allows for calculation with whatever method.

Thereafter, this difference is clearly noticeable in the results obtained.

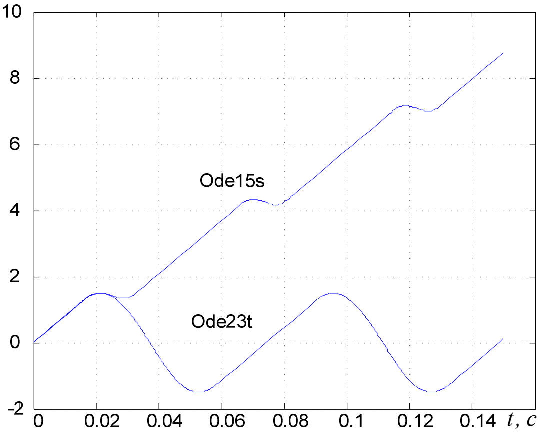


Figure 2. The calculation of (2) with the reactive torque at precision 10^{-8} using methods with variable step integration.

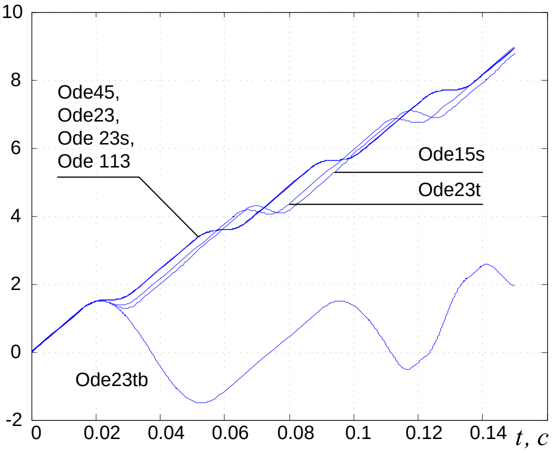


Figure 3. The calculation of (2) with the reactive torque at precision 10^{-6} using methods with variable step integration.

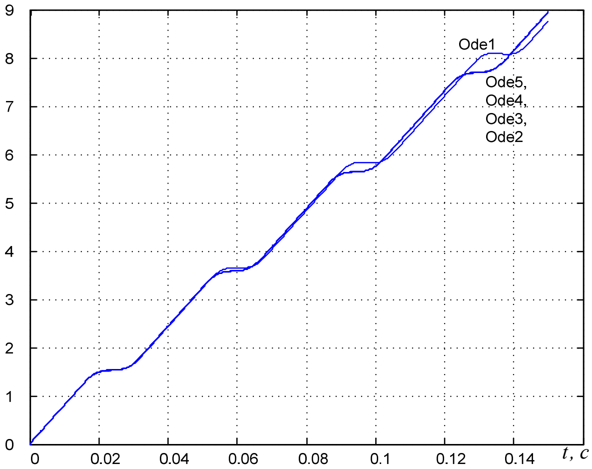


Figure 4. The calculation of system (2) with a reactive nature of the moment with an accuracy of 10^{-4} using methods with constant step integration

As a study object, we consider a mathematical model of asynchronous motor AC motor, which drives a ventilator.

Note that the system with electrical machines is nonlinear. Nonlinearity is mainly determined by two factors

- Dependence system parameters (resistance and inductance, coefficients of magnetization, gain of the regulators, etc.) of mode parameters.
- Nonlinear coupling mode parameters of the system between them.

Nonlinearity of the system parameters is usually not considered, except for special cases.

As a rule, Nonlinear coupling parameters of the system are taken into account.

