



Methodology and Tools for Computer-Aided Calculation of Characteristics of Electromechanical Clamping Drive Actuated by Induction Motor

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Abstract. The article is devoted to solving the problem of determining the parameters of electromechanical drives of clamping mechanism of lathes. The conducted research is directed at the creation of methodology for calculating the main characteristics of a mechanism for workpiece fixation, made on the basis of a new structure with an electromechanical drive. The obtained results were used to create a computer program, which presents the results of calculations in the form of characteristics to time dependency graphs. The use of the developed tools makes it possible to study the mechanism operation as a process consisting of separate strictly defined stages. The obtained model identifies the change in characteristics as they move from one stage of operation to another. The developed research tools also allow defining the optimal adjustment of this type of mechanism.

Keywords: Clamping mechanism · Electromechanical actuator · Calculation of characteristics · Computer program

1 Introduction

Significant progress in the development of electrical systems, and electric drives, in particular, gives new opportunities for their use in place of their mechanical counterparts. This trend also applies to machine tool knots. For example, a traditional drive that provides the main movement in the machine tool and contains a gearbox is often replaced by a motor spindle when creating advanced machine tool models. This opens up new potential for improving the performance of metalworking machines and requires improvements to its other subsystems. The advantages of electrical systems related to the efficiency of energy conversion and transmission, as well as the efficiency of control, have led to active proliferation to create modern mechanisms. It is known that improving characteristics of fixation of a workpiece on machine tools makes it possible to increase the processing modes; therefore, the use of electrical subsystems in a structure of modern clamping mechanisms is predictably expedient. The process of developing new high-tech machine components is often closely linked to the usage of mathematical modeling and automated calculation tools. The calculation of characteristics of mechanisms due to which dynamic loads occur is relatively complex, so it is especially important to use computer equipment.

Work cycles of mechanisms for clamping workpieces occur in the process of clamping and unclamping a workpiece. Machine tools with automation in mass production lines are characterized by the rapid execution of a limited number of operations (often their number is reduced to one). This requires frequent movement (reinstallation) of workpieces when processing them on different machine tools. Therefore, each of these processing steps is associated with the need to clamp and unclamp workpieces in automatic mode with minimal time (this often lasts for a split second). Therefore, the main period of operating a mechanism of the workpiece clamp occurs under unsteady (unstable) modes. As a result of non-linearity loading of mechanism elements, transition processes emerge not only at the beginning and the end of each clamping or unclamping cycle, but also during the transition between the different stages of these processes (gaps elimination, generation of tension, etc.). This leads to accelerated movement of the elements of the mechanism and the emergence of additional dynamic loads. The effect of significant centrifugal inertia forces resulting from the rotation of the clamping mechanism together with the machine tool spindle also has an impact on the performance of the mechanism. To effectively design clamping mechanisms with optimal performance and the ability to determine the optimal settings according to processing conditions, it is necessary to consider the above-mentioned features of its operation. This greatly increases the complexity of calculations and requires automation of this process based on a specially developed methodology.

Within the current tendency of active introduction of electrical subsystems into the structure of technological equipment, some constructions of clamping mechanisms with electromechanical actuators have been developed, which have several advantages in comparison with hydraulic, pneumatic, and mechanical ones. The developed constructions are based on a structure containing an induction motor and provide energy transfer to the input of the clamp mechanism through a magnetic field between the stator and the rotor of the motor. For further efficient design, manufacture, and operation of clamping

mechanisms with an electromechanical actuator, there is a necessity for multiple calculations, which are related to the determination of parameters of optimal interaction of their subsystems at different stages of the operation cycle under different operating conditions and different structural features of machine tools in the structure they are integrated into.

2 The Purpose of the Research

The purpose of the research is to develop a tool in the form of software for personal computers, which would allow simulating and calculating the basic characteristics of the electromechanical drive of the workpiece clamping mechanism with an induction motor taking into account the features of two main stages of operation, transients, and the possibility to simulate the load of the output link of the mechanism.

