Fast-Response electric drives of Mechanical Engineering objects

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Abstract. The article gives a solution to the problem of increasing the speed in the electrical drives of machine-building enterprises due to the application of a structure with ISC control. In this case, it is possible to get rid of the speed sensors. It is noted that in this case no circulating pulsations are applied to the input of the control system, caused by a non-identical interface between the sensor and the shaft of the operating mechanism. For detailed modeling, a mathematical model of an electric drive with distributed parameters was proposed. The calculation of such system was carried out by the finite element method. Taking into account the distributed characteristic of the system parameters allowed one to take into account the discrete nature of the electric machine’s work. The simulation results showed that the response time in the control circuit is estimated at a time constant of 0.0015, which is about twice as fast as in traditional vector control schemes.

1. Introduction. Statement of problem

In mechanical engineering, most of the actuating mechanisms must realize the movement with high speed. For example, the mechanisms of robot manipulator operating on the production line must realize the desired trajectory with the maximum possible speed.

When synthesizing electric drives with maximum speed, the speed sensor, which is mounted on the shaft of the operating element or the motor, has circulating ripple at the output and is required because of the inability to ensure an ideal alignment of the gear and motor shaft. The presence of circulating pulsations at the output of the motor restricts the limiting value of the regulator’s transfer factor, therefore the possibilities for achieving maximum speed are limited in the system [1].

On the other hand, electric motors are described by a system with lumped parameters. Meanwhile, the electric machine has a discrete nature and requires a more detailed description with the use of the finite element method. With this in mind, the task of finding structures of sensorless control that realize the maximum speed in an asynchronous electric drive is relevant. This task can be resolved more productively with a detailed description of the magnetic system of the induction motor.

2. Mathematical model of electric drive

"Model of the magnetic system“ included partial differential equations that took into account the distribution of magnetic fields in the electric machine. The finite element method was used in the variational formulation. The finite element method makes it possible to significantly reduce the errors in cases of abrupt change in the magnetic permeability upon transition from the ferromagnetic to the air medium, in comparison with the widely known finite difference method. Taking into account the configuration of the electromechanical converter, it is more convenient to use the finite element
method in the variational formulation. It is sufficiently substantiated in [2]. The values of the phase currents are fed to the input of the unit. Let us give a more detailed mathematical description of the electromechanical converter in the form of partial differential systems, which were obtained by the authors on the basis of Maxwell's equations [3], and they describe processes of harmonic oscillations of variables. These equations will be needed at the stage of synthesis of the parallel algorithm for calculating the drive system.

The element of the electric machine can be described by the equation of the total current for the section of the machine by the xOy plane [4]:

\[-\frac{\partial}{\partial x}(1/\mu \cdot A/\partial x) - \frac{\partial}{\partial y}(1/\mu \cdot A/\partial y) + \gamma \mu_0 (u \cdot A/\partial x + v \cdot A/\partial y) + \beta A = Y \]  

where \( A(x, y) \) is the vector potential of the magnetic field, \( \phi \) is an auxiliary function; \( u = -U_m \sin(\omega_p t) \), \( v = U_m \cos(\omega_p t) \) - the speed vector projection on axis \( x, y \); \( \omega_p \) - rotational speed of electric drive; \( \beta = j \omega \gamma \) is a coefficient proportional to the electric speed of change of the electromagnetic field in the gap (with a sinusoidal distribution); \( \gamma \) is the specific electric conductivity; \( j \) is the imaginary unit; \( Y \) is the current distribution density. It is a function depending on the actual value of the current generated in the phase windings of the electric drive; \( \mu \) is the magnetic conductivity of the medium.

It is useful to give a physical explanation to each of the elements of the total current equation. Here the expression takes into account the drop in the magnetic potential in the magnetic circuit.

\[-\frac{\partial}{\partial x}(1/\mu \cdot A/\partial x) - \frac{\partial}{\partial y}(1/\mu \cdot A/\partial y) \]  

\[\gamma \mu_0 (u \cdot A/\partial x + v \cdot A/\partial y).\]  

The sum of the terms in the parentheses of the expression takes into account the EMF. It is induced in the magnetic circuit, which varies by the magnetic field and is proportional to the eddy currents (this term can be neglected if you have only electromagnetic calculation; its parameters are calculated when it is necessary to take into account the heating of the rotor, especially in the case of a massive construction). Value \( \beta = j \omega \gamma \) is obtained from the condition of the sinusoidal field distribution in the gap of the electric machine [5].

