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TRANSIENT PROCESSES AND DYNAMIC LOADS IN ELECTRICAL MACHNES FOR MECHANISMS WITH IMPACT LOADIING

D I S S E R A T I O N   A B S T R A C T

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The dissertation work is discussed and scheduled for defence by extended Departmental Scientific Council of the Department ‘Electric Power Supply and Electrical Equipment’ at the Technical University - Gabrovo on 10/15/2015.

Studies on the thesis were carried out at the Department ‘Electric Power Supply and Electrical Equipment’ at the Technical University - Gabrovo.

PhD thesis contains four chapters, at 182 pages, which include formulas, 47 figures and graphs, 17 tables and 3 annexes. The list of references consists of 157 titles, including 75 in Cyrillic, 72 in English and 10 source on the Internet.

Numbers assigned to the figures and tables in the Dissertation Abstract, is the same as in the thesis.

The defense of the dissertation will be held on 11.12.2015 13:00, room 2603 at the Technical University - Gabrovo.

Materials according the defence are available to those interested in the office of the Department ‘Electric Power Supply and Electrical Equipment’ at the Technical University - Gabrovo.

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Title: Transient processes and dynamic loads in electrical machines for mechanisms with impact loading

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A. GENERAL DESCRIPTION OF DISSERTATION

Actuality of theme

The largest share of electricity consumed in the world occupy electric motors - about 60÷65% of it according to prevailing estimates. However the most commonly used are induction motors.

Induction motors are perhaps the most rugged and best-understood motors presently available. Alternating current asynchronous motors are considered to be the universal machine of manufacturing industry. It has been estimated that they are used in seventy to eighty per cent of all industrial drive applications, although the majority are in fixed-speed applications such as pump or fan drives. The main advantages of induction motors are their simple and rugged structure, their simple maintenance, and their economy of operation.

However, for electric drive of various mechanisms in industry and households induction motors with squirrel-cage rotor are widespread.

The operation of the induction machine is based on the electromagnetic interaction between the excited rotating field by means of current of the multiphase primary winding and the induced currents thereof in the secondary winding.

The operation of induction motors is accompanied by transient processes, while they develop their sizeable electromagnetic torques, several times exceeding nominal, starting and even critical (maximum) torque. These torques are the reason for the occurrence of dangerous mechanical stresses on the components of the kinematic chain of electromechanical system. They cannot ignore the stages of design and construction and in assessing the reliability of the electrical drive work.

In conducting researches often transient processes graphics in induction electric drives are built on static mechanical characteristics without consideration of electromechanical transient processes. Ignoring their influence leads to large errors in calculations.

Detailed study of electromagnetic and electromechanical transient processes allows more rationally calculated and constructed as induction machines and the mechanical part of the electromechanical systems.

This thesis is dedicated to the study of transient processes and dynamic loads in induction machines for mechanisms with impact loading.

Purpose and tasks of development.

The purpose of this thesis is the development and analysis of engineering methods, models, algorithms and methods for the study of electromechanical transient processes and dynamic loads in induction machines for driving mechanisms with impact loadings. To achieve this objective must solve a wide range of tasks. The main ones are:

- To develop mathematical models of induction machine, mechanisms and electromechanical systems;
- To develop algorithms and choose appropriate software for solving systems of differential equations describing electromechanical transient processes at various mechanisms with impact loadings;
- To develop algorithms and models for the study of dynamic loads in various transient processes of mechanisms with impact loadings;
- To explore the inflence of the parameters of electric drive and induction machine on the course of the transient processes in the different mechanisms with impact loadings.

Methods of study

The main methods of work used in solving the tasks in the thesis are: theoretical analysis and research by means of imitative modeling with application of numerical methods.

Structure and volume of thesis

PhD thesis contains four chapters, at 182 pages, which include formulas, 47 figures and graphs, 17 tables and 3 annexes. The list of references consists of 157 titles, including 75 in Cyrillic, 72 in English and 10 source on the Internet.

B. SUMMARY THESIS

In **Chapter 1 'Analysis of the problem. Formulating the aim and tasks.'** is conducted a research of electromechanical transient processes and dynamic loads in induction machines conducted in Bulgaria and abroad. From the analysis of the problem carried out can be drawn the following conclusions:

- There are models of induction machine in different coordinate systems in absolute or relative units;
- There are developed dynamic models of some production mechanisms;
- There are no known models developed for the determination of dynamic loads in mechanisms with impact loading;

- A study of the dynamic loads linear part of the static mechanical characteristics is often used and therefore can not be considered arisen in electromechanical transient processes impact currents and moments, the duration of transient processes, dynamic loads and accelerations;
- The parameters of induction machines is most often determined by the calculation methodology;
- Different software for the study of transient processes has been used.

Chapter 2 "Mathematical models of electromechanical system" aims at presenting the developed mathematical models of induction machine for different coordinate systems, the mechanical part of the electric drive and electromechanical system. For induction machine this is done with the help of linear transformations of the equations of the mechanical characteristics of the machine and a summary of phase transformations of variables. Computational schemes of mechanical part, typical static loads and equations of motion of the electromechanical system are described.

For analysis is accepted system of names which belong to the variable to one or the other winding is determined by the indices, which are labeled axes associated with the winding of generalized machine and a summary display that relate to the stator and the rotor. Most often the following subscripts are used:

- s, in the case of the stator;
- r, in the case of the rotor;
- α, β, in the case of a coordinate system rigidly connected to the stationary stator;
- d, q, in the case of a coordinate system connected to the rotor;
- u, v, when referring to a coordinate system rotating at any speed relative to the stator;
- x, y, when referring to a coordinate system rotating at synchronous speed relative to the stator.

Prominent advantages of the introduction of relative units in the research of electrical machines, and make an informed choice of a system of basic values used in researches. In practice, the selection and verification of electric motors for heating and overload, as well as to assess their starting and loading characteristics using the nominal moment of the motor shaft. Therefore, in research to be able to appreciate the above qualities of the electric motors and so we can compare them to each other, the rated torque as a base moment has been used.

The numerical methods used for mathematical modeling as two main groups have been presented: methods of integrating with separate steps (one-step methods) and methods with related steps of integration (multi-step methods). An justified choice of numerical methods for solving differential equations based on the attributes of some of the different numerical methods has been done – during further researches is used modern modification of the method of *Runge-Kutta*, a built-in function in a particular software.

The indicators of the quality of transient processes have been presented – the maximum overtunning, duration of the transient process, period of own fluctuations, etc.., and integrated assessments of the quality of transient processes also.

Conclusions to Chapter 2:

- Mathematical models of induction machine for different coordinate systems have been developed;
- A mathematical model of the mechanical part of the electromechanical system has been developed;
- A justified choice of a system of basic values that will be used in researches has been done;
- A justified choice of numerical method for solving differential equations, built as a feature specific computing product has been done;
- Indicators for the quality of transient processes have been selected.

Chapter 3 'Transient processes and dynamic loads of induction machines for forging press machines. Synthesis of simulation model to study the dynamic behavior of forging press machines' aims studies using the developed mathematical models of the operation of forging press machines.

The study of transient processes in induction machine is done under generally accepted assumptions.

The equations for the voltages of the windings of the induction machine are represented in a coordinate system 'x, y', rotating with the angular speed of the synchronous rotating magnetic field. This system of equations can be represented in relative units, using the conventional system of base values. It is necessary participating in the equations full magnetic fluxes to be expressed through respective currents with dependencies between them. For the purpose of convenience in solving mathematical model is presented in the form of *Cauchy*.

Using this coordinate system provides the convenience that the system differential equations present important parameter of the induction machine slip s.

After transformations, the equations for the electric equilibrium get:

$$\begin{aligned}
\frac{di_{sx}^*}{d\tau} &= \frac{L_r^*.L_m^*}{L_e^*}\left[\frac{u_{sx}^*}{L_m^*} - \frac{u_{rx}^*}{L_r^*} - \frac{r_s^*}{L_m^*}.i_{sx}^* + \frac{r_r^*}{L_r^*}.i_{rx}^* + i_{sy}^*.\left(\frac{L_s^*.L_r^* - s.L_m^{*\,2}}{L_r^*.L_m^*}\right) + (1-s).i_{ry}^*\right];\\
\frac{di_{sy}^*}{d\tau} &= \frac{L_r^*.L_m^*}{L_e^*}\left[\frac{u_{sy}^*}{L_m^*} - \frac{u_{ry}^*}{L_r^*} - \frac{r_s^*}{L_m^*}.i_{sy}^* + \frac{r_r^*}{L_r^*}.i_{ry}^* + i_{sx}^*.\left(\frac{s.L_m^{*\,2} - L_s^*.L_r^*}{L_r^*.L_m^*}\right) - (1-s).i_{rx}^*\right];\\
\frac{di_{rx}^*}{d\tau} &= \frac{L_s^*.L_m^*}{L_e^*}\left[-\frac{u_{sx}^*}{L_s^*} + \frac{u_{rx}^*}{L_m^*} + \frac{r_s^*}{L_s^*}.i_{sx}^* - \frac{r_r^*}{L_m^*}.i_{rx}^* + i_{ry}^*.\left(\frac{s.L_s^*.L_r^* - L_m^{*\,2}}{L_s^*.L_m^*}\right) - (1-s).i_{sy}^*\right];\\
\frac{di_{ry}^*}{d\tau} &= \frac{L_s^*.L_m^*}{L_e^*}\left[-\frac{u_{sy}^*}{L_s^*} + \frac{u_{ry}^*}{L_m^*} + \frac{r_s^*}{L_s^*}.i_{sy}^* - \frac{r_r^*}{L_m^*}.i_{ry}^* + i_{rx}^*.\left(\frac{L_m^{*\,2} - s.L_s^*L_r^*}{L_s^*.L_m^*}\right) + (1-s).i_{sx}^*\right].
\end{aligned} \qquad (3.4)$$

For the current value of the electromagnetic moment of the motor in satisfying the conditions of invariance of power, receive:

$$M^* = \frac{M}{M_N} = \frac{pL_b i_b^2 L_m^*}{M_N}\left(i_{sy}^* i_{rx}^* - i_{sx}^* i_{ry}^*\right) = \frac{pu_b i_b L_m^*}{M_N \omega_b}\left(i_{sy}^* i_{rx}^* - i_{sx}^* i_{ry}^*\right); \qquad (3.5)$$

Phase stator voltages in the system relative units have type:

$$\begin{aligned}
u_A^* &= k_U \cos(\tau + \varphi_0);\\
u_B^* &= k_U \cos(\tau + \varphi_0 - \frac{2\pi}{3});\\
u_C^* &= k_U \cos(\tau + \varphi_0 + \frac{2\pi}{3}),
\end{aligned} \qquad (3.6)$$

where: $k_U = \frac{U}{U_N}$ accounts the changes in voltage;

φ_0 – initial phase of the supply voltage.

