Efficient Transient Modes of Synchronous Drive for Mining and Smelting Mechanisms

V.A. Borodai[1, a], R. O. Borovyk[2, b], O.Yu. Nesterova[3, c]

1 – Candidate of Sciences (Tech.), State Higher Educational Institution "National Mining University", Dnipro, Ukraine

2 – Engineer, State Higher Educational Institution "National Mining University", Dnipro, Ukraine

3 – PhD, State Higher Educational Institution "National Mining University", Dnipro, Ukraine

a – Boroday_va@mail.ru

b – borovikra@bigmir.net

c – olnesterova1@rambler.ru

DOI **10.2412/mmse.71.21.693** provided by Seo4U.link

Keywords: high-capacity mining and smelting mechanisms, impact load, synchronous electric drive, method for impact load compensation, parameters justification and optimization.

ABSTRACT. Development of starting system for synchronous motors of high-power mechanisms in mining and smelting industry, which enables proper starting characteristics and reasonable compensation of impact loads by means of synchronous drive. Mathematical modelling was applied for the determination of parameters of field winding with direct and indirect split and capacitors, as well as for substantiation of function of purpose choice and limiting the factors of influence for solving the problem of determination of field system parameters and springy mechanic components of synchronous drive. As based on the definite motor evidence, it was proved that it is possible to operate synchronous motors with split field winding and capacitors, which enable obtaining proper starting characteristic for the mechanism requirements. The needed installations for starting system and values of spring linkages rigidity for reasonable impact loads damping were also determined. The methods used enable determining parameters of field winding with indirect split and active-reactive resistance, as well as calculating the reasonable level of voltage forcing, time for field voltage reducing and order of elastic clutch rigidity under the conditions of design load increase. The use of new field windings enables start of high-power mechanisms and thus, prevents equipment from unplanned idle operation. It also makes it possible to improve productivity of operating mechanism by means of motor load increase in the stable operating mode, as well as improves drive energy characteristics. The peculiarity of electric circuit design for winding with direct split enables use of traditional technological process of pole coils production and does not require new production equipment. The use of field system with innovative control procedure and elastic clutch with the proper rigidity significantly decreases amortization of field windings and prevents emergency states of synchronous drive caused by dynamic impact overloads.

Introduction. It is obvious that economic performance of any production activity depends on high competitiveness of the output product. Traditionally, the goal is achieved by means of enterprise productivity increase, innovative technology implementation into the output product, involving energy saving and resource saving. Considering the fact that nowadays the price for new production equipment is near 20% of its annual power supply costs, we can state that the energy saving is the priority for industrial sphere.

The possible way of problem solving is the use of modern electrical equipment with high performance index. The synchronous electric drive of controlled driving belongs to this type of equipment. If compared to other electric drives, the synchronous one has the following advantages: better power characteristic; high reliability resulting from significant air gap; high rigidity of speed-torque characteristic; low rate of rotation of driving shaft, which allows elimination of intermediate gears; low costs for drive control converters rather than frequency converters for total power motors. But the drives also have some disadvantages. They are as follows: the problem of secure triggering and decrease of the influence of impact loads in case of their alternate application. That is the reason for the urgency of the development of synchronous drive as based on the reasons mentioned above.

It is known that the mining mechanisms of disintegrating cycle have the starting static moment of variable rate from 1,2 to 2,5 of the rating moment. As a rule, in such cases the problem of complicated start is solved either by the application of additional accelerating engine, which operate only during the starting period, or by choosing the motors of 15 – 50% power reserve. Both methods have significant capital and power disadvantages. So, developers tend to use synchronous motors, as possessing significant advantages, in drives of high-power mining machines of disintegrating cycle. However, the problems of their start have not been solved yet.

Direct asynchronous start at a full grid voltage is the simplest and the most widespread method of asynchronous stock engines start. The main peculiarity of the method is that the starting moment is mainly created by damper winding; the resistance rate of the last one is determined by the type of cross-section and resistivity of its rods. Thus, the changes of geometric parameters and rods material enable variation of total resistance of damper winding. The resistance provides the significant starting moment and decreased input torque for increased active resistance, and vice versa, for the opposite circuit settings. The rational circuit design for the requirements of the definite mechanism with high starting and input torque, is also possible. However, the main disadvantage of the method is significant starting current limiting the number of sequential starts and decreasing the reliability of motor windings.