For simplicity's sake, we consider that the orthogonal model of AC motor in the system coordinate α,β and u,v:

$$\begin{cases} \dfrac{d\psi_{\alpha s}}{dt} = U_{\alpha s} - AR_s\left(\psi_{\alpha s}L'_r - \psi_{\alpha r}L_\mu\right); \\ \dfrac{d\psi_{\beta s}}{dt} = -U_{\beta s} - AR_s\left(\psi_{\beta s}L'_r - \psi_{\beta r}L_\mu\right); \\ \dfrac{d\psi_{\alpha r}}{dt} = -AR'_r\left(\psi_{\alpha r}L_s - \psi_{\alpha s}L_\mu\right) + \psi_{\beta r}\omega; \\ \dfrac{d\psi_{\beta r}}{dt} = -AR'_r\left(\psi_{\beta r}L_s - \psi_{\beta s}L_\mu\right) + \psi_{\alpha r}\omega; \\ M = \dfrac{3}{2}pL_\mu A\left(\psi_{\alpha s}\psi_{\beta r} - \psi_{\beta s}\psi_{\alpha r}\right); \\ \dfrac{d\omega}{dt} = \dfrac{1}{J}\left[M - M_c\left(\dfrac{\omega}{\omega_0}\right)^2\right]. \end{cases} \tag{3}$$

and

$$\begin{cases} \dfrac{d\psi_{1u}}{dt} = U_{1u} - \dfrac{R_s\Psi_{1u}}{L'_r\sigma} + \dfrac{R_sL_\mu\Psi_{2u}}{L'_rL_s\sigma} + \omega_0\Psi_{1v}; \\ \dfrac{d\psi_{1v}}{dt} = U_{1v} - \dfrac{R_s\Psi_{1v}}{L'_r\sigma} + \dfrac{R_sL_\mu\Psi_{2v}}{L'_rL_s\sigma} - \omega_0\Psi_{1u}; \\ \dfrac{d\psi_{2u}}{dt} = -\dfrac{R_r\Psi_{2u}}{L_s\sigma} + \dfrac{R_rL_\mu\Psi_{1u}}{L'_rL_s\sigma} + (\omega_0 - p\omega)\Psi_{2v}; \\ \dfrac{d\psi_{2v}}{dt} = -\dfrac{R_r\Psi_{2v}}{L_s\sigma} + \dfrac{R_rL_\mu\Psi_{1v}}{L'_rL_s\sigma} + (\omega_0 - p\omega)\Psi_{2u}; \\ M = \dfrac{3}{2}p\dfrac{L_\mu}{L'_rL_s\sigma}\left(\psi_{1v}\psi_{2u} - \psi_{1u}\psi_{2v}\right); \\ \dfrac{d\omega}{dt} = \dfrac{1}{J}\left[M - M_c\left(\dfrac{\omega}{\omega_0}\right)^2\right]. \end{cases} \tag{4}$$

Orthogonal models (3) and (4) were obtained by algebraic and trigonometric transformations of the three-phase model [11] and are linear in parameters but nonlinear in liaison. And they also contain a nonlinear function of speed.

Fig. 5 - 8 show the results of studies with the simulation of systems (3) and (4) as compared with the simulation in the three-phase system.

The integration was performed using the Adams-Beshforts-Moulton multi-step method (ode113) (method for prediction and correction of the variable order) for solving non-rigid SDE, which is effective at high precision [2].

During the simulation we considered regimes starting AC Motor (tab.1), unloaded and under load.

Table 2. Parameters of AC Motor taken in the simulation.

Parameter	Value
nominal power, kW	4
Nominal voltage, V	380
nominal rotational speed, rad / s	151,2
Nominal torque, Nm	26,5
Stator resistance, Ohm	1,66
Rotor resistance, Ohm	1,28
Stator Leakage inductance ohms	1,95
rotor Leakage inductance Ohm	3,36
inductance of magnetic circuit, H	59,38
Moment of inertia, kgm²	0,108

In Fig. 5 - 8, curve 1 – corresponds to the model in three-phase system of coordinates, curve 2 – to that in the coordinates α, β , curve 3 – to that in the coordinates u, v .