For imaging vector components of the stator voltages in satisfying the conditions of invariance of power we get:

$$\begin{aligned}
u_{sx}^* &= \sqrt{\frac{2}{3}} k_U \left[u_A^* \cos\tau + u_B^* \cos(\tau - \frac{2\pi}{3}) + u_C^* \cos(\tau + \frac{2\pi}{3})\right];\\
u_{sy}^* &= -\sqrt{\frac{2}{3}} k_U \left[u_A^* \sin\tau + u_B^* \sin(\tau - \frac{2\pi}{3}) + u_C^* \sin(\tau + \frac{2\pi}{3})\right].
\end{aligned} \qquad (3.7)$$

Since the electric motors are squirrel caged rotor type, $u_{rx}^{*} = 0$ и $u_{ry}^{*} = 0$.

After replacing (3.6) in (3.7) and the resulting transformation of trigonometric relationships, prove that:

$$u_{sx}^{*} = \sqrt{\frac{2}{3}}\kappa_U \frac{3}{2}\cos\varphi_0 = \sqrt{\frac{3}{2}}\kappa_U \cos\varphi_0; \qquad (3.8)$$

$$u_{sy}^{*} = -\sqrt{\frac{2}{3}}\kappa_U\left(-\frac{3}{2}\right)\sin\varphi_0 = \sqrt{\frac{3}{2}}\kappa_U \sin\varphi_0. \qquad (3.9)$$

According to the latest information for the production of "VAPTEH" JSC [148] and Schuler Group [149] in respect of the electrical mechanical presses are manufactured in the power range [2.2 to 130] kW. Given presented below these findings are different capacities of the drive electric motors.

Automated determining the power required and selection of electric motors for forging fly-press mechanisms.

By means of the crank mechanism, occurring component of the kinematic chain is obtained reciprocating movement without reversing the motor. But reduced to the motor shaft resisting moment and moment of inertia depends on the angle of rotation of the crankshaft: $M_{resist} = f(\alpha)$ и $J = f(\alpha)$. This leads to an uneven (pulse) load of the motor and greatly complicates its selection.

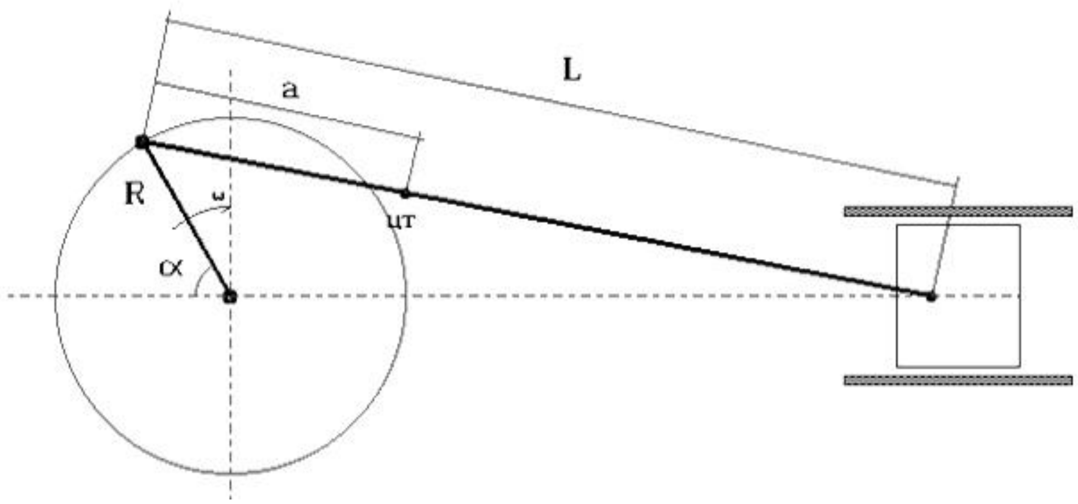


Fig. 3.1. Crank-rod mechanism.

R – knee radius; L – connecting rod length; CG – connecting rod center of gravity; a – distance to the center of gravity of the connecting rod; ω – angular speed of the crankshaft; α – turning angle of the crankshaft.

The block diagram of an algorithm for determining the power and the selection of the electric motor and the optimum moment of inertia of the flywheel of the electric drive of the crank mechanism with the reciprocating motion is given on Fig. 3.2.

According to the block diagram shown, the setting of the optimal parameters of the electric drive becomes the method of successive approximations, such as the importance of the individual units is:

Block 1. Choosing mechanism. From the main menu mechanism with reciprocating movement of the actuator has to be selected. In this case – forging fly-press mechanism.

Block 2. An input. Introduces input data specific to each mechanism.

Block 3. Preliminary determination of motor power by approximate method.

Block 4. Choosing motor by conditions: $P_{nom} > P_{ave}$ and conditions for starting, if necessary.

Block 5. In case of default of the conditions for the selection of the motor when there is not appropriate one in the catalog [66], a relevant message appears and suggests possible changes in the terms of assignment (for example: select another motor synchronous speed or to fill the catalog with new motors).

Block 6. Preliminary estimation of the moment of inertia of the electric drive by means of (3.15).

Block 7. Solving the fundamental equation of motion.

Block 8. Determine whether the inertia moment of the system is optimal and if so not, in *Block 9*. Correction of inertia moment has to been done and control returns to *Block 7*.

Block 10. Calculation of the equivalent moment of the motor by means of (3.21).

Block 11. Check whether $M_{eq} \leq M_{nom}$ and if so not, in *Block 12* is set the condition to seek a new motor with more power.

Block 13. Plot a graphs of performance of the electric drive in one cycle, namely:

$$M_{resist} = f(\alpha); M_{motor} = f(\alpha); n_{motor} = f(\alpha);$$

Block 14. Output results of the calculations.

The program calculates the resistance force, the moment and power of forging fly-press machines reduced to the motor shaft, selects an appropriate motor and checks according to permissible heating.

Input data in dialog mode are:

- crank arm radius, m;
- length of piston rod, m;
- distance to the center of gravity of the piston rod, m;
- mass of the piston rod, kg;
- mass of the slider and operating tool, kg;

- synchronous rotational frequency – 750, 1000, 1500 or 3000 min^{-1};
- time for one cycle of operation, s;
- efficiency of the mechanism;
- maximum resistive force, N;
- movement of the slider under the effect of the resistive force, mm.

The program automatically creates files in the current folder in which record and store raw data for individual mechanisms. All information necessary for the program is displayed on the monitor.

Database for electric motors incorporates such a rated voltage of 400 V in the power range of 0.37÷250 kW series AO, AO2, AOP, AOC, AM, 4AO, M, MO, MOM.

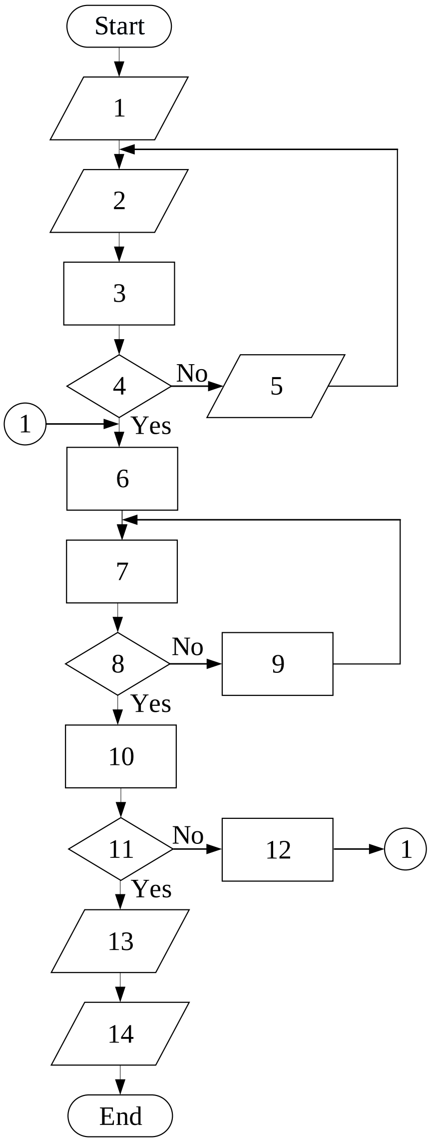


Fig. 3.2. Block diagram of the algorithm for determining the power and selection of an electric motor and the flywheel optimal moment of inertia of the electric drive of the crank mechanisms with the reciprocating movement

Tables 3.3, 3.4 and 3.5 contain part of results obtained from operation with program.

