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TRANSITIVE AND DYNAMIC PROCESSES A STARTER GENERATING SYSTEM

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Abstract- In this article, the process of transition to one-machine system considering borders of change of speed of an anchor of the starter-generator and internal combustion engine start-up carried out the starting by the switching device is considered. Dynamic process of the given system is also investigated. The basic mathematical parities of the static as well as the inertial moments and efforts, and the kinematics scheme of the mechanism are considered. The mathematical decision of rigidity of a cranked shaft with a belt drive is given. Under the theory of fluctuations the equation of movement of rotating system is worked out. The analysis shows the operating modes of the starter-generator taking into account various changes of kinematics.

Keywords: Starter, Generator, Cranked Shaft, Belt Drive, Pulley, Inertia Factor, Reducer.

I. INTRODUCTION

Basic elements of system of the electric equipment of automobile vehicles of a general purpose, tractors, agricultural cars, various military mobile installations and techniques, motorcycles, mopeds etc. are electric cars. In the specified vehicles systems the electric equipment are usually used as constant and alternating current. More difficult schemes are used now in motor transportation and in tractors where the questions are related to their convenience and reliability and management, traffic safety and comfort as the complex solutions.

The prospect of development of the electric cars applied in system of electric equipment is defined by requirements of increase of a resource, decrease mass dimensional indicators, increase of adaptability to manufacture of designs and expansion of functionality [1], with use of last achievements of science and progressive technology.

II. TRANSITION OF ONE-MACHINE SYSTEM IN THE EXTERNAL ELECTRIC NETWORK

In the theory of the electric cars, it is known that each electric car is capable to work both in implementation, and in generating modes. In that case, there is an interest to fundamental consideration for application of the electric car, starter-generator, external transport systems.

In modern onboard systems, the direct current (DC) cars carrying out with starter function does not work during very short time and the results are not used in the materials spent for performance of designing. Naturally, the operating ratio of these materials is become very low. To use these materials for creation of a generating mode, there is obvious a question of economy of expenses and nonferrous metals with high cost price in such mass production.

Naturally, the arrangement of separate electric cars for the starter and the generator has the following specific features:

a) Necessity to have collector-brush system for the direct current cars;

b) A wide range of speed of an anchor in a generating mode.

The analysis of chronological researches increase the number of onboard equipments and requirements for increasing the volume of their placing, economy, put forwarding for used materials, considering generalizations of stated features of two machine systems and also the necessary of transition to one-machine system of the starter-generator system.

The direct current car is accepted in view decision creation of the complex systems. Comparison of all scientific research regarding to carrying out now starter function, the technical and economical substantiations of the complex systems are conducted being based on the direct current cars. In modern systems the starter moment moves on a cranked shaft in one pair a tooth gearing. The optimum number of transfer is accepted in limits 8 to 13.

Naturally, the increase in number of transfer would lead to increase in speed of an anchor and finally would decrease overall dimensions. The accepted number of transferring is considered as extreme number towards increasing.

In transition to the system of "starter-generator" the mentioned reasons take the basic place. The engines of internal ignition established on cars have speed in a range of 1:6. As shown in Figure 1, if the starter-generator is chosen to communication with an ICE engine equal 2 (belt drive), the anchor will have speed 1:2. Corresponding to the mode of idling of speed n_0 in an anchor, the external network consumes almost from the storage battery. Below the critical speed n_{cr}, the anchors of the induced electromotive power will be equal to the power of the storage battery. This speed is minimum and begins in nominal operation of the ICE activities.

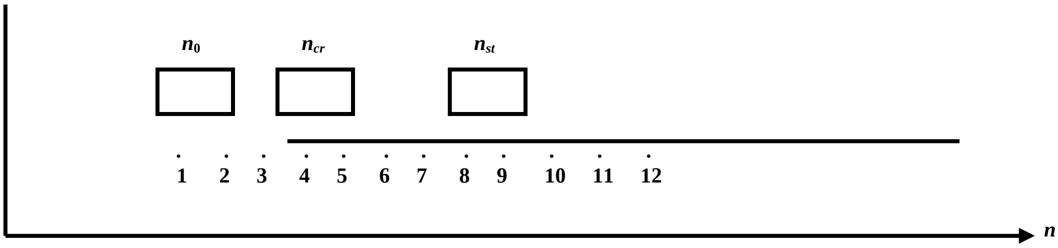

Figure 1. Borders of change of speed in an anchor of the starter-generator system

One of the characteristic points in the field of speed of the starter-generator system is its starting mode n_{st}. Designing, calculations and comparison of the operational regime and characteristics are carried out for this point and checked for a generating mode. The start-up mode is carried out with help of three stepped reduction of starting switch devices (SSD). The number of transfer of the reducer is 15-25 and the factor of transfer of the belt between the starter-generator is accepted approximately equal two. As a result, the transfer number is in the range of 30-50. For concrete designing, the given numbers can be varied which are accepted depending on the capacity of the mode of the starter and the zone of regulation in the generating mode.