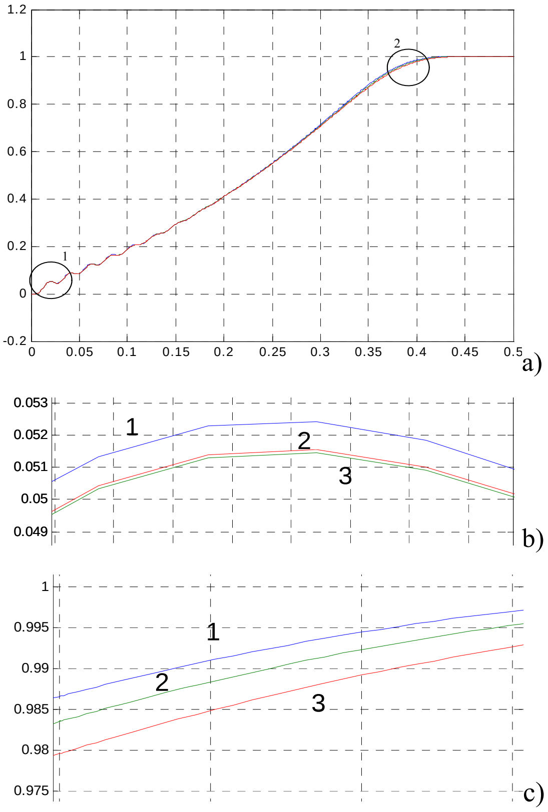


Figure 5.Speed rotation curve as a function of time of AC motor at loadless starting : a) - general view, b) - the first fragment, first oscillation , c) - second fragment, access to the stationary regime

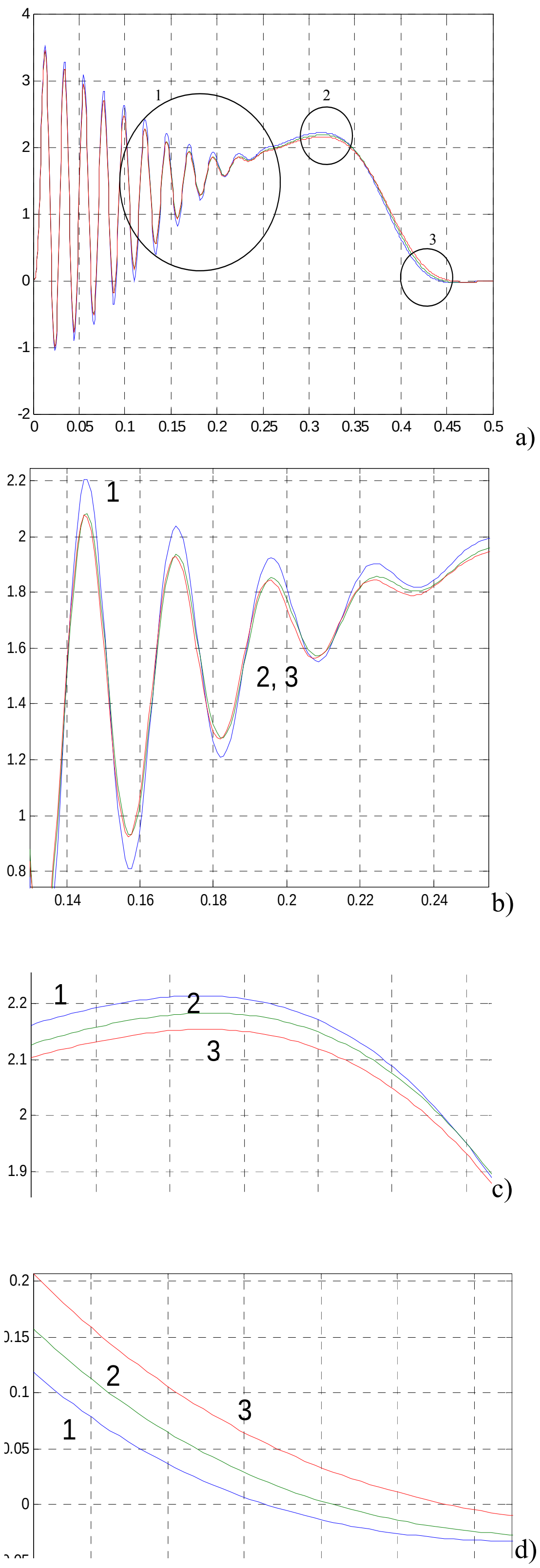


Figure 6. Electromagnetic torque curve as a function of time of asynchronous motor under load at loadless starting : a) - general view, b) - the first fragment, oscillation zone , c) - the second fragment, zone of maximum torque, d) - the third fragment, stationary regime zone.