Table 3.3. Results obtained for fly-wheel inertia moment $J_{FLYWHEEL}$, gear ratio i, equivalent moment M_{eq}, operating cycle t_{CYCLE}.

n_0, min^{-1}	Motor selected		η, %	$J_{FLYWHEEL}$, kgm^2	i	M_{eq}, Nm	t_{CYCLE}, s
	P_{nom}, kW	Type					
750	3.00	AM 132M-8	80.0	0.3575	3	36.10	0.26
		AO2132M-8	80.0	0.3709	3	32.31	0.26
		AO2-42-8	80.0	0.3712	3	32.31	0.26
1000	3.00	AO2132S-6	82.0	0.2395	4	27.42	0.26
		AM 132S-6	82.0	0.2384	4	27.71	0.26
		AO2-41-6	82.0	0.2399	4	27.11	0.26
1500	3.00	4AO 100LL-4D	82.0	0.1971	7	16.42	0.30
3000	2.40	AOC-42-2	78.4	–	13	7.67	0.29

Table 3.4. Results obtained for mean resisting moment and maximum resisting moment.

n_0, min^{-1}	P_{nom}, kW	$M_{resist.ave.}$, Nm	$M_{resist.max.}$, Nm
750	3.00	24.27	139.20
1000	3.00	18.20	104.40
1500	3.00	10.40	59.66
3000	2.40	5.60	32.12

Table. 3.5. Technical data of motors selected.

n_0, min^{-1}	Motor selected		I_{nom}, A	I_{st}/ I_{nom}	M_{st}/ M_{nom}	M_{max}/ M_{nom}	GD^2, kgm^2
	P_{nom}, kW	Type					
750	3.00	AM 132M-8	7.9	4.5	1.9	2.1	0.158
		AO2132M-8	8.0	5.4	1.5	1.5	0.162
		AO2-42-8	8.0	5.0	1.5	1.5	0.160
1000	3.00	AO2132S-6	7.0	6.2	1.7	2.3	0.123
		AM 132S-6	7.1	5.8	2.2	2.4	0.126
		AO2-41-6	7.0	6.1	1.7	2.2	0.123
1500	3.00	4AO 100LL-4D	6.9	6.0	2.4	2.8	0.00752
3000	2.40	AOC-42-2	6.2	5.5	2.8	2.8	0.040

The results of Table 3.3 and Table 3.4 are obtained, it is set the desired speed by the user and the program displays the possible case for electric motors (sometimes only one motor is suitable).

With increasing transmission ratio gearbox reduces the moment of inertia of the flywheel $J_{FLYWHEEL}$ necessary, time to conduct a cycle t_{cycle} remained constant, while the equivalent torque of the necessary motor decreases.

Optimal in terms of time for the conduct of one cycle and the minimum additional flapping moment is an option at n_0=1000 min^{-1}, the gear ratio i = 4, motor type AO2-41-6 with rated power P_{nom} = 3.00 kW.

Logically, with the rise of the synchronous speed in the range of 750-3000 min^{-1} inertia moment of the rotor decreases and increases the multiplicity of starting and maximum torque of the necessary motors.

With increasing synchronous speed in the range 750-3000 min^{-1} decreased the average and maximum resisting moments.

Dynamic study of forging fly-press driven by electric induction motor.

In order to limit the starting currents, and respectively, to reduce the starting torque of the motor it is necessary to analyze the influence of the operating conditions.

A mathematical model is proposed for examining the transient processes in the forging fly-press electric drive. The driven mechanism is presented with a single-mass dynamic model. The driven mechanism is presented with a single-mass dynamic model.

The kinematics scheme of crank forging fly-press is shown on Figure 3.4. The rotational movement from the electric motor *1* by means of wedge belt transmission *2* is turned over flywheel *3*, then by means of clutch *4* and toothed gearings *5* and *8* – to the crankshaft *7*. The rotational movement by means of the crank mechanism is transformed into advanced movement of slide-block *6*. The use of belts offers a potential cost saving over other methods of transmission.

The pressing operation is possible just when the slide-block is moving down. Usually working operation is going on when crankshaft rotates on angle α_{OP}=(0°÷30°) – this is precisely the impact in pressing. This angle has to be accounted in direction reverse to the direction of crankshaft angular speed ω, value of 0° corresponds to finite lower position of the slide-block. In the interval α_{OP}=(30°÷360°) there is no work, i.e. the forging fly-press floats (works on idle running). The electric motor operates with impact cyclic variable loading. The magnitude of the resisting moment during the working operation can exceed dozens of times the mean resisting moment for duration of cycle.

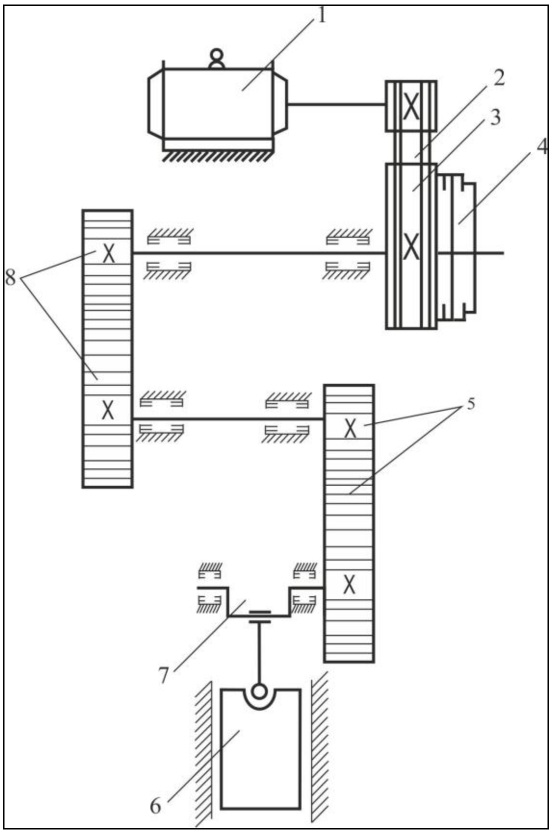


Figure 3.4. Kinematics scheme of forging fly-press
1 – electric motor; 2 – wedge belt transmission; 3 – flywheel; 4 – clutch;
5, 8 – tooth gear; 6 – slide-block; 7 – crankshaft

The impact pattern of the resisting moment leads to impact loading of electric motor – main feature of forging fly-press operation. In order to smooth the electric motor loading for cycle duration a flywheel with large moment of inertia is provided for in the kinematics scheme. During the working operation the flywheel gives a part of its kinetic energy helping in this way the electric motor for loading overcome. During the idle running the electric motor returns kinetic energy back to the flywheel (charges it again). In this way the electric motor loading during the impact decreases while during the idle running increases, i.e. smooth of $M= f(t)$ is completed (smooth of loading).

By applying of flywheel it is possible to decrease rated power of electric motor required on the average 6÷10 times in comparison with case of drive without flywheel.

The mechanical equipment is presented by means of a single-mass model. After transformation, the equation of motion is obtained to be:

$$\frac{ds}{dt} = -\frac{p}{J_{\Sigma}\omega_1}(M - M_L) \tag{3.38}$$

where: M_L – resisting moment of the mechanism; J_Σ – total inertia moment of the motor and of the mechanism, reduced to the motor shaft; p – number of pole couples of the motor; $\omega_1 = 2\pi f_1 = \omega_b$ – rotation frequency.

After transformation equation (3.38) is obtained to be:

$$\frac{ds}{d\tau} = -\frac{pM_b}{J_\Sigma \omega_b^2}\left[\frac{pu_b i_b L_m^*}{M_N \omega_b}\left(i_{sy}^* i_{rx}^* - i_{sx}^* i_{ry}^*\right) - M_L^*\right] \tag{3.39}$$

The full system of differential equations which describe the dynamics of the forging fly-press induction motor drive is formed by the equations (3.35) and (3.39).

The three time-dependent functions – ω, M, M_L describe the transient processes in forging fly-press electric drives.

The resisting moment $M_{resist.}$ for two operating cycles (3 s) is presented on Figure 3.5.

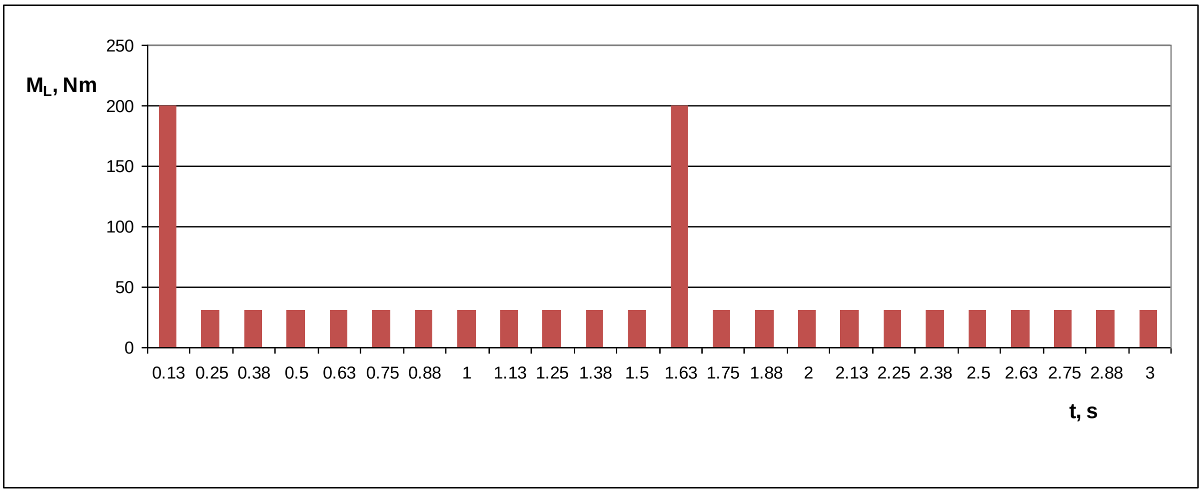


Fig. 3.5: Characteristic $M_{resist.}=f(t)$

The software product *MathCAD* [25] has been used for solving the system, including equations (3.35) and (3.39). Using the proposed mathematical model, the transient processes have been examined. Some of the results obtained are presented in the paper - Figures 3.6÷3.7.

The mathematical model developed in the paper helps to examine the transient processes when starting a forging fly-press mechanism. The mathematical model developed makes it possible to determine the impact electromagnetic moment and starting currents.