The linked winding of the car anchor in connection with transition of the starter-generator in the generating mode is adjusted on creation of the double electromotive power at values $\left(0.3-0.5\right)n_{st}$. So, the external electric network receives the rated voltage and the discharge of the storage battery is prevented. In system of the regulator, the power in all range of the speed (Figure 1) is created by the nominal input external power.

One of the constructive workings out at the problem decision is refusal from collector-brush systems which are unreliable knot for a long generating mode. By the calculations of transition in the starter-generating system it is possible to execute two modes at modern level of reliability and using materials twice less than in two machine system. Designing is carried out in a direction of technical and economical substantiation taking into account both modes.

III. MOVEMENT EQUATION OF ELECTRIC DRIVE OF STARTER-GENERATOR-CRANKED SHAFT

Changing the operating mode of the starter-generator leads to occurrence of dynamic processes in a complex owing to elastic deformation of transfer links such as the direct current car, the starting switch device and belt drive. Research of the starter-generator mechanism dynamics with conditionally accepted law of change of the operating moment, do not considering transients in the engine of a direct current and separate knots which can lead to considerable mistakes. The complex knots are considered as systems of the firm bodies forming kinematics networks, became outdated. In real mechanisms almost any link possesses the degree of pliability. It is known that in any elastic mechanical system with one or several degrees of freedom, the free and compelled fluctuations take place in unsteady processes [2].

In the starter-fluctuation system, the generator can be raised at change of the moment in an impellent mode. Start-up of the starter-generator in direct current engine can be considered as the reason of occurrence of these fluctuations. Thus rather than the little changes in the operating moments it can be possible to sign the variable power in shaft of the reducer and the starter-generator. These powers can lead to destruction or fast deterioration of the complex system.

Elastic fluctuations in mechanical system of the starter-generator influence the transients in the direct current engine which are being reflected in its speed and the moment. Naturally, there is an interrelation between transients in mechanical system and DC cars. This influence more considerable than in the complex system is elastic elements rather small rigidity.

Without dynamic oscillatory processes in mechanical system the starter-generator, it is impossible to design it correctly. Presence of elastic communications in the complex system at dynamic modes leads to additional efforts in elements of kinematics of design, creates vibrations and reduces accuracy of reproduction of the set moving of working bodies. This problem still causes the complicated vibration of independent objects and can creates the resonant phenomenon, integrity of elements pose threat and knots. The given complex concerns mechanisms with consecutive connection of the elastic links working in the conditions of free movement of all elements. The constructive scheme of the general configuration of the starter-generator with ICE is presented in Figure 2.

The shaft and belt drive are exposed in the beginning of ICE of deformation. The elements entering into this design are connected by elastic links. Movement of these elements is described by the differential equations which decision is inconvenient even by means of mathematical cars. For this reason, from numerous elements and communications points, it is allocated that the cores defining the basic character of movement led to one of the elements, e.g. the direct current engine, in the starter-generator regarding to the convenience of calculations operation with the systems.

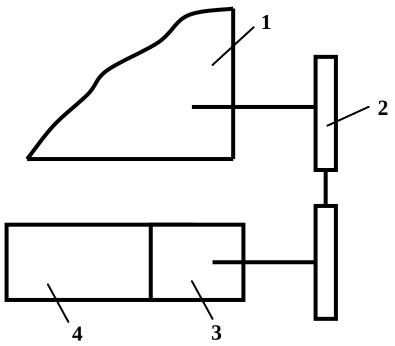

Figure 2. The constructive scheme of the general configuration of the starter-generator with ICE; 1- ICE; 2- belt drive; 3- starting switch device; 4- starter-generator

Considering the basic mathematical calculations of static moment's reduction, it will be effective on the inertia moments. The moment of all elements of the mechanism is led to the shaft of the starter-generator which the electric motor shaft is connected with the cranked shaft of ICE gear and belt transfers. The resulted static moment is defined as the Equation (1).

$$M_s = M_m \frac{1}{K} \tag{1}$$

where $K = K_1 K_2$ is transfer number of the engine in the mechanism and equals to product of transfer relations of gear and belt transfers, respectively; and M_m is the general moment of elements connected, respectively.