3 Research

The design of the electromechanical actuator as part of the clamping mechanism is considered to identify the initial calculation data. Its schematic diagram (Fig. 1) is typical for mechanisms like this. The mechanism is powered by electrical energy sources *ES* with voltage *U* through a switching device *SD*, which regulates the stator current of an induction motor with stator and rotor. As a result, an electromagnetic torque *Ma* appears on the cage motor rotor and gives it a rotational motion with frequency *n*. The torque of the rotor is converted by a drive self-braking mechanism (*DSBM*), which is made in the form of a screw transmission, into the axial force *F_{ax}*, which is transmitted to the collet clamping chuck (*CC*) and is converted by its conical connection into a radial force to fixate the object (*OC*).

A feature of the clamping mechanism of this design is that the input force is brought in contactless—due to the electromagnetic interaction of the elements of the stator and rotor of the electromechanical actuator, and the value of force *F_r* for clamping *OC* can be effectively changed, according to the needs, switching device *SD*. Also, using electronic means to control the operation of the electromechanical actuator motor different modes of operating of the clamping mechanism can be effectively set, depending on the sphere of

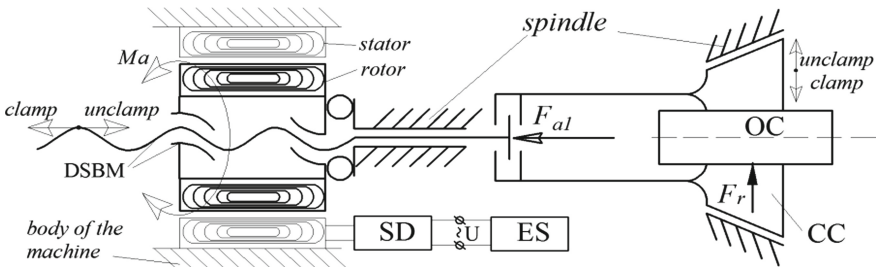


Fig. 1. The conceptual sketch of the electromechanical actuator of the clamping mechanism according to the patent of Ukraine Nu. 95323

usage: automatic and semi-automatic cycles and “push-button” control—for performing debugging operations.

The structure of the process of determining the characteristics of the electromechanical clamp actuator is shown in the form of an outline flowchart (Fig. 2).

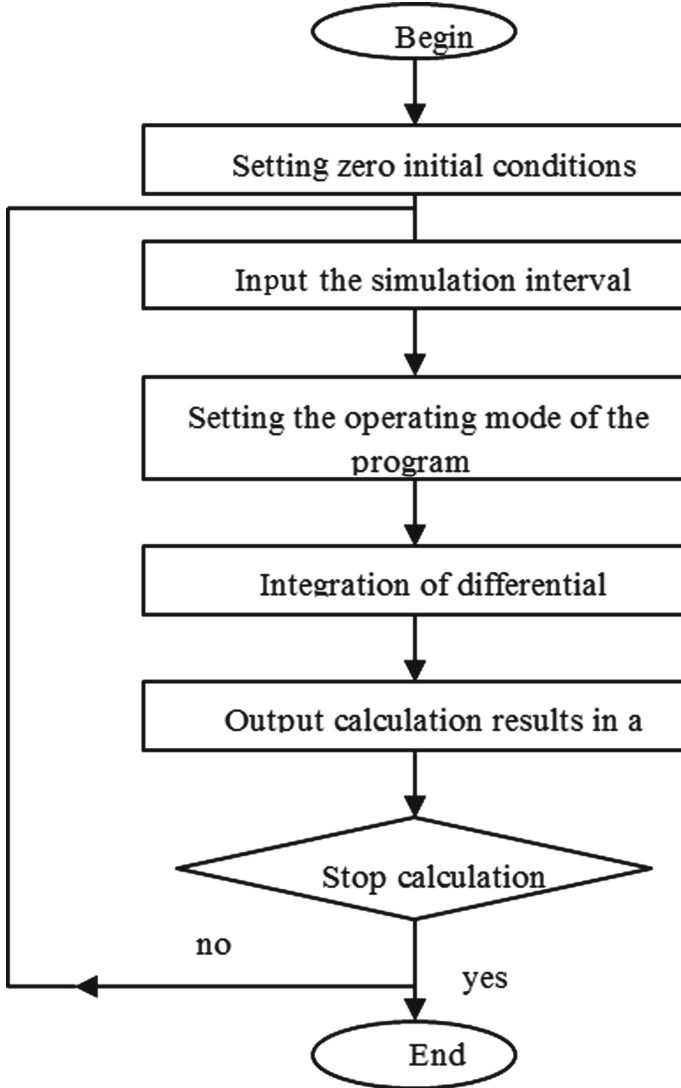


Fig. 2. Flowchart of the process of calculating the characteristics of the electromechanical clamping actuator

A mathematical model of the asynchronous cage induction motor used to create the computer program is designed to analyze the performance of an engine both

autonomously and as an element of a complex system. It allows us to calculate the basic electromechanical time dependencies and then analyze them as a separate element or element of the system as a whole.