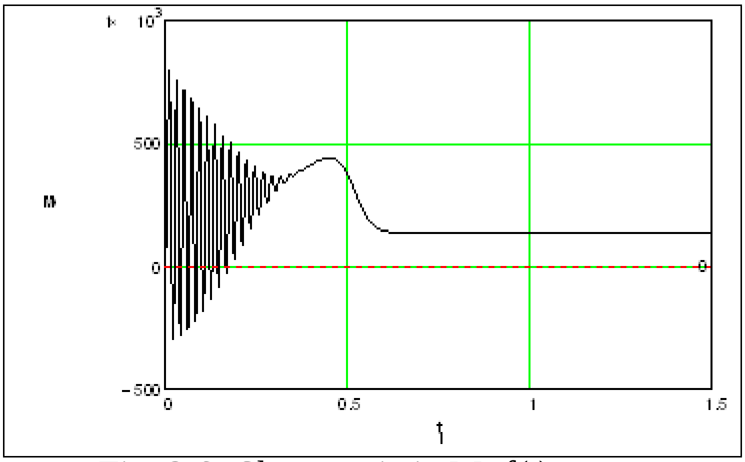


Fig. 3.6. Characteristic M=f(t)

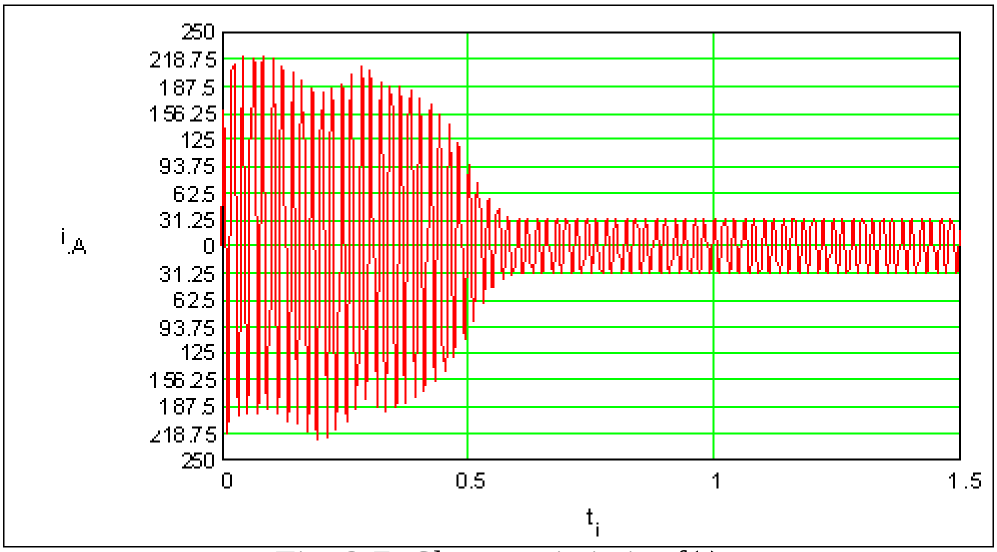


Fig. 3.7. Characteristic i_A=f(t)

Below are presented technical data of the electric motor used in the researches.

Technical data of the electric motor:

$P_N = 22kW$; $U_N = 380V$; $f_N = 50Hz$; $p = 2$;

$n_N = 1464\,\min^{-1}$; $Iph_N = 24.1A$; $J = 0.07646kgm^2$ $M_N = 143.5Nm$;

$\frac{I_{ST}}{I_N} = 7.0$; $\frac{M_{ST}}{M_N} = 1.7$; $\frac{M_{MAX}}{M_N} = 2.2$

$r_1 = 0.4843\Omega$; $x_1 = 1.154\Omega$; $r_2^{'} = 0.619\Omega$; $x_2^{'} = 1.195\Omega$;

$x_m = 51.719\Omega$;

Increasing the stator active resistance r_s^* leads to a significant reduction of impact currents and moments and to a slight increase in startup time. When decrease r_s^*, the size and the number of negative values for the moment increase, as increased time constants of the free components of the transient currents and moments.

Increasing active rotor resistance $r_r^{'*}$ results in a significant reduction of impact currents. The higher $r_r^{'*}$ the M_{IMP}^* rise, reaching a maximum value at such $r_r^{'*}$ when s_m≈1 and then decreases. With the increase of $r_r^{'*}$ startup time t_{ST} decreases, reaching minimum value at resistance $r_r^{'*}$ corresponding to the rotor resistance of the motor with high slip, and then increases. The resistance $r_r^{'*}$ has a similar influence as r_s^* on the size and number of negative values for the moment.

With increasing resistances x_s^* and $x_r^{'*}$ greatly reduce impact currents and moments.

With increased resistance x_m^* moment and time to start increasing slightly, and the impact current slightly decreases.

The results of studies on the influence of the supply voltage value, which is recorded with different values of the coefficient k_U at initial phase $\varphi_0 = 0$, on the transient processes are presented graphically in Fig. 3.8. ÷ Fig. 3.11.

For dependencies obtained approximation has been applied and approached dependencies are displayed.

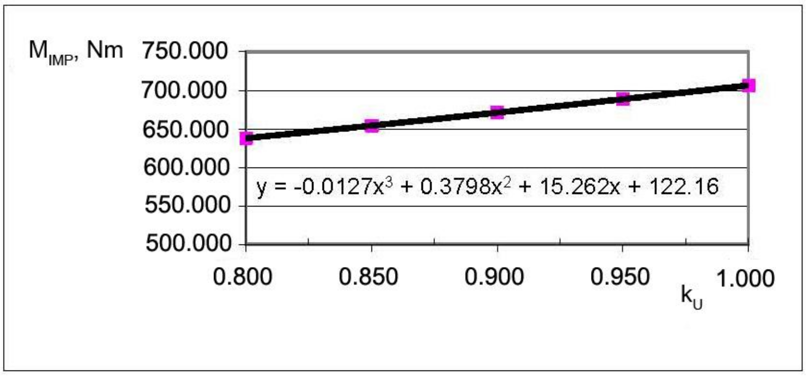


Fig. 3.8. Influence of k_U size on impact moment M_{IMP}.

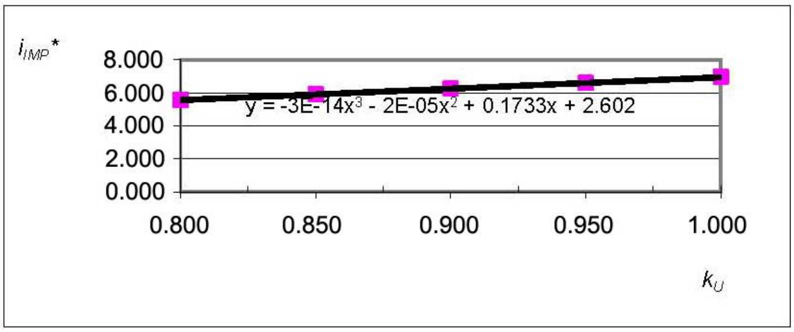


Fig. 3.9. Influence of k_U size on impact current i_{IMP}^*.

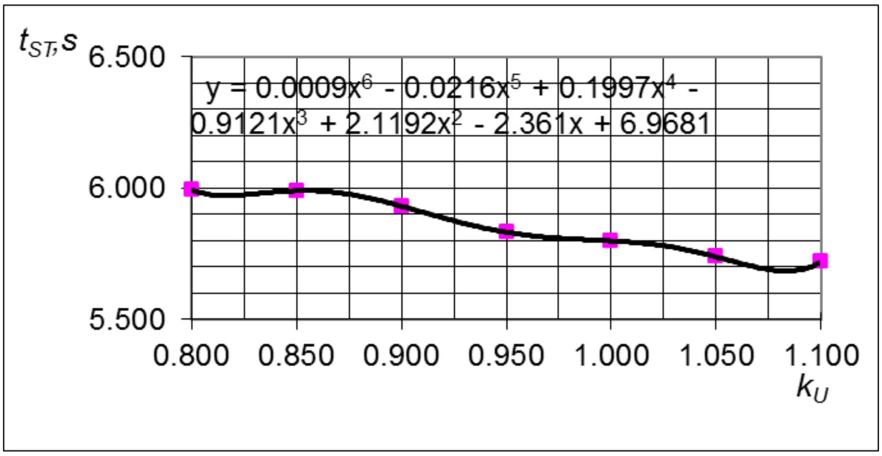


Fig. 3.10. Influence of k_U size on starting time t_{ST}.

The influence of the initial phase φ_0 of the supply voltage on transient processes has been investigated, as it is carried out only to $\varphi_0 = \pi$ rad, since it is found that for $\varphi_0 \in (\pi \div 2\pi)$ the results are repeated.

In the change of the initial phase in the range of 0 to π rad using the model is obtained, that the impact current i^*_{IMP} is altered by the smallest value 5.93 to the largest value of 6.87 and is appeared in different phases - an initial phase φ_0 influences on i^*_{IMP} which was amended by 13.68%. In other intervals of change in φ_0 the results are repeated.

The influence of load (static resisting moment $M^*_{resist.}$) and the summed moment of inertia J_Σ on transient processes has been investigated.

With the increase in the static moment of resistance $M^*_{resist.}$ change of the electromagnetic moment is oscillatory in nature with larger amplitudes and relatively slower attenuation. Sizes of i^*_{IMP} and M^*_{IMP} do not depend on $M^*_{resist.}$ and remain constant, but the time to start t_Π growing significantly with the increase of $M^*_{resist.}$.

The change of summed moment of inertia J_Σ has a significant impact not only on the duration of the transitient processes, but the nature of their conduct.

By increasing the ratio $\frac{J_\Sigma}{J_{MOTOR}}$ number of sizeable fluctuations of electromagnetic transient moment at the beginning of the transient process have increased and fluctuations in speed and electromagnetic moment in the area of synchronous speed reduced. In reducing the ratio $\frac{J_\Sigma}{J_{MOTOR}}$ number of fluctuations of the electromagnetic moment at the beginning of the transient process have decreased but sharply increased volatility of speed and torque of the electric motor in the area of synchronous speed, reaching very significant amplitudes in relatively small values of J_{Σ}. Upon increase of $\frac{J_{\Sigma}}{J_{MOTOR}}$ i^*_{IMP} almost not changed while M^*_{IMP} and the starting time increased significantly.

The determination of the reliability of operation for the units of electric drive mechanical equipment in many cases is associated with a quantitative estimate of the maximum value of the electromagnetic transient moment $M_{\max}$ of induction motor. Relatively simple analytical solution of differential equations system is possible only in this case, when the motor remains stationary during launch.

Then, the relationship $\frac{M_{\max}}{M_{START}}$ is obtained:

$$\frac{M_{\max}}{M_{\text{START}}} = 1 + e^{-(\alpha_1+\alpha_2)\tau_m} + \frac{\sqrt{1+\alpha_2^2}}{\alpha_2-\alpha_1} e^{-\alpha_1\tau_m} + \frac{(\alpha_2-\alpha_1)^2-(1+\alpha_1^2)}{(\alpha_2-\alpha_1)\sqrt{1+\alpha_2^2}} e^{-\alpha_2\tau_m}, \tag{3.38}$$

where α_1 and α_2 are the coefficients of attenuation and τ_m is x-axis of the first maximum in the curve of the electromagnetic moment. Determination of α_1, α_2 and τ_m has been shown in [63].