As based on the data of the traditional method of synchronous motor start, we can state that the general starting moment is created by rotor windings, where the main part is related to damper winding. In this case, the ratio of moment of field coil work, which is connected in an ordinary way, is not sufficient. Nevertheless, it is also known that it is possible to improve the startability of synchronous drive and redistribute voltage between rotor windings by means of drive circuit. As a result, the proposed methods allow reliability increase of the completely electromechanical system, as well as improvement of starting characteristic.

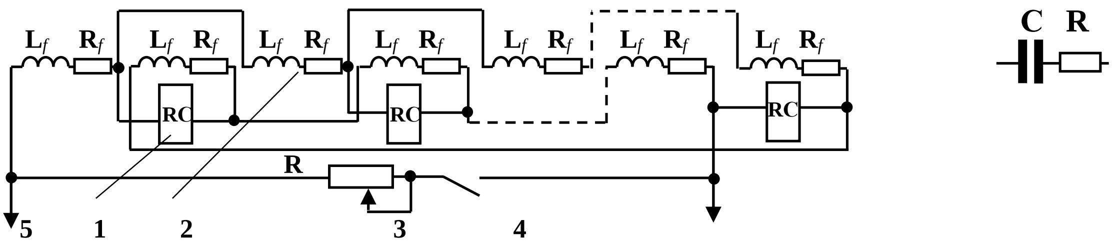
As the methods of starting characteristic improvement for synchronous electric drives with overvoltage decrease, the windings split with concentrated and allocated connection of capacitors are applied [1]. The ways of reactance decrease of rotor windings enable forming of starting mechanic characteristic with respect to requirements of working mechanism, but trouble the traditional technological process of pole coils production under the industrial conditions.

The analysis of existing methods has shown that the synchronous electric drives with improved starting characteristic have a range of advantages and disadvantages. The latter method can be pointed out as the most suitable for reconstruction of high power motors with explicit rotor poles. However, the disadvantage of complications of pole coils production for field coils limits their practical application. That is the reason for the need in designing of split windings with capacitors from both theoretical and practical points of view.

It is known that the synchronous motors in high power technological facilities may have more than 20 ports. That is why the direct split of each pole coil can be substituted by indirect way of split [2]. The mentioned circuit design describes the drive circuit, which is shown at the Fig. 1. In such a case the motor drive circuit (Fig. 1 a) includes undivided pole coils 2, with series sequence and creation of separate groups of coils, which are closed-in through the every other pole, where RC-circuits are created between adjacent poles consisting of capacitor C and resistor R (Fig. 1, b). The external terminals according to the working principle, new construction [2] 5, 6 connected to the first and the last pole coils, are also connected to discharge variable resistor R 3, which can be switched by the communicator 4, does not differ from the previous one [1]. However, as for this case, the poles assembly and the process of parameters determination for the circuit of rotor windings substitution are simplified. This is explained by the availability of the coil on the pole, which does not differ from the classical one, and the magnetic conditions are equal for both cases. Owing to the fact, the parameters of reactance of the definite pole coil can be determined as based on the published data provided by the producer.

$$X_{f_i} = \frac{X_{ad} + X_{fs}}{2p}, \; R_{f_i} = \frac{R_{fs}}{2p}, \tag{1}$$

where X_{ad} is reactance of armature reaction; X_{fs} is reactance of dispersion of classical field coil; R_{fs} is field active resistance; $2p$ is the number of ports.



a) *b)*

Fig. 1. Field coil of indirect split.

The conditions mentioned above do not require the destruction of magnetic couples of pole coils. The influence of magnetic cohesion of damper and inductor windings with each field bobbin is mentioned as EMF component and, thus, is calculated for the first quadripole according to the compensation theorem. So, the analytical drive circuit is in the form of (Fig. 2).