For the basis of the equations, we take the differential equations of a three-phase asynchronous motor in the cosogonal coordinate system, written directly in the normal Cauchy form [1]:

$$\begin{aligned} \frac{dI_S}{dt} &= A_S(U_S - r_S I_S) + A_{SR}(\Omega \Psi_R - r_R I_R); \\ \frac{dI_R}{dt} &= A_{RS}(U_S - r_S I_S) + A_R(\Omega \Psi_R - r_R I_R) \end{aligned} \tag{1}$$

where I_S, I_R —the columns of stator currents and converted rotor currents; U_S —the column of the source voltage; Ψ_R —the column of full flux linkage rotor windings; r_S, r_R —resistive resistors of stator and rotor windings; V_R —the column of rotor winding voltage; A_S, A_{SR}, A_{RS}, A_R —the matrix of coefficients.

$$\frac{dI_S}{dt} = A_S(U_S - r_S I_S) + A_{SR}(\Omega \Psi_R - r_R I_R); u(t) = \begin{bmatrix} U_{SA} \\ U_{SB} \end{bmatrix} = \begin{bmatrix} U_m \sin \omega t \\ U_m \sin(\omega t - 120^\circ) \end{bmatrix}. \tag{2}$$

It should be noted that the saturation of the magnetic circuit in asynchronous motors is rarely taken into account (positions in the matrix are marked with zeros). It appears in dynamic, capacitor, and valve braking process, overvoltages, etc. Therefore, for this variant, the matrix of the coefficients A of the motors is presented in the form (3).

$$A = \begin{bmatrix} A_S & A_{SR} \\ A_{RS} & A_R \end{bmatrix} = \begin{bmatrix} \alpha_S - \frac{\alpha_S^2}{\alpha_S + \alpha_R + \alpha_m} & 0 & -\frac{\alpha_S \cdot \alpha_R}{\alpha_S + \alpha_R + \alpha_m} & 0 \\ 0 & \alpha_S - \frac{\alpha_S^2}{\alpha_S + \alpha_R + \alpha_m} & 0 & -\frac{\alpha_S \cdot \alpha_R}{\alpha_S + \alpha_R + \alpha_m} \\ -\frac{\alpha_S \cdot \alpha_R}{\alpha_S + \alpha_R + \alpha_m} & 0 & \alpha_R - \frac{\alpha_R^2}{\alpha_S + \alpha_R + \alpha_m} & 0 \\ 0 & -\frac{\alpha_S \cdot \alpha_R}{\alpha_S + \alpha_R + \alpha_m} & 0 & \alpha_R - \frac{\alpha_R^2}{\alpha_S + \alpha_R + \alpha_m} \end{bmatrix}. \tag{3}$$

The angular velocity matrix Ω according to [1] will have the form

$$\Omega = \frac{\omega}{\sqrt{3}} \begin{bmatrix} -1 & -2 \\ 2 & 1 \end{bmatrix}, \tag{4}$$

where $\alpha_S, \alpha_R, \alpha_m$ —inverted inductance of dissipation stator and rotor windings and main inverted inductance of the motor; ω —angular velocity of rotation of the rotor.

The column of full flux-linkage is as follows:

$$\Psi_{Rj} = \frac{I_{Sj} + I_{Rj}}{\alpha_m} + \frac{I_{Rj}}{\alpha_R}, \quad j = A, B. \tag{5}$$

The equation of the electromagnetic state should be supplemented by the equations of the mechanical state to calculate the angular velocity ω shown in (4):

$$\frac{d\omega}{dt} = \frac{p_0}{J}(M_E - M(\omega)); \quad \frac{d\gamma}{dt} = \omega; \quad n = \frac{30\omega}{\pi}. \tag{6}$$

$$M_E = \sqrt{3}p_0\alpha_m(I_{RA}I_{SB} - I_{RB}I_{SA}), \tag{7}$$

where $M(\omega)$ —mechanical torque; p_0 —the number of pairs of magnetic poles; J —moment of inertia of the rotor; M_E —electromagnetic torque, γ —the angle of rotation of the rotor in electric radians.