After the calculation is obtained $M_{\max} = 2.582 M_{START} = 629.879 Nm$; $M^*_{IMP} = \frac{M_{\max}}{M_N} = 4.389$.

It is seen that resulting from the above expression impact moment is close to the values obtained using the model.

Determination of optimal fly masses at forging press machines.

Determining optimal fly masses and electric drive power is crucial. When reducing fly masses electric motor will be overloaded during the work operation, while increasing fly masses – during idling. Influenced ratio during the operation and idling. At least during idling electric motor fails to recover energy of fly masses and in the next operational cycle it will be overloaded.

The dynamic behavior of the forging fly-press machines can be described by the system differential equations of the first order, in which the independent variable is the angle of rotation of the crankshaft *α*, and unknown functions are *ω* and *t*:

$$\begin{cases} \dfrac{d\omega}{d\alpha} = \dfrac{M_{motor} - M_{resist}}{J\omega} \\ \dfrac{dt}{d\alpha} = \dfrac{1}{\omega} \end{cases} \tag{3.39}$$

Because induction motors are used exclusively for driving the presses, then for the determination of $M_{motor}=f(\omega)$ Klos formula can be used:

$$M_{motor} = \frac{2M_k}{\frac{s}{s_k} + \frac{s_k}{s}} = \frac{2M_k(\omega_o - \omega).(\omega_o - \omega_k)}{(\omega_o - \omega)^2 + (\omega_o - \omega_k)^2}, \tag{3.40}$$

where: ω_0 – synchronous angular speed;
ω_k – critical angular speed;
M_k – critical moment;
s_k – critical slip.

System differential equations is obtained:

$$\begin{cases} \dfrac{d\omega}{d\alpha} = \dfrac{2M_k(\omega_o - \omega).(\omega_o - \omega_k) - M_c}{J\omega\left[(\omega_o - \omega)^2 + (\omega_o - \omega_k)^2\right]} \\ \dfrac{dt}{d\alpha} = \dfrac{1}{\omega} \end{cases} \tag{3.41}$$

The solution of the system (3.41) are two functions – $\omega=f(\alpha)$ и $t=f(\alpha)$. Since they produce dependence $\omega=f(t)$, which in turn leads to the determination of motor moment change as a function of time – $M_{motor}=f(t)$. On the other hand, by $t=f(\alpha)$ can be prepared system resisting moment change $M_{resist.}=f(t)$.

After examining the kinematic scheme and diagram of operation of the crank forging press machine, and the differential equations describing the dynamics of the electric drive of the crank forging fly-press machines can proceed to the study of dynamics through composite algorithm based on which was established MATLAB program for PC.

The computer program implemented works in interactive mode. It should be implemented consistently instructions.

The technical data are entered:

- a synchronous rotational frequency of the electric motor, min^{-1};
- nominal rotational frequency of the electric motor, min^{-1};

- ratio between the electric motor shaft and crankshaft;
- multiplicity of the maximum torque of the electric motor;
- rated power of the electric motor;
- accuracy (tolerances) for speed and time in solving differential equations;
- values of the components of the moment of inertia of the electric drive, kgm^2;
- values for resisting moment in the range $0 \div 30^o$;
- values for resisting moment in the range $30 \div 360^o$;

Figure 3.12 presents dialog window of the program.

The program works with default values for all parameters. If the user wants to change a value, enter a number and then confirm with Enter. All results are recorded as an ASCII text file in the folder where the file presa.m -> presa.txt. This simulates CSV file format and can be imported into Excel (if it has any meaning for the user).

Calculations were carried out with the established program for different values of rotational moment, ie various flywheels with the same electric forge-press machine. Every time program returns back from a certain point onwards, i.e. consistently can assign different flywheels, i.e. flywheels with different moment of inertia in order to assess the behavior of the entire electromechanical system.

The program displays on screen the characteristics ω, M_{motor}, $M_{resist.}$ as a function of time for different values of moment of inertia of involved as a component in the electric drive flywheel, as part of the results obtained are presented on Figure 3.13.

In conclusion it can be said that the impact loading causes fluctuations in the torque and the current of the electric motor. Furthermore, this leads to an increase of the variable loss of electric power in the electric motor and the electric supply network, as these losses are proportional tothe value of the current squared. In leveling the load schedule those losses of electricity are reduced.

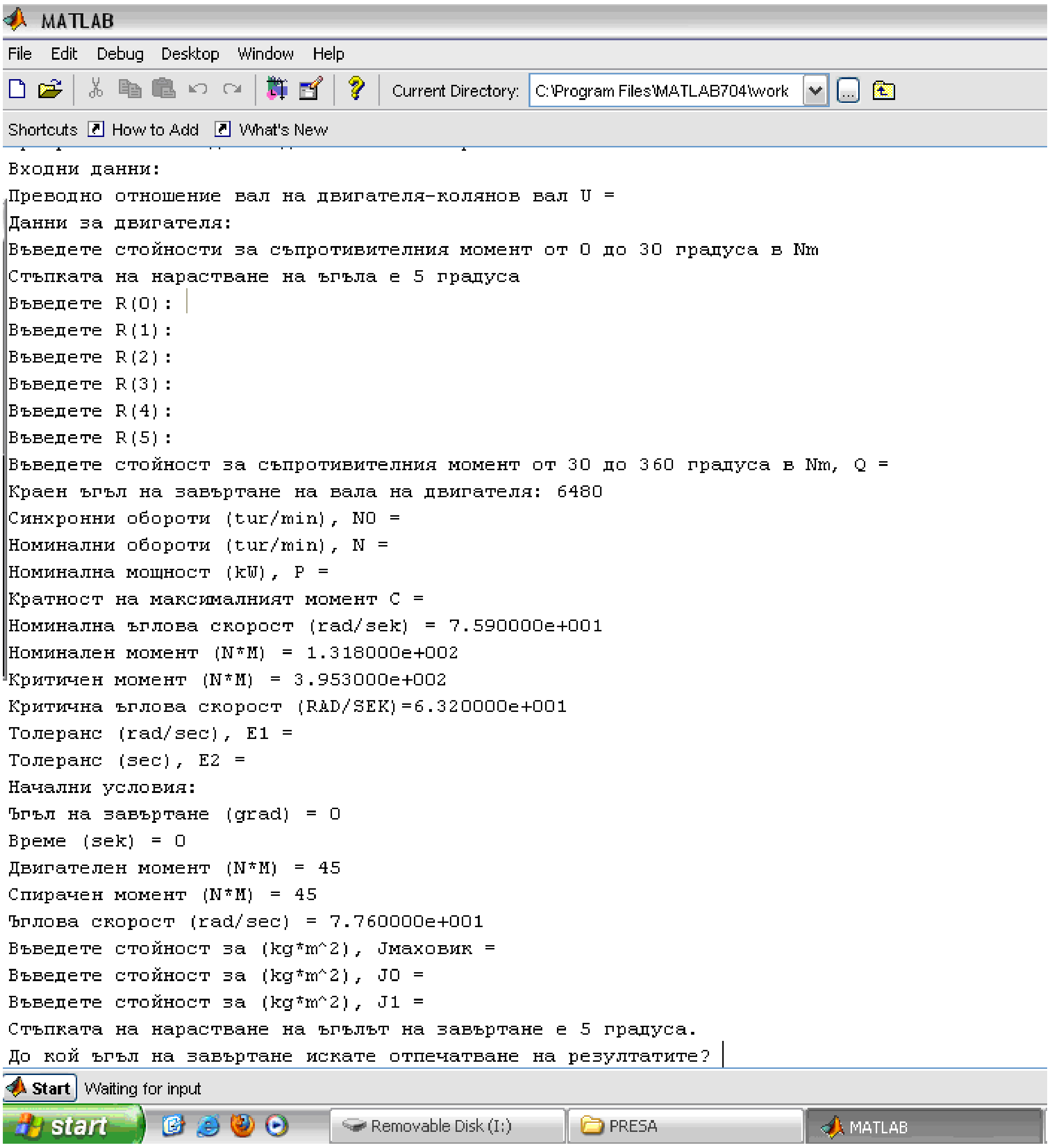
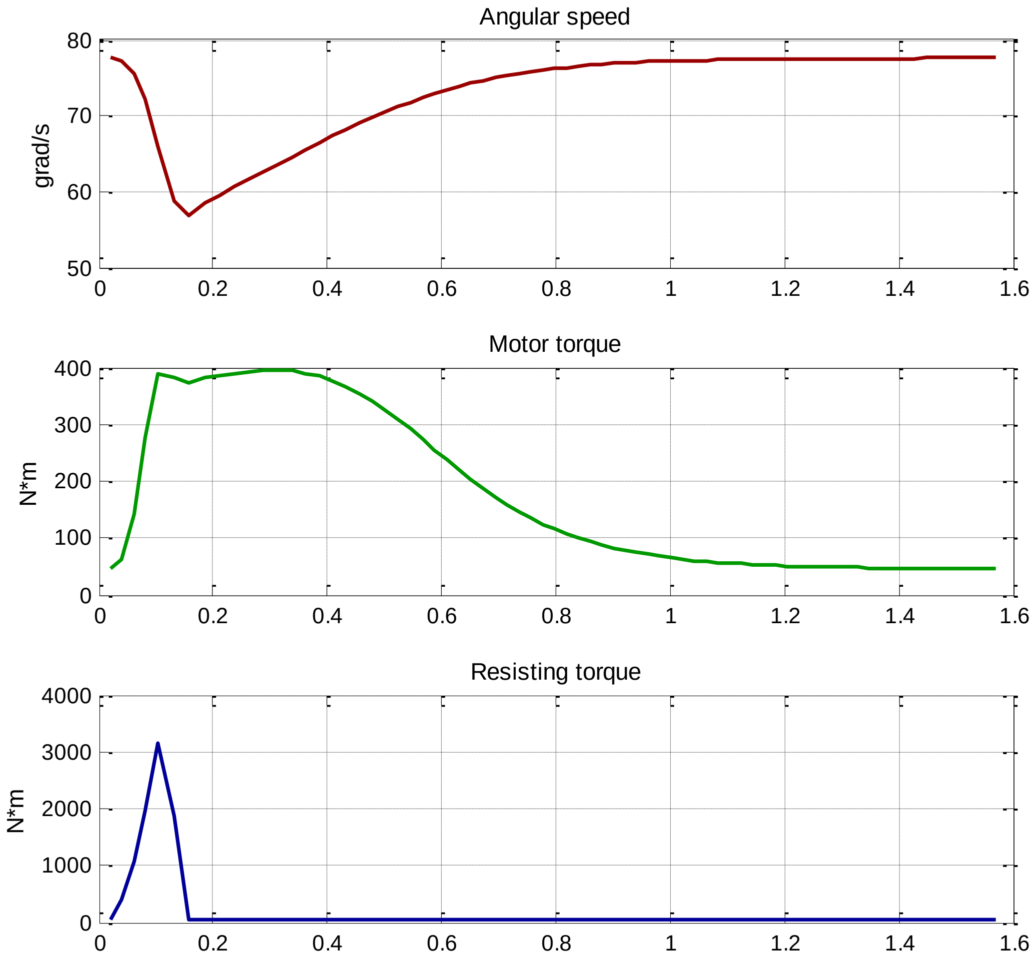


Fig. 3.12. Dialog window of the program.