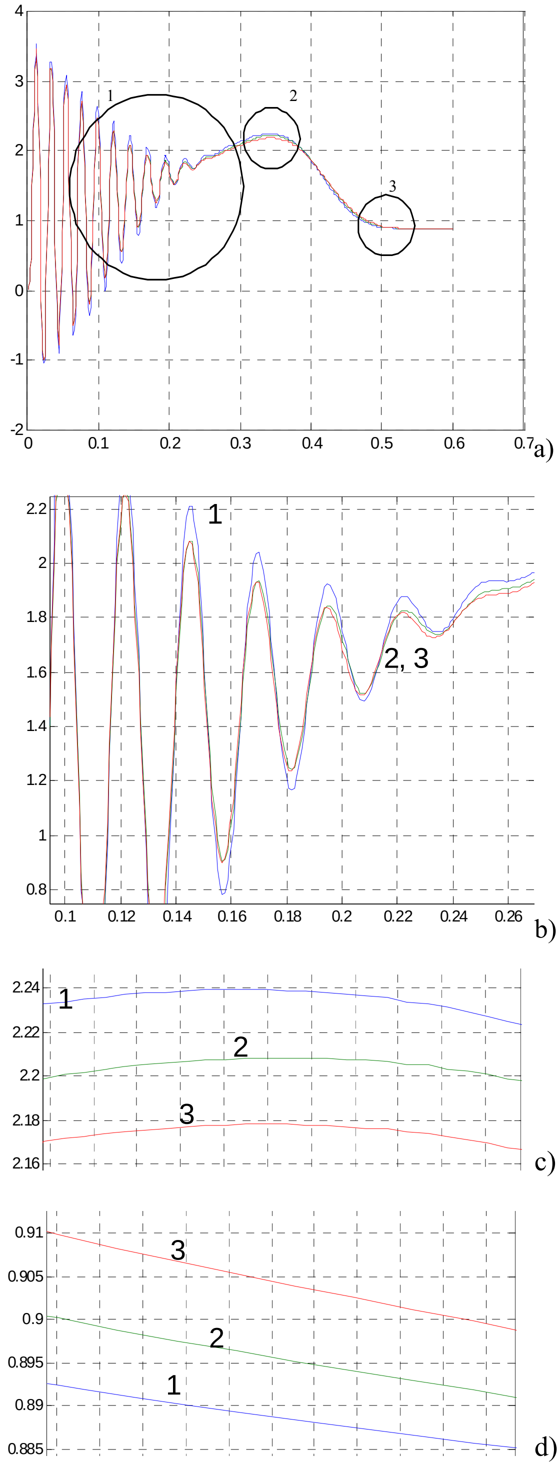


Figure 7. Electromagnetic torque curve as a function of time of AC Motor in the starting-up under load : a) - general view, b) - the first fragment, oscillation zone , c) - the second fragment, zone of maximum torque, d) - the third fragment, steady state zone.