The differential Eqs. (1), (6) are a circular A-model of a three-phase induction motor. For practical use of this model, it is necessary to know the resistive resistances of the stator windings R_S and the rotor R_R , inverted inductance of dissipation α_S, α_R windings, the moment of inertia J , the number of pairs of magnetic poles p_0 , the voltage of stator windings U_S , and the mechanical torque on the rotor shaft $M(\omega)$.

In case of absence of complete information about the EMF motor from the manufacturer, the values of its inductive and active resistances can be calculated. The magnitudes of the inductances of the stator and rotor of electromechanical CA are determined by calculation, based on the previously known passport data of a typical motor prototype and the parameters of the L-shaped or T-shaped scheme (Fig. 3) substitution in the following order [2]. In the presented calculation, the parameters of the L-shaped substitution scheme for series 4A electric motor in relative units were used to determine the required parameters.

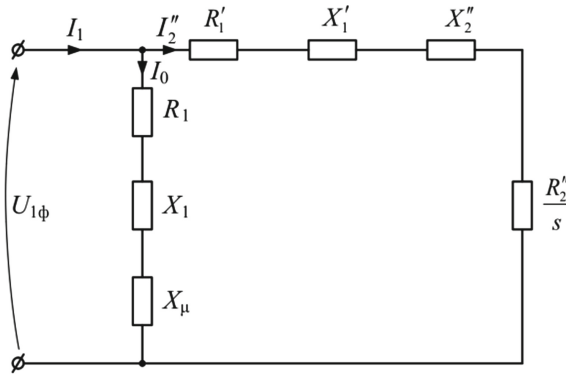


Fig. 3. L-like alternate circuit of electric motor

After calculating the parameters of the electric motor, we proceed to the absolute values of the resistances:

$$r = R' \cdot \frac{U_{f.nom}}{I_{f.nom}}; \quad x = X' \cdot \frac{U_{f.nom}}{I_{f.nom}}, \tag{8}$$

or in expanded form

$$\begin{aligned} x_m &= X_m \cdot \frac{U_{\phi-HOM}}{I_{\phi-HOM}}; r_1' = R_1' \cdot \frac{U_{f.nom}}{I_{f.nom}}; x_1' = X_1' \cdot \frac{U_{f.nom}}{I_{f.nom}}; \\ r_2'' &= R_2'' \cdot \frac{U_{f.nom}}{I_{f.nom}}; x_2'' = X_2'' \cdot \frac{U_{f.nom}}{I_{f.nom}} \end{aligned} \tag{9}$$

where the rated phase current of the motor is taken from the reference book [3] or calculated by the formula

$$I_{f.nom} = \frac{P_{2nom}}{3 \cdot U_{f.nom} \eta_{nom} \cos \varphi_{nom}}. \tag{10}$$

According to [3], the value of the inductive resistance of dissipation of the stator winding phase is found

$$x_{\sigma 1} \approx \frac{2x'_1 x_m}{x_m + \sqrt{x_m^2 + 4x'_1 \cdot x_m}} \quad x_{\sigma 1} \approx \frac{2x'_1 x_m}{x_m + \sqrt{x_m^2 + 4x'_1 \cdot x_m}}. \tag{11}$$

Further, based on [2], the stator phase resistances are determined r_1, x_1 .

$$r_1 = \frac{r'_1}{m_T}. \tag{12}$$

$$x_1 = \frac{x'_1}{1 + \tau_1} - r_1 \rho_1, \tag{13}$$

where m_T —is the coefficient of reducing the active resistance to the calculated operating temperature [1–4], which is determined by the insulation class for heat resistance (for insulation classes *F* and *H*, $m_T = 1.38$); τ_1, ρ_1 respectively, the dissipation coefficients and the stator phase resistance.