The complex impedances in its structure are calculated in the following way: $Z_{f_i} = X_{f_i} + R_{f_i}$ is the impedance of pole coil; $Z_{c_i} = r\frac{m_{zf}}{Z_б} - \mathrm{j}\frac{m_{zf}}{\omega_б \cdot Z_б \cdot s^2 \cdot C}$ is the impedance of traversal circuit, where r is additional active resistance; m_{zf} convergence ratio of field resistance; $\omega_б ; Z_б$ are basic cyclic frequency and resistance; $s; C$ are slip and capacitance.

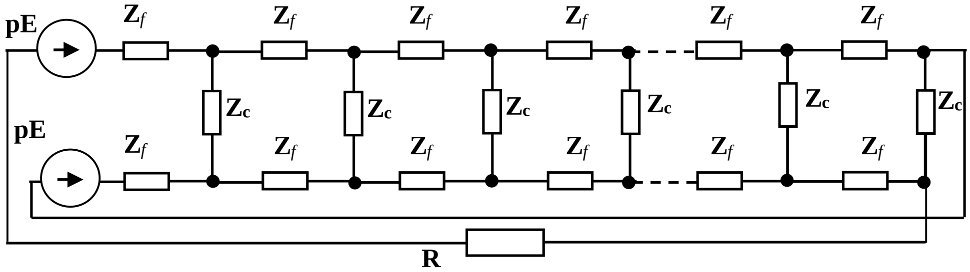


Fig. 2. Analytical circuit for field coil.

The presence of various reactive resistances in the circuit (Fig. 2) makes it dependent on the rate of slip value. As a result, the current field impedance value for the process of starting can be calculated by means of power balance.

The same as for the previous varieties of split winding, the circuit (Fig. 2) can not be analysed directly. To make it possible we used the abovementioned methods of transition from ladder circuits of passive two-ports to the proper long lines and further its substitution by the single line of the same parameters, and length, which is equal to the sum of lengths of its components (Fig. 3).

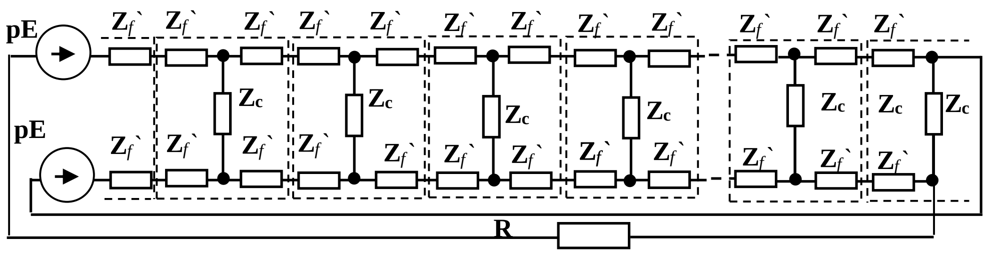


Fig. 3. Transformed circuit of field coil for interim quadripoles folding.

In the proposed interim circuit the longitudinal circuit resistances are equal to the half of impedance of pole coil, i.e. $Z_{f_i}` = Z_{f_i}/2$.

For the transition from initial quadripoles to the quadripoles of T-type the auxiliary coefficient is determined $\beta_k = \frac{Z_{f_i}`}{2Z_{f_i}`} = 0{,}5$. The direct transformation of initial T-type quadripoles into a long line requires the calculation of A-type coefficients

$$A_1 = 1 + \frac{2Z_{f_i}`}{Z_c};\ B_1 = 2Z_{f_i}`\left(2 + \frac{2Z_{f_i}`}{Z_c}\right);\ C_1 = \frac{1}{Z_c};\ D_1 = A_1. \tag{2}$$

and the parameters of the proper long line $Z_л = \sqrt{\frac{B_1}{C_1}}$ is wave impedance; $\gamma_1 = \mathrm{a}\,cosh(A_1)$ is the parameter of a line.