Фиг. 3.13. Characteristics ω, M_{motor}, $M_{resist.}$ as a function of time for values of the moment of inertia of the flywheel $J_{FLYWHEEL}$ =4 kgm^2.

Research on energy losses in electric induction motor for forging fly-press drive.

The analyzis of the behaviour of the induction machine has been carried out both from the stator and rotor position.

The induction motor transforms electrical energy loaded from power supply mains to the stator into mechanical energy received at the rotor shaft. Moreover this energy conversion is accompanied by a losses. The equation of the active power balance can be written as

$$P_1 = \Delta P_{e1} + \Delta P_{M1} + \Delta P_{e2} + \Delta P_{MECH} + \Delta P_{ADD} + P_2, \qquad (3.42)$$

where: $P_1 = m_1 U_1 I_1 \cos\varphi_1$ – electrical power received from power supply mains to the stator; (3.43)

$\Delta P_{e1} = m_1 I_1^2 R_1$ – electrical losses of power related to the heating of the windings of the stator, wherein the current flows in them; (3.44)

$\Delta P_{M1} = U_1^2 f^{1,3}$ – magnetic losses of power related to steel core of the stator remagnetization and its heating by eddy currents; (3.45)

$\Delta P_{e2} = m_2 I_2^2 R_2$ – electrical losses of power in rotor windings; (3.46)

ΔP_{MECH} – mechanical losses of power due to friction in the bearings and rotating parts of air (ventilation losses); (3.47)

ΔP_{ADD} – additional difficult accounted power losses from eddy currents, determined by the magnetic stray field, by the magnetic flux pulses, by the presence of harmonics (additional losses are $\Delta P_{ADD} \approx 0{,}005 P_{1NOM}$); (3.48)

P_2 – mechanical power on the motor shaft.

The electrical losses in the rotor are directly proportional to the slip:

$$\Delta P_{e2} = s P_{EM} , \tag{3.49}$$

where P_{EM} – electromagnetic power of the motor:

$$P_{EM} = P_1 - (\Delta P_{M1} + \Delta P_{e1}) . \tag{3.50}$$

According to magnetic ΔP_{M1} and mechanical ΔP_{MECH} losses of power, they are essentially not dependable on the load [38]. The sum of these losses is roughly constant.

Mechanical losses of power for motors with outer blowing (with outer diameter of the stator $0{,}1 \le D_a \le 0{,}5$ m) are:

$$\Delta P_{MECH} = K_T \left(\frac{n}{10} \right)^2 D_a^4 ; \tag{3.51}$$

$n = n_S (1 - s)$ – rotational frequency of the motor; (3.52)

$K_T = 1$ for motors with 2p=2 and $K_T = 1{,}3(1 - D_a)$ at 2p≥4;

D_a – outer diameter of the stator.

Bearing-friction and windage losses are small as a rule, and may be neglected for rough calculation.

The choice of the point of maximum efficiency depends on the designer, efficiency has a maximum in the area where fixed losses (ΔP_{M1} and ΔP_{MECH}) are equal to the variable losses – electrical (ΔP_{e1} и ΔP_{e2}). The electrical losses in rotor are proportional to the slip and thus induction motors are economical in small slips – 1÷4%.

Adopted energy from the grid in starting mode is:

$$W_{ST} = \sum_{k=0}^{a_{n-1}} \left[\left(P_{a_k} \right) t_n \right] + \sum_{k=0}^{a_{n-1}} \left[\left(P_{b_k} \right) t_n \right] + \sum_{k=0}^{a_{n-1}} \left[\left(P_{c_k} \right) t_n \right] \tag{3.53}$$

- a_{n-1} – number of point of the time axis, which lasts until the transient process.
- P_{a_k}, P_{a_k}, P_{a_k} – power consumed respectively by phase A, phase B and phase C.

Adopted energy from the grid at steady state mode is:

$$W_{SS} = \sum_{k=a_{n-1}}^{n-1} \left[\left(P_{a_k} + P_{b_k} + P_{c_k} \right) \right] \left[(n-1)\delta t - t_n \right] \tag{3.54}$$

- δt – a discrete of time axis in seconds;
- t_n – duration of the transient process in seconds.

The energy losses in butts (frontal connections) in starting mode are:

$$W_{1ST} = 0.5 r_1 \sum_{k=0}^{a_{n-1}} \left[\left(I_{a_k} \right)^2 + \left(I_{b_k} \right)^2 + \left(I_{c_k} \right)^2 \right] \delta t \tag{3.55}$$

- r_1 – resistance of one phase of the stator winding;
- I_a, I_b, I_c – phase stator currents.

The energy losses in butts (frontal connections) in steady state mode are:

$$W_{1SS} = 0.5 r_1 \sum_{k=a_{n-1}}^{n-1} \left[\left(I_{a_k} \right)^2 + \left(I_{b_k} \right)^2 + \left(I_{c_k} \right)^2 \right] \delta t \tag{3.56}$$

The energy of moving parts and effective work in starting mode is:

$$W_{MMST} = 0.5 J \omega_b^2 + M_L \omega_b t_{a_{n-1}} \tag{3.57}$$

where J – total inertia moment of the electric drive;
ω_b – rated circular frequency;
M_L – resisting moment, Nm

The energy of moving parts and effective work in steady state mode is:

$$W_{MMSS} = \sum_{k=a_{n-1}}^{n-1} \left[M_k \omega_k \delta t \right] \tag{3.58}$$

Heat released in motor in starting mode:

$$W_{HST} = W_{ST} - W_{MMST} \tag{3.59}$$

Heat released in motor in steady state mode:

$$W_{HSS} = W_{SS} - W_{MMSS} \tag{3.60}$$

It has been pointed out that the most advisable, effective and economical way for increasing of the energy given by the flywheel is increasing of electric motor speed at the beginning of every cycle. It is necessary to ensure speed control of the electric motor. The most expediently is applying of electric motor frequency control since when the frequency of power supply increases, the synchronous speed increases also, from there the initial speed at the beginning of working operation also. In case of such kind of control even at short idle running time the fast speed increasing have been achieved. Using of adjustable electric drive raise the cost of forging fly-wheel presses up to 5-15% but the additional expenditures will be recovered quickly because of productivity increasing.

The technical data of the electric motor used in the model studies were presented above.

Solving of differential equations system which describes the dynamic behavior of forging fly-press electric drives is a complicated task. The software *MathCad* has been used for solving the system of differential equations. Using the proposed mathematical model, the components of energy losses have been calculated in case of different values of power supply frequency. The results obtained are presented on Figure 3.17 and Table 3.7.

The mathematical model developed helps to examine the transient processes when starting a forging fly-press mechanism with frequency control and further define the components of the energy losses. The mathematical model developed makes it possible to determine the proper adjustment of frequency control parameters in order to achieve customized requirements.

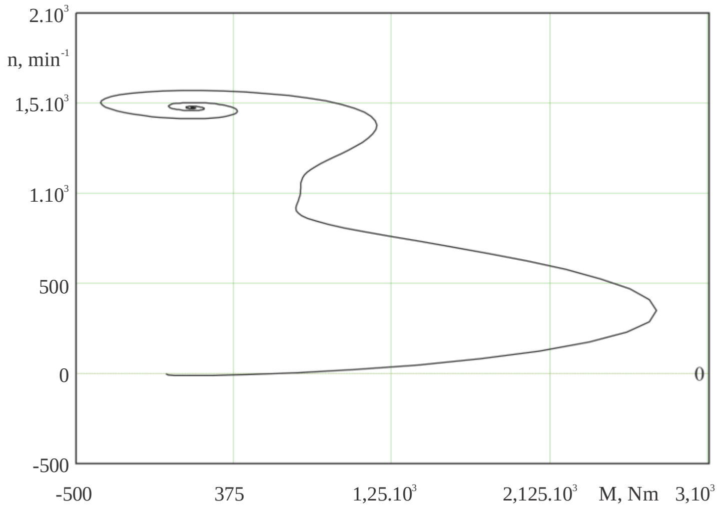


Fig. 3.17. Torque-speed characteristic M=f(n), frequency 50Hz.