In the general case, when describing electric machines with non-sinusoidal feeding, when in the gap, the magnetic field is distributed according to other laws, function \( \beta A \) can be expanded in a Fourier series in terms of harmonic components. For example, the third harmonic is most pronounced in the electric drive with a FRRM with a rectangular MMF shape. Variable \( \omega \) is preserved, but correction coefficients are applied for the corresponding field shape. These coefficients can be found in the reference literature on electric machines [6]. The problem occurs when the shape of the field in the gap of the electromechanical converter is unknown.

The presented equations describe one of the units of the electric drive - an electromechanical converter at the micro level, which makes it possible to detail the processes in individual engine nodes. The solution of the total current equation by analytical methods is possible only for very particular situations [7]. In the general case, this equation should be solved by numerical methods: the method of finite differences, finite elements in the variational formulation, finite elements in combination with the Galerkin method.

The method of finite differences gives significant errors when taking into account the integral of the function [8]:

\[\frac{\partial}{\partial x} \left( \frac{1}{\mu} \cdot A/\partial x \right).\]  

This is due to the fact that value \( \mu \) changes discontinuously to the transition from one medium, for example, from the ferromagnetic to the air.
The equation of the total current can be solved by minimizing the functional [9]:

$$F(A)=1/2 \iiint \{1/\mu (\partial A/\partial x)^2+1/\mu (\partial A/\partial y)^2+2\phi(\mathbf{u}\cdot \partial A/\partial x-\phi A/\partial y)+\beta A^2-2YA\}dxdy$$  \hspace{1cm} (5)

If one finds an extremal of a given functional, then its solution coincides with the solution of the total current equation. It is mathematically proved [10]. In this case, the derivative of quantity $1/\mu$ does not find in the integral expression, as it is done in the total current equation.

The authors replaced the required function in the form of a trial function by triangular elements in the case of two independent variables:

$$A(x,y)=N_i^kA_i+N_j^kA_j+N_m^kA_m$$  \hspace{1cm} (6)

In a more general case, the test elements are elements of the tetrahedron.

Next, the authors performed a replacement of the required function in the form of a trial function and found a derivative of function $A_n$ and obtained the following result:

$$A_n\sum_{i\in M/A}\iint_{(S_i)}(b_i^k/b_i^k)(4\mu_i^kS_i^k)+c_i^k/(4\mu_i^kS_i^k)+\beta_i^k(N_i^k)^2dxdy$$

$$+\sum_{i\in M/A}A_i\iint_{(S_i)}(b_i^k/b_i^k)(4\mu_i^kS_i^k)+(c_i^k/c_i^k)/(4\mu_i^kS_i^k)+\beta_i^kN_i^kN_i^kdxdy$$

$$+\sum_{i\in M/A}A_i\iint_{(S_i)}b_i^k/b_i^k(4\mu_i^kS_i^k)+(c_i^k/c_i^k)/(4\mu_i^kS_i^k)+\beta_i^kN_i^kN_i^kdxdy$$

$$-\sum_{i\in M/A}b_i^k\iint_{(S_i)}N_i^kN_i^k \phi_i^k+\gamma_i^k/(\mathbf{u}\cdot \mathbf{c}_i^k)dxdy$$  \hspace{1cm} (7)

where in the system of equations: $k$ is the number of the final element, $S_i$ is the area of the final element; $b$, $c$ with indices - proportionality coefficients between linear basis functions and coordinates $x$, $y$.

The last term in equation (7) can be neglected, if at the stage of designing the electric drive there is no need for thermal calculation of the rotor. This is possible in cases where the rotor is selected not as a massive, but as a reclam structure.

The number of equations is determined by the number of nodes and it is proportional to the finite elements to which the active part of the electromechanical converter was "broken".

Such detailed summary of the equations was needed for the following reasons [11,12]. On the one hand, the main variables for calculation and their positional notations were introduced. On the other hand, the obtained data will be used in the synthesis of the parallel calculation algorithm.