In case of reverse transformation the resistances of the adequate quadripole for the circuit of the folded unit are calculated with respect to the coefficients:

$$\begin{aligned} A &= cosh((p-1)\cdot\gamma 1); \\ B &= Z_л \sinh((p-1)\cdot\gamma 1); \\ C &= \frac{\sinh((p-1)\cdot\gamma 1)}{Z_л};\ D = A. \end{aligned} \tag{3}$$

Then the impedances of quadripole are

$$Z_{fv}` = \frac{A-1}{C}(1-\beta_k);\ Z_{fn}` = \frac{A-1}{C}\beta_k;\ Z_{fk}` = \frac{1}{C}. \tag{4}$$

The final simplified split circuit with respect to folded units of quadripoles is transformed into the form of Fig. 4.

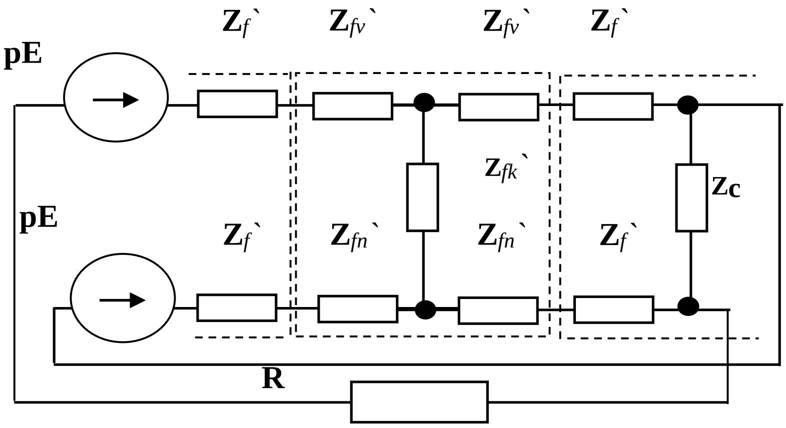


Fig. 4. Simplified circuit for field coil.

To calculate it the empirical coefficients are determined in accordance with power balance

$$\beta_1 = 2\frac{ZZ - ZZ1\cdot(Z_{fv}`+Z_{fk}`+Z_{fn}`+2Z_f`+Z_c)}{ZZ3 - ZZ2\cdot(Z_{fv}`+Z_{fk}`+Z_{fn}`+2Z_f`+Z_c)}, \tag{5}$$

$$\delta_1 = 2-\beta_1;\quad \beta 2 = \frac{2\cdot(Z_{fn}`+Z_f`+Z_c) - \beta_1(Z_c - Z_{fk}`)}{Z_{fv}`+Z_{fk}`+Z_{fn}`+2Z_f`+Z_c},\quad \delta_2 = 2-\beta_2,$$

where

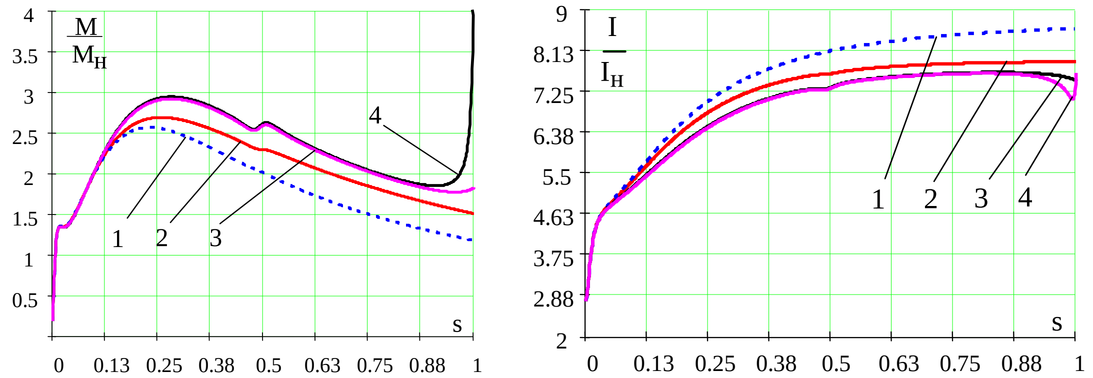
$$ZZ = (Z_{fn}`+Z_f`+Z_c)\cdot(Z_c - Z_{fk}`);\ ZZ1 = (Z_{fn}`+Z_f`+Z_c+R);$$

$$ZZ2 = Z_{fv}`+Z_{fk}`+Z_{fn}`+2Z_f`+Z_c+R;\ ZZ3 = (Z_c - Z_{fk}`)^2 \tag{6}$$

As based on them, the equivalent resistance of field coil is calculated and its parameters in the motor substitution circuit are determined as: $R_{fs} = \frac{Re(Z_{fe})}{s}$ is active component of resistance; $X_{fs} = j(Im(Z_{fe}) - X_{ad})$ is reactive component of resistance.