Table 3.7. Components of energy losses

Frequency, Hz	t_{st}, s	W_{ST}, x10^6 Joule	W_{SS}, x10^6 Joule	W_{1ST}, x10^3 Joule	W_{1SS}, Joule	W_{MMST}, x10^4 Joule	W_{MMSS}, x10^4 Joule	W_{HST}, x10^6 Joule	W_{HSS}, x10^6 Joule
50	0.492	4.971	7.062	2.539	144.49	5.356	4.466	4.917	7.017
60	0.248	3.167	10.990	4.012	225.25	5.640	6.628	3.110	10.930
70	0.346	6.734	9.476	6.136	253.05	7.710	7.118	6.657	9.405
80	0.594	17.460	5.918	9.019	241.73	10.710	6.357	17.350	5.854

Conclusions to Chapter 3:

- A mathematical model of electromechanical system of forging press machines has been developed;
- A selection of parameters of the electromechanical system and the boundaries of their change during researches have been done;
- A computer method for solving mathematical model has been chosen;
- There has been automatically determine the required power and choice of electric motors for forging machines;
- The influence of the supply voltage on the magnitude of the transient processes has been investigated;
- The influence of the initial phase φ_0 of the supply voltage on the magnitude of the transient processes has been investigated;
- The influence of load and summed moment of inertia of the system on transient processes has been investigated;
- The influence of the parameters of the equivalent circuit of the induction machine on the magnitudes of transient processes has been investigated;
- Calculations were carried out with the program created for different values of moment of inertia, i.e. with flywheels with different moment of inertia in order to assess the behavior of the entire electromechanical system;
- The components of energy losses at starting of mechanism of forging press machines with frequency control have been estimated.

Chapter 4 'Transient processes and dynamic loads of induction machines for reciprocating compressors. Study the dynamic behavior of the reciprocating compressors electric drive.' covers studies of electric drives of reciprocating compressors, whose work is also characterized by impact loadings.

The technical characteristics of the compressors have been described.

Reciprocating compressors are composed mainly of working cylinder and piston; there are suction and discharge valves usually located in the cylinder cover. To impart to the pistons a reciprocating movement in most compressors have mechanism - crank arm with the crankshaft.

In the piston compressor, the piston performs a rectilinear reciprocating movement in-cylinder 5 – Fig. 4.2. Upon movement of the plunger 4 from left to right in the cylinder a vacuum, under the influence of the external (atmospheric) pressure opens the suction valve 1 and gas is sucked into the cylinder. The gas flows through the suction pipe 3, which is normally at its top is provided with a filter. When the piston starts its return stroke, the suction valve is closed, the gas pressure in the cylinder increases. The pressure valve 2 opens and compressed air is pushed into the discharge pipe 6. In it usually gas is fed into a special reservoir, and then to consumers. This reservoir reduces the pressure oscillations of compressed air users.

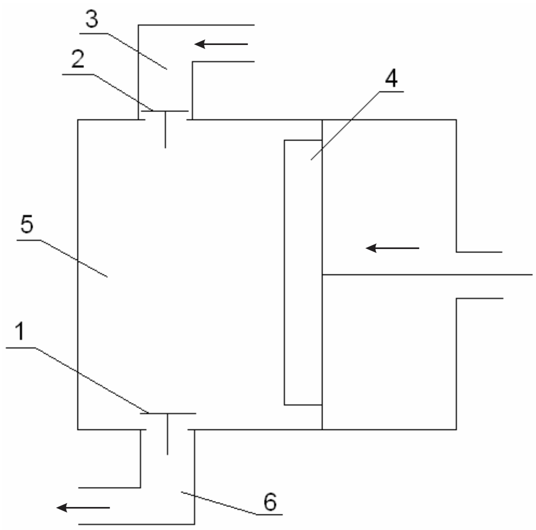


Fig. 4.2. Structure of the reciprocating compressor

Subject to the studies are appropriate determining of the power required, analyzing the performance and behavior of compressor systems for opportunities to improve energy efficiency for existing systems, and to those in the design stage.

Using basic dependencies describing characteristic quantities in piston compressors, specific electric motors have been selected while the particularities in different cases are taken into account – two compressors operating in parallel; a single two-stage compressor, this is done by various methods. This is a step towards automated design of such machines.

Automatically determining of the power required and selection of electric motors for reciprocating compressors has been performed, as the block diagram is the same as in forging press machines - Fig. 3.2. The same is also the database relating to the possible for selection electric motors.

Input data are:

- type of crowding gas – air, oxygen, hydrogen, chlorine, carbon monoxide, carbon dioxide, ethane, ethylene, acetylene, helium, nitrogen, ammonia, propane or propylene;
- number of cylinders;
- synchronous rotational frequency – 750, 1000, 1500 or 3000 min^{-1};
- gear ratio;
- efficiency of the gearbox;
- efficiency of the compressor;
- way of starting - idle or maximum load.

Results obtained in repeated use of the program are given in the Table 4.8 and Table 4.9.

Confirm the claim that on the selection and sizing of the drive system has a relatively large influence range of alteration of static moment, which is the ratio of static moments at minimum and maximum loading of the mechanism (usually calculated at nominal speed).

With increasing transmission ratio gearbox reduces the moment of inertia of the flywheel required $J_{FLYWHEEL}$ and the time to start t_{START} and increasing the time for running a cycle t_{CYCLE}.

Optimal in terms of minimum time for starting and the minimum additional flapping moment is an option at n_0=750 min^{-1} and gear ratio i = 30.

The choice of synchronous (and hence nominal) speed of electric motors is done against the rated speed of the mechanism and the gear ratio of the transmission. In this respect it is good that there is a possibility to conduct variant calculations. Appropriate choice of the speed of the electric motors and gear ratios affect the course of the transient processes, and hence the performance of the mechanisms.

It is always necessary compromise between two tendencies:

- mechanisms designers prefer smaller ratios and hence low rotational speeds of the electric motors, which leads to an increase in mass-overall dimensional indicators of the electric motors;

- electrical designers in turn prefer the opposite – electric motors with possible higher speeds and smaller size and weight, leading in turn to a large gear ratios and a higher price.

Table 4.8. Results obtained for fly-wheel inertia moment, equivalent moment, operating cycle, breakout time in case of maximum load when starting (number of cylinders – 1, gearbox efficiency 95%, compressor efficiency 70%)

n_0, min^{-1}	i	Motor selected		$J_{FLYWHEEL}$, kgm^2	M_{eq}, Nm	t_{CYCLE}, s	t_{START}, s
		P_n, kW	Type				
750	10	4.0	AM 160MK-8	2.4409	19.20	0.818	1.970
750	20	2.2	AO2-41-8	1.3747	10.61	1.639	2.729
			AO2 132S-8	1.3611	10.63	1.639	2.704
			AM 132-8D	2.3311	9.44	1.639	3.282
750	30	1.5	4AO 112M-8D	0.0343	8.82	2.460	0.066
750	40	1.1	4AO 100LL-8D	0.2554	6.48	3.281	0.674
750	50	0.75	4AO 100L-8D	0.2475	5.17	4.113	0.962
1000	10	4.0	AM 132MK-6	1.2501	19.20	0.818	1.970
1000	20	2.2	4AO 112M-6D	0.3831	10.61	1.639	2.729
1000	30	1.5	4AO 100L-6D	0.2474	8.82	2.460	0.066
1000	40	1.1	4AO 90L-6D	0.1532	6.48	3.281	0.674
1000	50	1.1	4AO 90L-6D	0.0262	5.17	4.113	0.962
1500	10	5.3	AOC-52-4	0.3596	16.44	0.423	0.815
1500	20	3.0	4AO 100LL-4D	0.2223	11.04	0.822	0.741
1500	30	2.0	AOC-42-4	0.4612	5.41	1.270	2.194
1500	40	1.5	4AO 90L-4D	0.0932	6.04	1.657	0.581
			AOC-41-4	0.4835	4.04	1.694	3.028
1500	50	1.1	4AO 90S-4D	0.0894	4.82	2.076	0.860
3000	10	10.0	AO2П-51-2	0.4885	16.02	0.205	2.104
3000	20	5.3	AOC-52-2	0	6.55	0.419	276.12
3000	30	4.0	4AO 112M-2D	0.1308	6.14	0.617	1.196
3000	40	2.4	AOC-42-2	0.1183	4.04	0.847	1.763
3000	50	2.2	4AO 90L-2D	0.0487	4.26	1.034	0.799

Table 4.9. Results obtained for mean resisting moment and maximum resisting moment in case of maximum load when starting (number of cylinders – 1, gearbox efficiency 95%, compressor efficiency 70%)

n_0, min^{-1}	i	$M_{resist.ave.}$, Nm	$M_{resist.max.}$, Nm
750, 1000, 1500, 3000	10	12.04	77.32
750, 1000, 1500, 3000	20	6.02	38.66
750, 1000, 1500, 3000	30	4.01	25.77
750, 1000, 1500, 3000	40	3.01	19.33
750, 1000, 1500, 3000	50	2.41	15.46

In an analogous manner as in Chapter 3, were obtained from systems of differential equations describing transient processes in the electrical drive of the reciprocating compressors.

The induction motor electric drive of a piston compressor has been studied.

The mechanical characteristic of the motor has been plotted, assign different values to slip *s*, and to obtain the corresponding values for motor torque M_{motor} and angular velocity ω_i.

The values of the angular moment of the motor shaft for different angles of rotation of the shaft of the compressor have been determined. As specified in [28] the following relationship is in force:

$$M_{motori} = \frac{M_{resisti} + (M_{ave} - M_{resisti})e^{-\frac{t_i}{T_M}}}{i}, Nm \qquad (4.36)$$

$M_{resist.i}$ – resisting moment of the shaft of the compressor for a specific angle.

Also times for rotating the shaft of the respective angles have been calculated. By means of data calculated graphics $M_{motor} = f(\alpha)$ has been plotted.

The determination of the current values of the corresponding output of the electric motor and the current has been carried out by:

$$P_{2i} = M_{motori} \cdot \omega_i, \text{W}; \qquad I_{motori} = \frac{P_{2i}}{\sqrt{3}.U_{н} \cdot \eta \cos}, A \qquad (4.38)$$

From the values obtained for I_{motori} is defined equivalent current.

The selected motor for that mechanism satisfies the presented methodology to the nature of the process.

Graphic results are shown in Fig. 4.21 and Fig. 4.22.