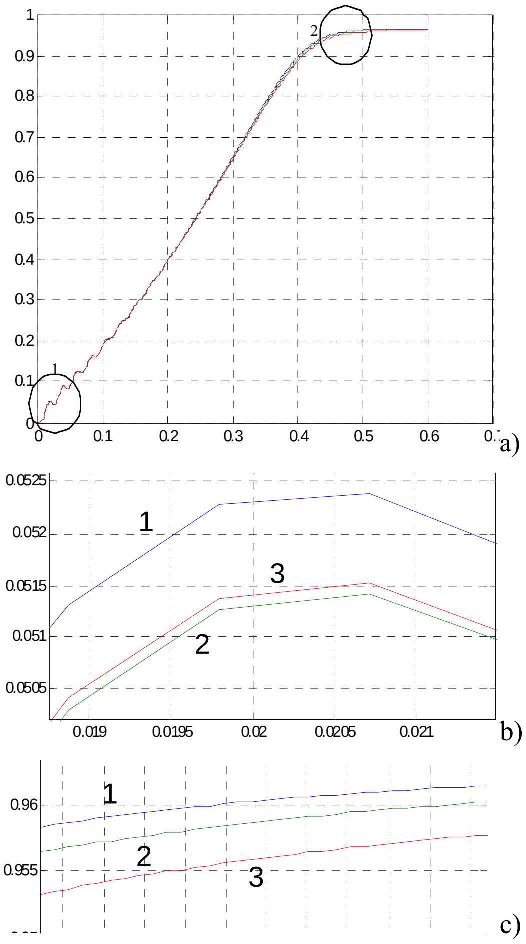


Figure 8. Speed rotation curve as a function of time of AC motor in the starting-up under load : a) - general view, b) - the first fragment, first oscillation , c) - second fragment, access to the stationary regime .

Table 2: Mismatch in modelling AC motor for various models

calculation without load on the motor shaft			
Mismatch in the frequency of rotation		Mismatch in the torque	
At starting	stationary regime	At starting	stationary regime
2%	0,2..0,5%	5,5%	1..27%
Calculation under load			
Mismatch in the frequency of rotation		Mismatch in the torque	
At starting	stationary regime	At starting	stationary regime
1,7..2,2%	0,2..0,6%	3,18%	0,8..6,7%

The relative errors obtained, shown in Table 2, are small enough. In many cases, it would seem, such mismatches can be ignored. However, recent major studies have been devoted to developing algorithms for a vector drive which provides high precision control. In "the operation of control system keeping of speed rotor in zero as with nominal load and without, has been shown. The Error of maintaining of the zero speed is no more than 0,01 rad/s" [12, p. 327]. Errors, which can be obtained in the simulation, considerably exceed the error control.

The real error may be substantially higher, since, in the simulation of electric drives, a real form of energy converter is not considered: voltage regulator (VR) or frequency converter (FC) (Fig. 9).

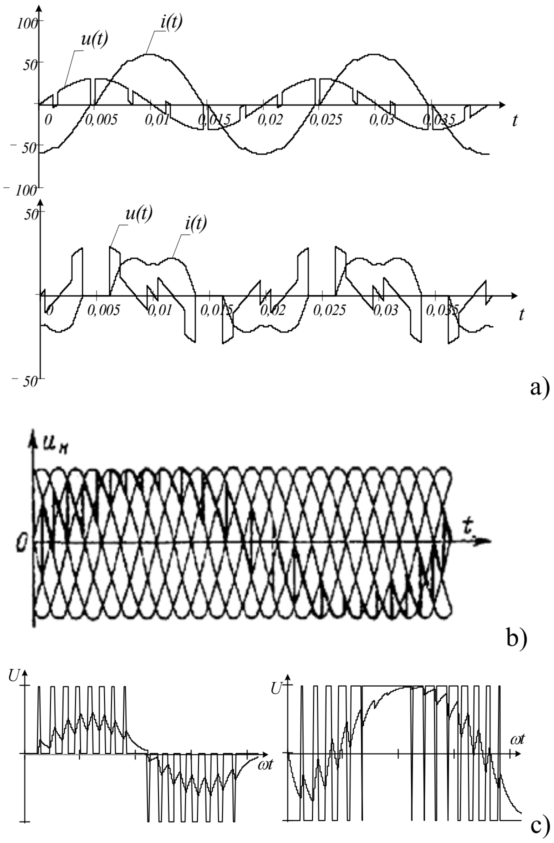


Figure 9. Electric drive current and voltage as a function of time: a) VR - AC motor, b) NFC-AC motor, c) FC-AC motor with PWM control.