$$\begin{aligned} Z_{fe} &= \beta_1^{2}(Z_f`+Z_{fv}`)+\delta_1^{2}(Z_f`+R+Z_{fn}`)+\rightarrow \\ &\rightarrow+(\beta_1-\beta_2)^2\cdot Z_{fk}`\ \beta_2^{2}(Z_f`+Z_{fv}`)+\rightarrow \\ &\rightarrow+\delta_2^{2}(Z_f`+Z_{fn}`)+(\beta_2-\delta_1)^2\cdot Z_c. \end{aligned} \tag{7}$$

The studies of motor mathematical model have shown its functionality even under the conditions of connection to each port of capacitors of equal capacitance (Fig. 5). Thus, as based on the studies results for SDSZ-20-29-54-80-UHL4 motor with slightly split field coil, it was stated that the starting moment may reach 1,5 of its rated value for 4 μF capacitance value of capacitors and absence of active resistance. In addition to that, its starting current does not exceed the value of current for the motor in traditional connection.



a) *b)*

Fig. 5. Mechanical starting (a) and electromechanical (b) characteristic of SDSZ-20-29-54-80-UHL4 *motor: 1 is naturally occurring characteristic; 2, 3, 4 are simulated ones for C = 4, 12,7 and 14 μF respectively.*

The resultant curves show the decrease of starting point for the whole range of slip scale. The fact is reasoned by the influence of the other circuits, the number of which is halved if compared to the previous structure. In addition, every separate circuit has twice-increased inductive reactance, this caused capacitance reduction of pole capacitors. The further increase of capacitance creates the maximum moment of starting characteristic, although it happens in the limited range. The resistances connected to capacitor in series allow control of circuit quality, as well as broadening of its working interval. The developed circuit creates some more maximum for mechanical characteristic under the conditions of further increase of the capacitance of pole capacitors. Their occurrence is reasoned by the mutual influence of adjacent circuits. So, for working machines with the required starting moment of no more than 1,5 of the rated value (e.g. high-powered rattlers) the capacitance of the capacitors should correspond to the level, which provides no or only single maximum increase of moment.

One more problem of mining and smelting mechanisms is the influence of occasional impact loads of the mechanisms of coarse grinding and the machinery for metals soft treatment.

As a rule, such equipment used DC motors or asynchronous drive with considerable slip and flywheel kinetic energy storage system. Despite the efficient technological work of electric drive systems, their energy characteristics do not meet modern requirements. Synchronous drive may be considered as an alternative for asynchronous drive for impact loads mechanisms. However, the exploitation of synchronous drive as a component of rolling mill of seamless tube has shown the disadvantages of the drive.

In case of technologically compliant exploitation of synchronous drive of forming rolls, there arise the contingency caused by mechanical wear of end coils in the output point for working wires in magnetic core. The authors of the paper state that [3] the contingency is caused by significant dynamic current rushes of field magnet, which are attended by mechanical clang of end coils. As a rule, the effect of such impact blows is equilibrated by mechanical or electrical means. They are the following: flywheel mechanism, regulation of deflection rate of elastic clutch, and the use of automatic field system with voltage forcing parameter.

The high rate of mechanical characteristic rigidity does not allow use of flywheel mechanism load as a damper of intensified application. The practical use of flywheel, as a component of synchronous drive, has shown its inexpediency because of its incapacity to turn into practice the stored energy resulting from motor speed «slump».

The second way of impact loads compensation is the introducing of elastic clutches into kinematic diagram. It should be noted that the most difficult case of absolutely rigid constraint use has uncovered the system inoperability as resulted from the significant decrease of its oscillativity [3]. So, the researchers are required to determine the level of spring linkage rigidity, which enables both positive results of damping and the satisfactory operability of a drive.