The inertia moments are led to one axis, being based on equality of kinetic energy of the starter-generator and the resulted intermediate links. The inertia moments led to the shaft of the direct current engine as the Equation (2):

$$J_i = J_d + J_1 \frac{\omega_1^2}{\omega_d^2} + J_2 \frac{\omega_2^2}{\omega_d^2} \tag{2}$$

where J_i is the inertia moment led to the shaft of the engine, J_d is the inertia moment of rotating parts of the engine; J_1, J_2 are the inertia moments of shaft of the starting switch device and the cranked shaft; and $\omega_d, \omega_1, \omega_2$ are speed of corresponding knots of the system. The Equation (3) is getting taking into account the transfer numbers:

$$J_i = J_d + J_1 \frac{1}{k_d^2} + J_2 \frac{1}{k_d^2} \tag{3}$$

Before passing to the reduction operation, it is required to define rigidity of the links through the related factors which is a problem of reduction of these factors. As it is known, rigidity is resistibility of details of the given mechanism to deformation under the influence of external forces and the moments [2, 3]. The rigidity existing between the moment and deformation is proportionally depending on the related factor.

The expressions of the rigidity of various parts are depending on their geometrical forms and sections. In the starter-generator system, the mode of ICE starting is participating in transfer of the moment shaft which has almost constant section. It is possible to express the rigidity factor of the shaft at torsion case through the module and depending on the geometrical sizes of deformable communication which is defined by following expression:

$$C_p = \frac{C \pi d^4}{32 L} \tag{4}$$

where C is the module of elasticity of the shaft; d is the diameter of cross-section; and L is the length of the deformable site.

The designed belt drive influence can be calculated in the form of rigidity factor with a preliminary tension.

$$C_p = \frac{2 E S r^4}{L} \tag{5}$$

where E is the elasticity module at the stretching of the steel shaft; S is the area of cross-section of the steel shaft; r is the radius of the leading pulley; and L is the length of shaft from the moment action scene (Figure 3).

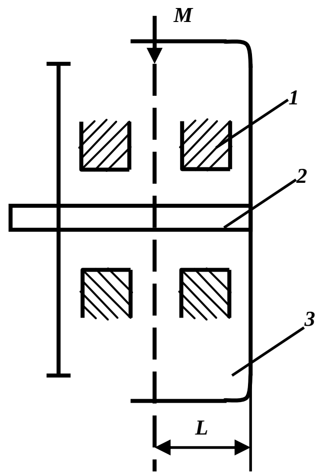

Figure 3. Communication centre shaft of the starting switch devices with a belt drive, 1- bearings rocking; 2- shaft; 3- pulley

The general rigidity factor for this knot of the mechanism can be expressed as follows:

$$C_2 = C_k + C_p \tag{6}$$

Calculation of rigidity of the cranked shaft with belt drive C_3 is defined also as C_2. For this knot definition sharpness C_k and C_p are resulted by means of Equations (4) and (5).

The condition of equality potential energies of the resulted system is expressed as reduction basis sharpness. Based on the elastic links of the connected starter-generator system, we shall get:

$$\frac{1}{C_p} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \tag{7}$$

where C_p is the equivalent resulted factor of three consecutive elastic links; C_1 is the factor of rigidity of the shaft of direct current engine; C_2 is the rigidity factor of the starting switch devices; and C_1 is the rigidity factor of target part of the cranked shaft. Accordingly, equivalent factor of pliability can be expressed as follows:

$$e_p = e_1 + e_2 + e_3 \tag{8}$$

For drawing up the equivalent settlement scheme of the "starter-generator-cranked shaft" mechanism (with elastic mechanical communications) the sharpness of the links is led to the shaft of the direct current engine. According to Figure 4, the kinematics scheme of the mechanism is made on the basis of the connected elastic elements including (1) the shaft of the engine, (2) the starting switch device, (3) the belt drive, and (4) cranked shaft ICE. Considering the transfer numbers, we define the rigidity of separate sections as:

$$C_2' = C_2 \frac{1}{K_1^2}\ ,\ C_3' = C_3 \frac{1}{\left(K_1 K_2\right)^2} \tag{9}$$

As in Figure 4, the basis of the resulted kinematics scheme taking into account the angular co-ordinates is consistently located in settlement system with the general movement of all elements. The angular turn is spent through the transfer relation. For example, the influence of moments M_3 and J_3 is turned on the corner α_2 that spending the rotational angle of the engine shaft as the following:

$$\alpha_2' = \alpha_2 K \tag{10}$$

where K is the transfer relation of the tooth gearing.