From the signal voltage power converters, we can see that all the signals have steep fronts during the commutation of the control switches. Value of the derivative voltage can make 20-500 V / ms. This means that there are discontinuities and, indeed, nonlinearity. Simulation of electrical drive with the real form of the supply voltage is a complex problem. At the same time the solution is almost impossible to verify, as for example, examples of electrical drive models from SimPower Systems Matlab libraries can be calculated only for those parameters specified in the settings for this model.

Through analysing the voltage of the system's autonomous inverter exit [frequency converter-asynchronous motor] (FC-Motor AC) (fig.9, c), it can be shown that, for certain values of the step of integration, information on the real voltage at the inverter exit will be lost. The narrow impulses of the tension at the beginning and end of a half-cycle are between the adjacent steps of an integration $h > \tau_i$ where h - integration step. The number of such voltage pulses depends upon modulation frequency f_m and duty cycle γ. Figure 10 shows the variations in the duration of pulses τ depending on their numbers i at the end of a half-period of the exit voltage. The curves in the same Figure correspond to modulation frequencies 4,8,16 kHz. Modulation frequencies are taken on the basis of studies used and applied in most industrial frequency converters. For comparison, we distinguish the curves obtained for an integration step of 1µs (microsecond) (with such h, there is no information loss) and the limit mode is 50 µs.

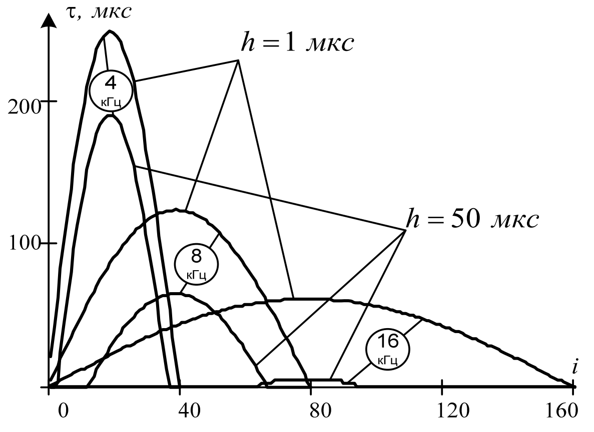
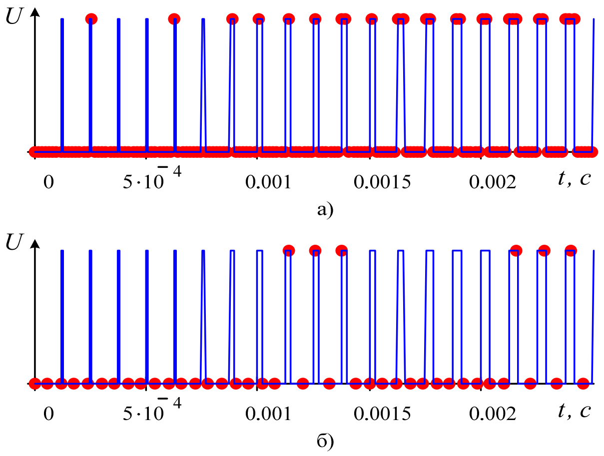


Fig. 10. variations in the duration of pulses τ depending on their number i of a half-period of the output voltage

The results of the simulation of electrical drives run by frequency converters with a real form of the modulated voltage at the invertor exit show that a distortion of voltage occurs at the exit. For example, Figure 11 shows the results of simulation of output voltage for a frequency of 8 kHz and a duty cycle $\gamma =$ 0.5 at the beginning of the initial alternation of the period in the 0……0.0025 s. interval. Voltage points calculated for integration steps of a) 10 µs and b) 50 µs are more marked on voltage pulses.



a)

б)

Figure 12. Simulation of voltage at the invertor exit with a modulation frequency of 8 kHz

In Figure 12, a reduction in bursts of pulses is clearly observable. This leads to errors during calculation of the voltage's fundamental harmonic.

Results of the study of discretisation error during the simulation are shown in Table 4. The study was carried out for evaluation of the effective value of the exit voltage of the autonomous invertor with modulation frequencies $f_{м} = 4000$ Hz , $f_{м} = 8000$ Hz and an integration step $h = 50$ µs.