Besides the mechanical approaches to the problem of synchronous drive operation, the use of automatic field system control should be also considered. But it is needed to formulate the control law or determine the fixed parameters of system setup. As it is shown by [3], at the initial point of impact load application the motor operates at attenuated field, which may cause significant slumps of inductive current. The possible way of effect reduction may be in preliminary voltage forcing of the determined value.

The analysis of emergencies origin shows that two methods may be used for impact loads compensation. They are the control of resilient members rigidity in the range, which does not cause considerable mechanical oscillation, and preliminary field forcing of the stated level. The solution should be based on the optimization problem formulation, which will enable the system parameters determination under the definite conditions of drive operation.

Using mathematical modelling, let us show the fundamental possibility of parameters determination for SDSZ-20-29-54-80-UHL4 drive of rated load surge from idle operation mode. The frame of optimization factors control is experimental data:

- order of field forcing is 1…1,75 of the rated one, which is limited by actuator capacity;

- the range of order of elastic clutch rigidity is 1…4, which is limited by the maximum of electromechanical system oscillativity;

- the possible time of preliminary forcing turn on is 0…3 second before load occurrence; it is determined by five time constants of field coil. As a function of purpose, the minimum mean square deviation from constant of field magnet current in case of rated load surge is considered [4].

$$\sigma = \sqrt{\sum_{i=0}^{n} \frac{(I_i - I_{\text{уст}})^2}{n-1}}, \tag{8}$$

where I_i, I_{ycm} are momentary and constant values of current of field magnet, n is discrete step. The task solution is done by means Minimize operator from MathCAD software package, which is used as gradual way for optimizing.

The dynamics of synchronous drive start is traditionally estimated with respect to electromagnetic transients. We used the Park-Gorev equation for motor modelling [5]:

$$\begin{cases} \frac{d\psi_d}{dt} = U_d + \psi_q \omega_\partial - r_a i_d; \quad \frac{d\psi_q}{dt} = U_q - \psi_d \omega_\partial - r_a i_q; \\ \frac{d\psi_f}{dt} = U_f - r_f i_f; \\ \frac{d\psi_{kd}}{dt} = -r_{kd} i_{kd}; \quad \frac{d\psi_{kq}}{dt} = -r_{kq} i_{kq}; \\ \frac{d\omega_\partial}{dt} = \frac{M_\partial - \beta(\omega_\partial - \omega_м) - C_o \frac{(\varphi_\partial - \varphi_м)}{p}}{T_{M\partial}}; \quad \frac{d\varphi_\partial}{dt} = \omega_\partial; \quad \frac{d\theta}{dt} = 1 - \varphi_\partial, \\ \frac{d\omega_м}{dt} = \frac{\beta(\omega_\partial - \omega_м) + C_o \frac{(\varphi_\partial - \varphi_м)}{p} - M_м}{T_{Mм}}; \\ \frac{d\varphi_м}{dt} = \omega_м \end{cases} \tag{9}$$

Momentary values of currents and moment were determined with respect to subtransient parameters of synchronous motor:

$$x_d'' = \frac{D}{x_f x_{kd} - x_{ad}^2}; \quad x_q'' = \frac{x_q x_{kq} - x_{ad^2}}{x_{kq}}; \quad x_f'' = \frac{D}{x_d x_{kd} - x_{ad^2}};$$

$$x_{kd}'' = \frac{D}{x_f x_d - x_{ad}^2}; \quad x_{dkd}'' = \frac{D}{x_f x_{ad} - x_{ad}^2}; \quad x_{fkd}'' = \frac{D}{x_d x_{ad} - x_{ad}^2}; \tag{10}$$

$$x_{fd}'' = \frac{D}{x_{kd} x_{ad} - x_{ad}^2}; \quad x_{qkq}'' = \frac{x_q x_{kq} - x_{aq}^2}{x_{ad}},$$

where $D = x_d x_f x_{kd} - x_{ad}^2 (x_d + x_f + x_{kd}) + 2x_{ad}^3$.