For drawing up of the equation of movement in Figure 4, it is possible to describe rotating system in the generalized angular co-ordinates. In the theory of fluctuations, it is accepted to mark moving systems in number of degrees of freedom. So, settlement the system of "starter-generator-cranked shaft" is defined by four generalized co-ordinates $\left(\alpha_1, \alpha_2, \alpha_3, \alpha_4\right)$ and hence has four degrees of freedom.

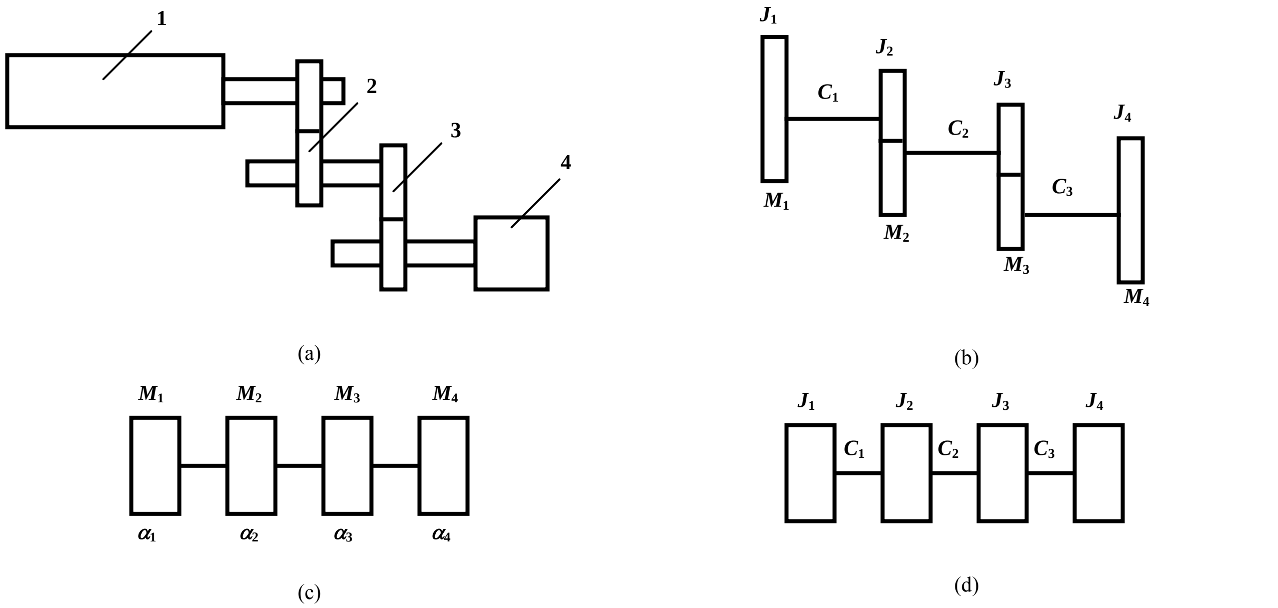

Figure 4. Reduction of the kinematics scheme "starter-generator-cranked shaft" with elastic communications
(a) kinematics scheme; (b) four the mass equivalent scheme; (c) consistently located kinematics scheme; (d) consistently located settlement scheme

The conclusion of the movement equation can be executed using the D'Alembert's principle. The dynamics of the system is represented in the form of a static problem by this principle to show the moments operating and forces in settlement system. The forces are added to the system caused by inert of concentrated moving weights. Therefore, the equation of movement record is drawn as static information. Based on the D'Alembert's principle, the balanced dynamic condition can be made taking into account the settlement system connected by elastic communications as the following:

$$M_{e_{n-1}} - J_n \frac{d_2 \alpha_c}{dt^2} + M_n - M_{e_n} \tag{11}$$

where $\frac{d\alpha}{dt} = \omega$ is the angular speed, α is the generalized co-ordinate defining movement of the system, $M_{e_{n-1}}$ is the moment operating on nth inertial link transferred through (n-1)th elastic communication from the element at the left, M_{e_n} is the moment of forces of resistance from outside nth inertial link which transferred through nth elastic communication from the element on the right, J_n is the moment of inertia of nth link and α_n is the generalized angular co-ordination.