$$\tau_1 = \frac{x_1}{x_m}, \quad \rho_1 = \frac{r_1 m}{x_1 + x_m}. \tag{14}$$

Having resolved jointly (12), (13), (14), the possibility of calculating the resistances of the rotor’s windings was obtained:

$$r'_2 = \frac{r''_2}{m_T(1 + \tau_1)^2 \cdot (1 + \rho_1^2)}; \quad x'_2 = \frac{x''_2}{(1 + \tau_1)^2 \cdot (1 + \rho_1^2)}. \tag{15}$$

It follows that the inverted motor inductances can be calculated by the formulas

$$\begin{aligned} \alpha_1 &= \frac{1}{L_1} = \frac{\omega}{x_1}; & \alpha'_2 &= \frac{1}{L_2} = \frac{\omega}{x'_2}; & \alpha_m &= \frac{1}{L_m} = \frac{\omega}{x_m}, \\ \alpha_1 &= \frac{1}{L_1} = \frac{\omega}{x_1}; & \alpha'_2 &= \frac{1}{L_2} = \frac{\omega}{x'_2}; & \alpha_m &= \frac{1}{L_m} = \frac{\omega}{x_m}, \end{aligned} \tag{16}$$

where $\omega = 2\pi f = 2 \cdot 3.14 \cdot 50 \text{ Hz} = 314 \text{ s}^{-1}$ —the angular frequency of voltage in the electrical grid.

Initial calculation data which characterizes a specific electromechanical clamping actuator should be entered into the corresponding cells of the main program window (Fig. 4). By changing these values, a selection of optimal characteristics can be performed. The input data for the calculation are

- maximum voltage stator windings, V ;
- the angular frequency of supply voltage, s^{-1} ;
- active resistance of the stator winding phase, Ωm ;
- active resistance of the rotor winding phase, Ωm ;
- inverted value of inductance of dissipation (leakage inductance) of the stator phase, Hn^{-1} ;
- inverted value of inductance of dissipation (leakage inductance) of the rotor, Hn^{-1} ;
- the main inverted value of the inductance of the magnetic circuit (magnetization branches), Hn^{-1} ;
- moment of inertia of the rotor, $kg \bullet m^2$;
- number of pole pairs of the electric motor;
- duration of the first stage of ACM operation, s ;
- the resistance torque which counteracts rotor rotation during clearance adjustment (eliminating gaps on the first stage of motion), Nm ;
- duration of electricity supply to the mechanism (can be less than the duration of the clamping process due to the work of inertia forces), s ;
- the maximum axial workload on the output link, determined by the required amount of force to clamping the workpiece, N ;
- the time constant;
- the thread diameter of the screw gear, m ;
- the thread pitch of the screw, m ;
- reduced angle of friction in the screw gear, $^{\circ}$.

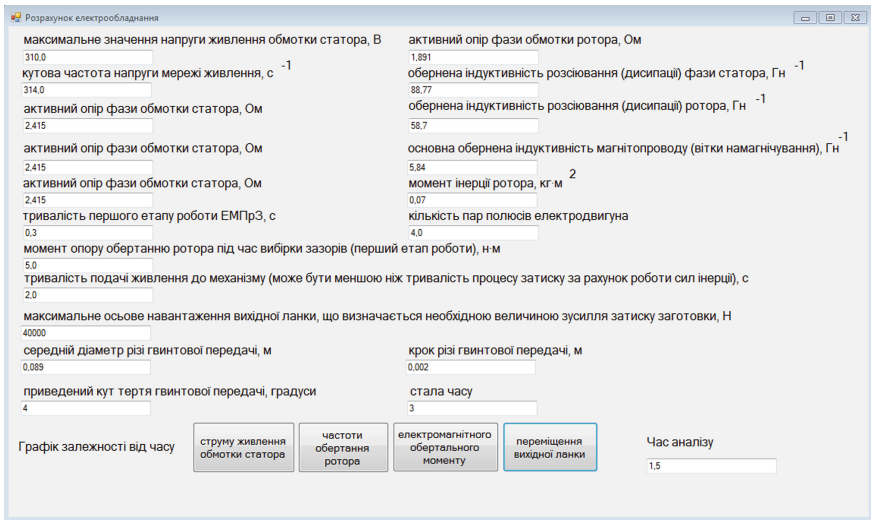


Fig. 4. The main window of the program

The presented program realizes the possibility of determining the characteristics of the *DSBM* as a two-stage process—elimination of gaps and creation of mechanical tension. The first stage is characterized by an increase in the velocity of the units of *DSBM*