When calculating volumetric problems, when it is necessary to take into account the induction distribution not only in the section of the stator boring, but also along the axis of rotation, the problem of reducing the calculation volumes due to the transition to a part of the electric motor model becomes actual. This approach is possible of the magnetic symmetry of the electric machine. Special boundary conditions must be taken into account here: the first kind (Dirichlet), the second kind (Neumann), and in rare cases of the third kind when working with superconductors (Cauchy). In the technical literature, these conditions are described in sufficient detail mathematically [13,14]. But in this case, little attention is paid to physics and geometric interpretation of these equations by the example of the design scheme of a classical circular motor. In our opinion, this is a significant omission, since in engineering calculations it does not allow engineers to correctly use the results of scientific work[15]. Thus, the plane on which the normal induction component is constant (in particular, $B_n=0$) cuts out the second part of the electric machine. The Dirichlet conditions are satisfied on this boundary. In fact, the machine is magnetized apropos this plane. The second plane, which is located at an angle of 90 degrees, cuts off part of the machine. It is the boundary plane, on which the Neumann conditions are satisfied. In this case, the tangential component of the magnetic field strength is zero on the plane[16].

The electromagnetic moment created by the electric drive can be found in two ways: as a result of the interaction of the current element with induction (Lorentz force) [17], or on the basis of the Maxwell tensor. The Maxwell tensor takes into account the components of the electromagnetic forces created both by the interaction of the current element with induction and the interaction of the ferromagnetic elements, which is most relevant for reluctance machine. Therefore, the calculation of
the electromagnetic moment will be performed of the Maxwell tensor for the surface case [18]:

\[ F = \frac{1}{2} \oint (H \cdot B_n + B \cdot H_n + n \cdot (B \cdot H)) \, ds \]

where \( H, B \) - the intensity and induction of the magnetic field, \( ds \) - the element of the surface on which the electromagnetic force acts.

Such assumption does not reduce the accuracy of calculations, does not take into account the nature of the distribution of effort by volume, but significantly reduces the computational load on the computer.

In the further analysis, the following configurations of the magnetic system will be investigated as the electromechanical converters: the "smooth" stator and the "smooth" rotor (the case of an asynchronous electric machine), the "smooth" stator and the salient-pole rotor with the excitation winding, the "smooth" stator and the salient-pole rotor passive (non-winding) rotor. By the term the "smooth" the authors mean the non-pole, in spite of the fact that the stator and the rotor can be having teeth. Calculation of the magnetic circuit involves a number of preliminary actions [19].

Simulation of the electromechanical system begins with the synthesis of the geometry of the electric drive. The Solid Works program is the most suitable program. Work in the application package allows one to minimize the design time for 3D geometric engine components. Series of electromechanical converters with asynchronous motors, synchronous motors and reluctance machines in a power range from 10 to 350 kW (more than 16 units for each type of machine) was designed in this work. At the same time, the geometric parameters of serial electric machines (asynchronous and synchronous) were selected from the catalogs of the electrical industry as old series, for example, 4 A [20], and new series of relatively recently mastered by a number of electric machine-building plants [21, 22].

The proposed mathematical model of the electric drive can be successfully used in solving problems of synthesis and modeling of asynchronous and synchronous electric drives.

3. Synthesis of the electric drive control system. Math modeling
In asynchronous electric drives the sensorless control circuit does not allow one to provide quality control processes [23]. In this research, the uncontrolled structure of the relay-vector control is proposed, which makes it possible to provide specified quality indicators. The absence of the speed sensor allows one to significantly increase the speed of the system. In this case, the best regulating variables can be achieved in structures, the control of variables in which is performed with respect to stator vectors. One such regulation structure is the ISC system - Indirect Stator-Quantities Control. The basic structure of regulation is shown in figure 1.

![Figure 1. The basic structure of ISC](image)

However, this scheme (Fig. 1) does not have feedback on the electromagnetic moment, which negatively affects the quality of regulation.

During the simulation, the variable processes (speed, torque, etc.) were calculated from the
previously developed model [24]. To reduce the pulsations of the electromagnetic moment, the original circuit (Figure 1) can be supplemented with a number of nodes (Figure 2).

Thus, augmented structure along one channel regulates the amplitude value of the stator flux linkage vector, and on the other - the rotational speed. It is with the effect being carried out on the dynamic and static components of the stator flux vector and thereby maintaining the magnitude of the electromagnetic moment.