On the other hand, it is possible to express the moment of forces of elasticity through rigidity C and angular co-ordinates α as deformation without the inertial link taking into account transferring in linear static system and submits to the law of Hook.

$$M_{e_{n-1}} = C_{n-1}\left(\alpha_{n-1} - \alpha_n\right) \tag{12}$$

$$M_{e_n} = C_n\left(\alpha_n - \alpha_{n+1}\right) \tag{13}$$

Taking into account Equations (11) and (13), it is possible to write down the following expression:

$$J_n \frac{d\alpha_n}{dt^2} = M_n - C_{n-1}\left(\alpha_{n-1} - \alpha_n\right) - C_{n-1}\left(\alpha_n - \alpha_{n+1}\right) \tag{14}$$

Accepting the symbol of differentiation $P=d/dt$ for settlement the system of “starter-generator-cranked shaft”, we can write system of the equation as:

$$\begin{aligned} &J_1 p^2 \alpha_1 = M_1 - C_1\left(\alpha_1 - \alpha_2\right) \\ &J_2 p^2 \alpha_2 = M_2 + C_1\left(\alpha_1 - \alpha_2\right) - C_2\left(\alpha_2 - \alpha_3\right) \\ &J_3 p^2 \alpha_3 = M_3 + C_2\left(\alpha_1 - \alpha_3\right) - C_3\left(\alpha_3 - \alpha_4\right) \\ &J_4 p^2 \alpha_4 = M_4 + C_3\left(\alpha_3 - \alpha_4\right) \end{aligned} \tag{15}$$

Writing down the differential equation concerning to angular co-ordinate α_1, it is excluded variables $\alpha_2, \alpha_3, \alpha_4$:

$$\begin{aligned} &\frac{J_1J_2J_3J_4}{C_1C_2C_3} p^8 \alpha_1 + \\ &+\left(\frac{J_1J_2J_3}{C_1C_2} + \frac{J_1J_2J_4}{C_1C_3} + \frac{J_1J_2J_4}{C_1C_2} + \frac{J_1J_3J_4}{C_1C_3} + \frac{J_1J_3J_4}{C_2C_3} + \frac{J_1J_3J_4}{C_2C_3}\right) p^6 \alpha_1 + \\ &+\left(\frac{J_2J_3}{C_1} + \frac{J_1J_2}{C_1} + \frac{J_1J_3}{C_2} + \frac{J_1J_4}{C_1} + \frac{J_2J_3}{C_2} + \frac{J_3J_4}{C_2} + \frac{J_1J_4}{C_2} + \frac{J_1J_4}{C_3} + \frac{J_3J_4}{C_3}\right) p^4 \alpha_1 + \\ &+\left(J_1 + J_2 + J_3 + J_4\right) p^2 \alpha_1 = \\ &= M_1 + M_2 + M_3 + M_4 + \frac{J_2J_3J_4}{C_1C_2C_3} p^6 M_1 + \\ &+\left(\frac{J_2J_3}{C_1C_2} + \frac{J_3J_4}{C_2C_3} + \frac{J_3J_4}{C_1C_2} + \frac{J_2J_4}{C_1C_3} + \frac{J_2J_4}{C_1C_2}\right) p^4 M_1 + \\ &+\left(\frac{J_2}{C_1} + \frac{J_3}{C_1} + \frac{J_4}{C_2} + \frac{J_4}{C_1} + \frac{J_4}{C_2} + \frac{J_4}{C_3}\right) p^2 M_1 + \frac{J_3J_4}{C_2C_3} p^4 M_2 + \\ &+\left(\frac{J_3}{C_2} + \frac{J_4}{C_3} + \frac{J_4}{C_2}\right) p^2 M_2 + \frac{J_4}{C_3} p^2 M_3 \end{aligned} \tag{16}$$

Generally, the movement equation consistently located in settlement systems of the electric drive taking into account the elastic mechanical communications is written as the following [5]:

$$\sum_{i=1}^{n}\left(A_i P^{2i} \alpha_1\right) + \alpha_1 = \sum_{i=1}^{n}\left(B_i M_i\right) + f\left(M_1, ..., M_{n-1}\right) \tag{17}$$

where n is the number of degrees of freedom.

The left part of Equation (17) is the sum of even derivatives of required co-ordinates with factors A_i depending on the moments of inertia and rigidity of elastic links and co-ordinate of α_1. The right part of the equation consists of two parts including the first one is the sum of all moments operating in system with the factors which is depending on the moments of inertia and rigidity. The second one is the sum of even derivative of the operating moments with related factors.