and, in particular, the angular velocity of the rotor of the motor. Therefore, energy is expended to provide the motion of the mechanism in the idle mode (equal to the electromechanical torque M_a^{\min}) and to overcome the forces of inertia. The amount of torque on the motor rotor that is required for idling the mechanism (overcoming friction forces while moving units without creating mechanical tension) can be determined approximately experimentally. The load of the output link in the second stage of the *DSBM* operation can be set constant or in the form of an exponential time-dependent function with maximum value Fa , which is indicated in the corresponding cell of the program window and depends on the required amount of clamping force. This maximum load value corresponds to the electromagnetic torque on the motor rotor M_a^{\max} .

Controlling the rate of the exponential growth of the load on the output link to the maximum (setpoint) is achieved by changing the time constant in the corresponding cell of the program window. The zero time constant corresponds to the absence of load on the output link of the *DSBM* in the second stage, which means the clamping process takes place in the idle (without the workpiece). The value of the time constant of one or higher means an increase in the rate of increase of the load until its maximum (preset) value.

The minimum duration of the first step of clamping can be taken to be equal to the length of time t_{k1} during which the rotor of the motor is accelerated before the steady-state operation with a predetermined torque M_a^{\min} . The value t_{k1} can be determined from the graph of electromagnetic moment dependence on time (Fig. 5) as the point where $M_a \approx M_a^{\min}$. That is, to detect the minimum value of that time interval, it is necessary to set a known longer duration of the first stage of the EMRP operation and to find the value of the start time of the condition $M_a \approx M_a^{\min}$ on the graph. The value t_{k1} can also be determined by estimating the nature of the changes in other characteristics, such as the rotor speed. According to the graph (Fig. 5), for $M_a^{\min} = 5HM$ with stable execution of the condition $M_a \approx M_a^{\min}$, the minimum required duration of the first stage of work is defined as $t_{k1} = 0.3$ s. Therefore, the second stage of operation of this *DSBM* begins at a time after $t_{k1} = 0.3$ s and related to emerging the load on output link by the force which corresponds to the electromagnetic moment $M_a \approx M_a^{\min}$. In a real mechanism, the duration of the first stage can be adjusted by changing the free run (acceleration) of the rotor on the threaded surface without moving other elements of the *DSBM*.

The results of the calculations are displayed in the form of graphs of time dependencies: rotor speed n , magnitude of the current of a stator winding I , electromagnetic torque M_a (Fig. 5) arising on the rotor, and displacement of the X_T of the output link of the *DSBM*. The program can be adapted (by code settings) to build dependencies between the other specified values (not time).

4 Conclusions

Automation of the calculation of the performance characteristics of the *DSBM* is one of the factors of successful solutions to the problems of their design, and increase of operational efficiency. The developed computer program helps to increase the efficiency of designing *DSBM* and the process of operation by automating the process of selection of more optimal parameters of work and settings. The obtained results also contribute to the development of automation tools for the search design of these mechanisms [5–9].

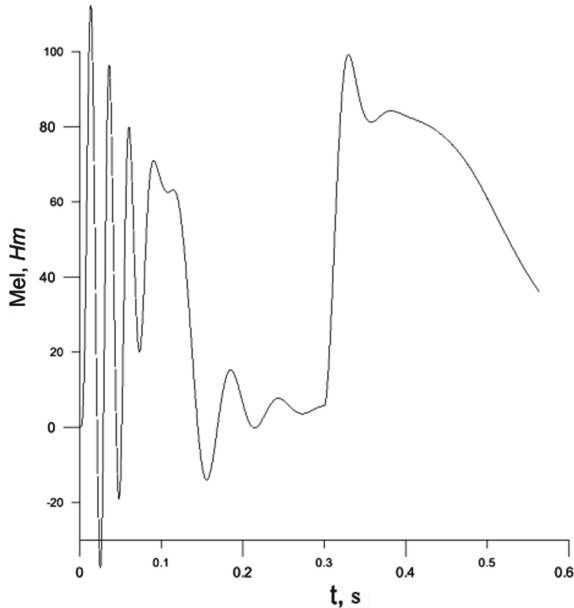


Fig. 5. Dependence of electromagnetic moment on time

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