The solution of the system of differential equations is done with respect to the forms for currents and electromagnetic moment calculations:

$$i_d = \frac{\Psi_d}{x_d''} - \frac{\Psi_f}{x_{fd}''} - \frac{\Psi_{kd}}{x_{dkd}''}; \quad i_q = \frac{\Psi_q}{x_q''} - \frac{\Psi_{kq}}{x_{qkq}''}; \quad i_f = \frac{\Psi_f}{x_f''} - \frac{\Psi_d}{x_{fd}''} - \frac{\Psi_{kd}}{x_{fkd}''};$$

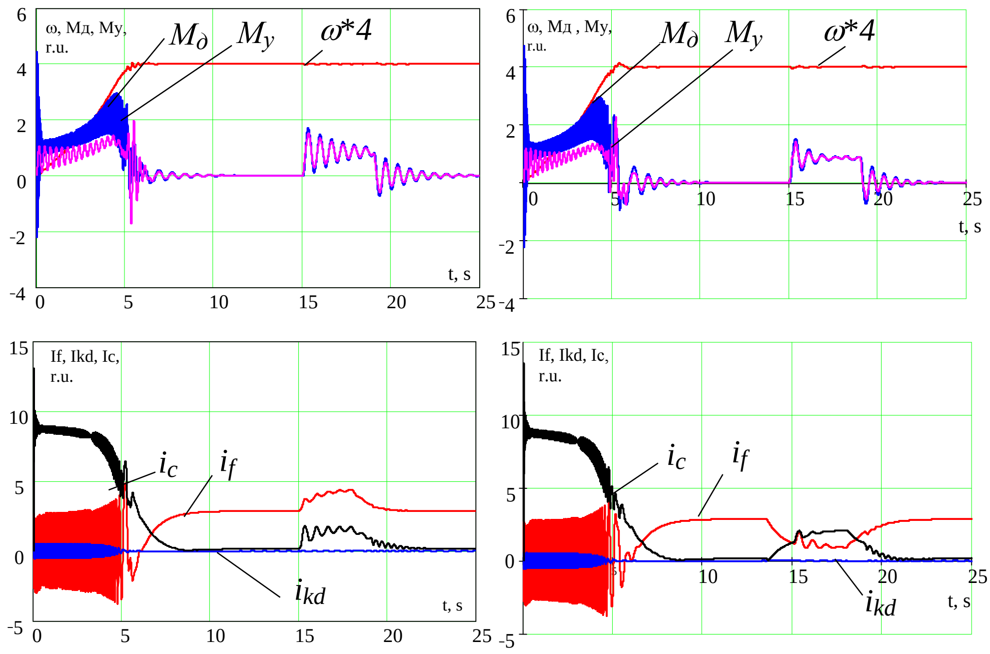
$$i_{kd} = \frac{\Psi_{kd}}{x_{kd}''} - \frac{\Psi_f}{x_{fkd}''} - \frac{\Psi_d}{x_{dkd}''}; \quad i_{kq} = \frac{\Psi_{kq}}{x_{kq}''} - \frac{\Psi_q}{x_{qkq}''}; \tag{11}$$

$$M_\partial = (\Psi_d i_q - \Psi_q i_d); \quad i_c = \sqrt{i_d^2 + i_q^2},$$

where i_c is field magnet current, r.u.

The results of modelling process are shown at Fig. 6, where i_c, i_f, i_{kd} are field magnet current, field current, damper winding current, r.u.; M_∂, M_y are electromagnetic moment and torque applied by spring, r.u.; ω is engine speed; r.u.

The value of mean square deviation was determined as σ = 0,002707, order of field forcing and rigidity 0,178012 and 1,436994 respectively for the 1,5 second time of preliminary turning on of field voltage. The system oscillativity increased for the synchronization section, but the quality of transients was improved in whole. In case of lower boundary limitation for order of drive by 1, the optimization problem also has a solution. But then the forcing and time of preliminary y turn on increase in comparison to Fig. 6, and transients quality decreases. The criterion of lower boundary of forcing choice, as being more or less than one, should be minimum power in the field magnet winding, which is determined by the area under the curve of field current in the section of load surge. This is peculiar for the case shown at Fig. 6 (b). Comparing the loss power of control for the classic field system (Fig. 6 (a)) and of optimized one (Fig. 6 (b)), we may state that area increase under the curve of current is not sufficient. The fact proves the possibility of maintenance of heat load of electrical machine almost on the level stated by its producer.



a) *b)*

Fig. 6. The example for optimization problem solution: a) stands for the standard parameters; b) stands for optimized parameters.