![Figure 2. The ISC structure with two control channels](image)

The installation in the regulating circuit of the calculator (observer) of the variables of the stator flux linkages, the rotor currents makes it possible to build a complete control system. Figure 4 shows a block diagram of an observing device. At the output of the "ISC" voltage in $\alpha\beta$-coordinates, this is converted into polar coordinates (angle, amplitude) by the block «alpha-beta to angle magnituda». Then it enters the input of the "SVPWM" block. The SWPVM unit issues control actions (PWM) to the power transistors, which form the voltage for the motor. The "observer" block receives real values of the voltages measured by voltage sensors and converted into $\alpha\beta$-coordinates.

"Observer" provides estimated values of flows to the "ISC" block. The phase currents are removed from the motor by means of current sensors, and by means of the speed sensor - speed, which are also sent to the "ISC" block.

Figure 3 shows the transient response of the electromagnetic moment in the system by ISC control. Figure 3 shows that the motor develops a predetermined moment in time equal to 0.0015 s, which corresponds to five PWM periods (PWM frequency $f_c=3000 \, kHz$), hence the PI controller of the active torque component is optimally tuned.

![Figure 3. The transient process of the electromagnetic torque](image)
4. Conclusion
For the electric drives of the technological mechanisms of machine-building enterprises, the use of control structures with ISC control will make it possible to get rid of the speed sensor and thereby achieve the greatest speed. The simulation results showed that the response time in the control circuit is estimated at a time constant of 0.0015, which is about twice as fast as in traditional vector control schemes.

References
[1] Usinin U S, Grigoriev M A, Vinogradov K M, Gorozhankin A N and Gladyshev S P 2009 SAE Technical Papers
[2] Lapshina V A, Popov A A and Gulyaev I V 2017 Russian Electrical Eng. 88(6) 347-350
[3] Gladyshev S P, Usinin Y, Valov A, Grigoryev M and Bychkov A 2010 SAE Technical Papers
[4] Grigoryev M A, Gorozhankin A N, Kinas S I and Belousov E V 2014 Russian Electrical Eng. 85(10) 638-640
[5] Usinin Y S, Grigoriev M A, Vinogradov K M and Gladyshev S P 2008 SAE Technical Papers
[6] Belousov E V, Grigor’ev M A and Gryzlov A A 2017 Russian Electrical Eng. 88(4) 185-188
[7] Grigor’ev M A 2014 Russian Electrical Eng. 85(10) 601-603
[8] Gorozhankin A N, Grigor’ev M A, Zhuravlev A M and Sychev D A 2015 Russian Electrical Eng. 86(12) 697-699
[9] Kavalerov B V and Odin K A 2017 Russian Electrical Eng. 88(5) 310-313
[10] Zasov V A, Zheleznov D V, Mitrofanov A N and Belonogov A S 2017 Russian Electrical Eng. 88(3) 115-119
[11] Shpiganovich A N, Shpiganovich A A and Pushnitsa K A 2017 Russian Electrical Eng. 88(6) 378-380
[12] Kozyaruk A E, Khitrov A A and Khitrov A I 2016 Russian Electrical Eng. 87(3) 119-124
[13] Afanas’ev V V, Kovalev V G, Tarasova V V and Tarasov V A 2017 Russian Electrical Eng. 88(7) 443-447
[14] Grigoryev M A and Kinas S I 2014 Russian Electrical Eng. 85(10) 645-648
[15] Gryzlov A A, Grigor’ev M A and Imanova A A 2017 Russian Electrical Eng. 88(4) 193-196
[16] Grigor’ev M A 2015 Russian Electrical Eng. 86(12) 694-696
[17] Khayatov E S and Grigor’ev M A 2017 Russian Electrical Eng. 88(4) 197-200
[18] Belykh I A, Grigor’ev M A and Belousov E V 2017 Russian Electrical Eng. 88(4) 205-208
[19] Usinin Yu S, Grigoriev M A, Vinogradov K M and Gladyshev S P 2007 SAE Technical Papers
[20] Grigor’ev M A, Naumovich N I and Belousov E V 2015 Russian Electrical Eng. 86(12) 731-734
[21] Grigor’ev M A 2013 Russian Electrical Eng. 84(10) 560-565
[22] Grigor’ev M A 2017 Russian Electrical Eng. 88(4) 189-192
[23] Usinin Y S, Grigoriev M A, Vinogradov K M and Gladyshev S P 2008 SAE Technical Papers
[24] Minullin R G 2017 Russian Electrical Eng. 88(2) 61-70