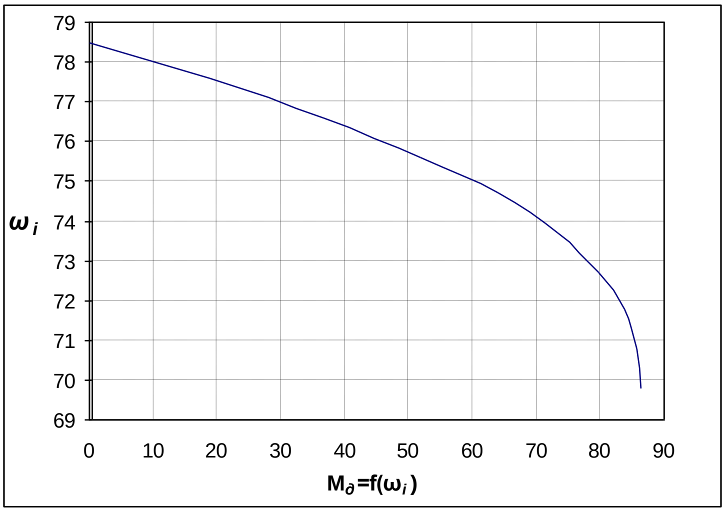


Fig. 4.21. Working section of the mechanical characteristic.

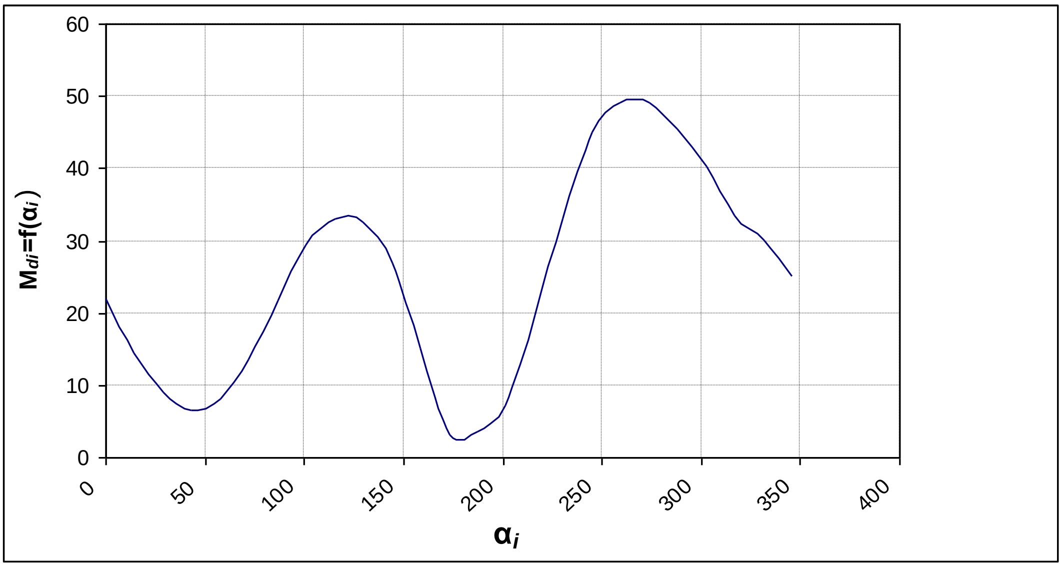


Fig. 4.22. Values of the moment of the motor shaft to the various angles of rotation.

It examines the work of the complex system production unit – electric motor. Following the operation of the model of the mechanical system - piston compressor, in concert with the natural mechanical characteristics of induction motor is obtained function $\omega = f(t)$, it appears slip of the induction motor $s = f(t)$, which determines the nature of its dynamic load. All values are represented in the time domain.

The loading is dynamic, but only within certain limits of slip *s*. The motor at first only covers gear and friction losses. The analysis shows that for a certain period of time, the time of the compressor exceeds that of the motor, but the kinetic energy accumulated takes the load. Then the motor accelerates and takes the load inertial masses, which accumulates kinetic energy again. Once the cycle is complete again will start recurrence.

From the graphic plotting of the motor moment is not clearly delineates the dynamic maximum torque, but can be read about that this torque is less than the maximum torque of the mechanical characteristics of the motor, so the motor has options and covers the biggest moments of the load during his cycle of work.

Dynamic changes are determined by the balance of moments, i.e. when the load increases on the motor shaft slip increases, which reduces the reduced active resistance of the rotor, which increases the current in the rotor I'_2, and hence the moment $M_{дв}$ on the shaft, i.e. all variables related to the characteristics of induction motor follow the dynamic changes of slip.

Conclusions to Chapter 4:

- By means of methodology presented electric motor for reciprocating compressors has been selected and verified;
- Specific electric motors have been selected using basic dependencies describing characteristic quantities in piston compressors, while the particularities in different cases are taken into account;
- A mathematical model of electromechanical system of reciprocating compressors has been developed;
- A selection of parameters of the electromechanical system and the boundaries of their change in research have been done;
- A computer method for solving mathematical model has been selected;
- There has been automatically determine the required power and selection of electric motors for reciprocating compressors;
- The influence of the value of rotational frequency and gear ratio gearbox on the necessary additional flapping moment has been developed, i.e. need flywheels with different moment of inertia in order to assess the behavior of the entire electromechanical system.

CONCLUSION

Subject to work on the thesis are applied mechanisms (forging press machines and piston compressors) and their electrical components.

Mathematical models of the induction machine, the mechanisms of forging press machines and piston compressors and the electromechanical system during transient processes have been developed. Algorithms and models for the study of dynamic loads have been developed. Using appropriate software electromechanical transient processes and dynamic loads at different initial conditions and parameters of the electrical and mechanical part of electric drives have been investigated. They were examined the influences of the parameters of the induction machine and of the mechanisms on the magnitudes of the electromechanical transient processes. With their participation can improve methods for calculating the power, selection and checking electric motors for heating and overloading. With their use will improve the definition of energetic performance and losses in electric motors in dynamic modes. The power consumption and energy losses in induction machines during transient processes have been defined, which is directly related to the design and selection of electric motor.

The resulting models of rotating electrical machines and electrical drives are directly applied to the study and optimization of dynamic characteristics in the design (synthesis) and their study and design of systems for control and regulators for adjustable electric drives. This is in direct connection with the possible implementation of energy efficiency measures and identification using analytical techniques possible energy savings. The models developed and proposed can be used except for analysis and for finding a solution to the inverse problem - the development of electric motors and control systems with parameters guaranteeing transient processes at user-specified requirements. This detailed study of electromagnetic and electromechanical transient processes leads to more rational and appropriate design of electrical drives.

C. AUTHOR’S REFERENCE FOR CONTRIBUTIONS IN THE THESIS

In the present thesis are considered important for engineering practice problems associated with electromechanical transient processs and dynamic loadings in applied mechanisms (forging press machines and reciprocating compressors) and their electrical components.

The main scientific and scientific-applied contributions can be summarized in the following few points:

1. New mathematical models have been proposed that describe and integrate the interactions in configuration induction electric machine - working machines with impact loadings (forging press machines and reciprocating compressors). In the resulting system of differential equations for the first time the factor slip of combined electromechanical system has been taken into account. This approach is effective for its applicability.

2. On the basis of the previous point are constructed algorithms for direct practical application of the models.

3. Different suitable for specific tasks software has been selected for solving systems of differential equations describing electromechanical transient processes at different machines with impact loadings.

4. A new methodology for determining the moment and speed of induction machines operating in dynamic mode associated with forging press machines and reciprocating compressors.

5. A picture of the different transient processes of forging press machines and reciprocating compressors has been obtained as a function of the parameters of the induction machine and loading, i.e. their impacts on the course of the transient processes have been examined. With their participation can improve methods for calculating the power, for selecting and checking electric motors for heating and overloading.

6. Application of methodology for determining power consumed and energy losses in induction machines during transient processes, which is directly related to the design of electric drives for machines with impact loading and selection of electric motors and opportunities to improve the energy efficiency of electric drives in wide range. Using high efficiency drive systems or approve existing ones could save a certain amount of electric power, which would reduce the need to generate enough electricity and therefore would save capital and resources.

7. The models obtained of rotating electrical machines and electric drives are directly applied to the study and optimization of dynamic characteristics in the design (synthesis) and their study and design of systems for control and

regulators of adjustable electric drives. This is in direct connection with the possible implementation of energy efficiency measures and identification of possible savings using analytical techniques in operating machines with impact loading. The models developed and proposed can be used except for analysis and for finding a solution to the inverse problem – the development of electric motors and control systems with parameters guaranteeing transient processes at user-specified requirements. This detailed study of electromagnetic and electromechanical transient processes leads to more rational and appropriate design of electrical drives.

8. Presence of the educational element of the thesis. Computer programs with which studies are carried out could find direct application in the educational process in certain subjects of the curriculum in order to improve its quality.

D. PUBLICATIONS OF THE AUTHOR RELATED TO THE DISSERTATION

[A1] Rachev S., K. Karakoulidis, L. Dimitrov. Dynamic Study of Forging Fly-Press driven by Electric Induction Motor. Proceedings of 12th International Conference ‘Research and Development in Mechanical Industry’ RaDMI 2012, Vrnjačka Banja, Serbia, 2012, vol. 2, pp. 1157 – 1164. ISBN 978-86-6075-037-4.

[A2] Rachev S., K. Karakoulidis. Determination of the optimal fly masses for forging press machines. Journal of Technical University - Gabrovo, vol. 46, 2013, pp. 89 ÷ 93. ISSN 1310-6686. (in Bulgarian)

[A3] Rachev S., K. Karakoulidis. Research on Energy losses in Electric Induction Motor for Forging Fly-Press Drive. Proceedings of XXIInd International Conference ‘Ecological Truth’ EcoIst ‘14, Bor, Serbia, 2014, pp. 131 – 136. ISBN 978-86-6305-021-1.

[A4] Karakoulidis K., S. Rachev. Study of induction motor electric drive for reciprocating compressor. Proceedings of International Conference on Technics, Technologies and Education ICTTE 2014, Yambol, Bulgaria, 2014, pp. 385 – 392. ISSN 1314-9474. (in Bulgarian)

[A5] Karakoulidis K. Automated Determining the Power Required and Slection of Electric Motors for Reciprocating Compressors. Information, Communication and Control Systems and Technologies, Rousse University ‘Angel Kanchev’, Bulgaria, 2014, ISSN 1314-7455.

[A6] Karakoulidis K. Automated Determining the Power Required and Selection of Electric Motors for Forging Fly-Press Mechanisms. JOURNAL OF ENGINEERING SCIENCE AND TECHNOLOGY REVIEW, Eastern Macedonia and Thrace Institute of Technology, Kavala, Greece, Vol. 8, Issue 2, 2015, ISSN:1791-2377.