Summary. The researches carried out drove us to the following conclusions:

• The use of indirect split of drive circuit enables decrease of power reserve for driving electric motors;

• The technological and economic advantages of the project are substantiated by the decrease of idle periods number caused by mechanism dead starts. This is urgent for mechanisms with significant shearing couple or in the need for increase of motor induction torque in the specific slip zone in case of asynchronous start;

• Indirect way of field winding split simplifies the magnetic system of rotor, and, thus, simplifies its calculations and cuts production costs;

• As for synchronous drive with no flywheel, the compensation of impact loads is possible in case of regulation of rigidity of spring linkages and order of field forcing;

• The optimization problem can be solved using the gradual method and function of purpose of the minimum mean square deviation of momentary value of field magnet current from its constant value in case of load surge;

• The limitations of optimization factors are substantiated by technical feasibility of field magnet, permissible amplitude of system oscillation and the time constant of field coil;

• The fundamental evidence of possibility of impact loads compensation by means of synchronous drive. As based on the evidence of SDSZ-20-29-54-80-UHL4 drive, it was determined for the first time that contingency avoidance for such drive types is possible under the conditions of reduced order of field voltage of 0,18, time for field voltage reducing of 1,5 second, and the order of elastic clutch rigidity of 1,44;

• The optimization parameters cause the significant decrease of dynamic current surges of drive windings, as well as improvement of transients quality;

• The parameters of system installation cause insignificant loss power of control, which maintains heating rate of synchronous motor.

Summary. The paper contains the discussion of the issues of starting characteristic improvement and protection from impact loads of synchronous motors in the drives of high-power mining and smelting mechanisms. The problem of complicated start is proposed to be solved as based on the additional starting moment created by field coil with pointed and distributed active-reactive characteristic. It is proposed to minimize the problem of impact loads of the stable mode by means of complex usage of spring linkage and specific settings for the standard field system.

References

[1] Patent. UA 31044 A, 6 B 02K 19/36 Ukraine. Synchronous Motor. /V.I. Kyrychenko, V.S. Homilko, V.A. Borodai; patentee and Patent Holder NMU; appl. 03.07.1998; publ. 15.12.2000. Bul. №7-II.

[2] Patent. UA 102792 C, 2 H 02K 19/02, 36 Ukraine. Synchronous Motor. //V.I. Kyrychenko, V.A. Borodai; patentee and Patent Holder NMU; appl. 10.07.2012; publ. 25.04.2013. Bul. №8-II.

[3] Development of Recommendations for the Exploitation of Synchronous Motor of the Main Drive for Automatic Tube Rolling Mill OOO “INTERPIPE NIKO TUBE”: Research Report (Final.) / State HEI «NMU»; Scientific Research Work on the Contract №1120/030383 from 04.12.2012. – Dnepropetrovsk, 2013. – 34, pict.

[4] Borodai V.A. Method and Criterion for Starting Characteristic Optimization of Synchronous Motors of difficult start conditions / Borodai V.A., M.O. Nesterenko – Dnipr-s'k: Mining Electromechanics and Automation, Sci. – Techn. col. – Issue. 85. – 2010 – P. 180 – 183.

[5] Pavliuk D.P. Starting and Asynchronous Modes of Synchronous Motors / D.P. Pavliuk, S. Bidnaryk – Moscow: Energia, 1971. – 271 p.

[6] M.S. Mahmoud, F.M. AL-Sunni, Control and Optimization of Distributed Generation Systems, Power Systems, Springer International Publishing Switzerland 2015, DOI 10.1007/978-3-319-16910-1_2

Cite the paper
V.A. Borodai, R. O. Borovyk, O.Yu. Nesterova (2017). Efficient Transient Modes of Synchronous Drive for Mining and Smelting Mechanisms. *Mechanics, Materials Science & Engineering*, Vol *8*.
doi:10.2412/mmse.71.21.693