Relative error was calculated depending on exact value of voltage. As the results show (Table 4), the relative error of fundamental harmonic amplitude $\delta U_{\left(\frac{f}{f_{м}}\right)}$ depends on the coefficient of duty cycle γ and is within the limits of 1…17% for $f_{м} = 4000$ Hz and 1…..27% for $f_{м} = 8000$ Hz.

Table 4. Evaluation of relative errors in simulation of the system's voltage (FC-Motor AC) with PWM

Frequency PWM, f_M, Hz	Frequency f, Hz	γ	Relative error of voltage, %
8000	50	1	0,692
		0,5	9,434
		0,25	11,079
	25	1	1,968
		0,5	0,438
		0,25	21,548
	10	1	0,486
		0,5	6,899
		0,25	17,312
4000	50	1	0,82
		0,5	9,358
		0,25	27,241
	25	1	0,229
		0,5	7,954
		0,25	8,637
	10	1	0,149
		0,5	6,106
		0,25	18,397

Figure 13 presents the curves of variation in average relative error for determination of the amplitude of the voltage depending on the frequency of the electrical drive system (FC-Motor AC) with PWM for $f_M = 8000$ Hz and $h = 50$ µs.

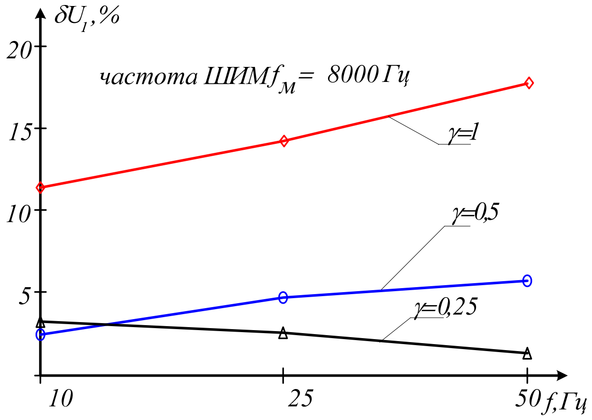


Fig.13. Functions of the average relative error for determination of voltage amplitude

Therefore, during simulation of asynchronous electrical drive systems run by invertors with voltage at PWM, we note the appearance of errors in determination of the voltage's integration characteristics. The reason is a form of signal following the presence of a large number of fronts caused by high modulation frequency $f_M = 4000$ Hz and $f_M = 8000$ Hz. In this regard, the question comes up of choice of integration step, which should be chosen on the basis of calculation of modulation frequency f_M and coefficient of duty cycle γ.

The analysis carried out reveals the type of errors produced during simulation of alternative electrical drives, regulated asynchronous electrical drives in particular.

4. Conclusions

Increase in the precision of the methods employed in the resolution of the rigid differential equations systems (SDE) enables reduction of the percentage of error, but its value is located at the level 1.8..0.5%. Such data has been obtained only for the equation of order 2. For models of electromechanical systems constituted by 5 equations, error will be considerably higher.

The presence of nonlinearity, even for a two-mass system, gives not only quantitatively but qualitatively different solutions for different numerical methods. If there is no nonlinearity, all the numerical methods give the same result in the calculation. Simulation must precede the analysis of the frequency characteristics and the stability of the system. It is possible to have a preliminary computation to get an idea of the nature of the running processes and justification of the numerical method for integration of differential systems equations DSE depending on its structure for adequate quality solutions and low enough calculation errors.

For systems with discontinuous nonlinear functions, stable solutions can be obtained by methods with a constant step of integration and with preliminary evaluation of the step size.

In some cases, it appears that a more complete differential equation (when taking into account a large number of peculiarities of the system) gives worse results under inaccurate task conditions of initial data.

A more complete equation may be more sensitive to error variations.

Additional studies should be done on the asymmetry of motor parameters, as the system is not only nonlinear but also asymmetric, which will result in non-uniform assessment of accuracy of differential equations model resolution, as well as variables and nonlinear parameters.

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