Taking into account the generalized Equation (17) for the system “starter-generator-cranked shaft”, the Equation (16) can be written down as the following:

$$\begin{aligned} &A_4 p^8 \alpha_1 + A_3 p^6 \alpha_1 + A_2 p^4 \alpha_1 + A_1 p^2 \alpha_1 = \\ &= B_3 p^6 M_1 + B_2 p^4 M_1 + B_1 p^2 M_1 + + C_2 p^4 M_2 + \\ &+ C_1 p^2 M_2 + D p^2 M_3 + M_1 + M_2 + M_3 + M_4 \end{aligned} \tag{18}$$

where A, B, C and D can be defined in the Equation (16) which have been written down for the given system.

The considered examples [4] explain the processes of transition from of the kinematics scheme of the electric drive regarding to its resulted settlement mechanical scheme and possibility of the simplification issue. It is noticed that absolutely polytypic mechanisms are reduced to three settlement schemes including three-mass elastic system, two-mass elastic system and a rigid mechanical link. Taking into account such distribution of typical settlement schemes, the settlement scheme of the mechanism of “starter-generator-cranked shaft” concerns four-mass elastic system. The mechanism as the electromechanical systems of the automated electric drive is used in rare instances when there is a necessity of more detailed analysis of traffic conditions in the mechanical part. For the problem decision, such cases are usually used as mathematical modeling in computers. For researching of separate physical features of four and three-mass systems, as a rule, it is reduced to two-mass elastic system with two degrees of freedom that is the basic object of research in the theory of the automated electric drive.

For electric drive of the system “starter-generator-cranked shaft”, it is the object to design the belt drive between the shaft of starting switch devices (SSD - reducer) and cranked shaft. Considering the moment of the resistance for raising the elasticity of the belt, it is not required to change the cranked shaft in the shaft of a reducer except. These processes as the mixes connected with compression in cylinders ICE or further burning are not constant in the frequency of occurrence in the system of “cranked shaft-belt drive”. All the high-frequency forces to be accounting in the mathematical system, varying in amplitude, time, frequency and the form are very difficult and will not bring the big benefit at short-term work of the starter-generators.

Besides, all the high-frequency moments operating in a cranked shaft are extinguished by a flywheel rigidly connected with cranked shaft, and elasticity of a belt drive. Considering this circumstance, it is possible to come to the conclusion about system transfer in two-mass (Figure 5).

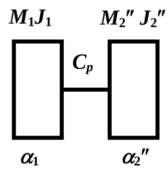

Figure 5. Two-mass elastic system of the mechanism “starter-generator-cranked shaft”

The moments of rigidity entering into the settlement scheme and the moments of inertia of links are resulted taking into account factors of transfer and angular moving by the Equations (1), (3), (7) and (10). In this case the equations of balance of system with two degrees of freedom will be:

$$\begin{aligned} &J_1 p^2 \alpha_1 = M_1 + C_p\left(\alpha_1 - \alpha_2''\right) \\ &J_2'' p^2 \alpha_2'' = M_2'' + C_p\left(\alpha_1 - \alpha_2''\right) \end{aligned} \tag{19}$$

where J_2'', M_2'', C_p are the moment of inertia of the shaft of the starter-generator, the moment of resistance and sharpness elements, respectively. They also are easily defined in the Equations (1), (3) and (7). The joint subsystem in Equation (19) rather than α_1 gives the equations of the following two-mass system:

$$\frac{J_1 J_2''}{C_p} p^4 \alpha_1 + \left(J_1 + J_2''\right) p^2 \alpha_1 = M_1 + M_2'' + \frac{J_2''}{C_p} p^2 M_1 \quad (20)$$

It is easy to find the sum of the derivatives of the required co-ordinate with factors A_i in the system of the moments including the factors of inertia and rigidity regarding to the general equation of the system of “starter-generator-cranked shaft” [4, 5].

The operating mode of the starter-generator has frequent character of short-term and often repeated-short-term. Actually, it is transitive and varies depending on the numerous factors including fluctuations of power, temperatures of windings (anchor and excitation at repeated-short-term modes), time of the included condition etc. It is difficult to investigating all these modes by means of received above equations as it was already marked even by means of mathematical cars. Therefore, transition of four-mass to two-mass should justify itself with input of the additional factors considering strengthening of reliability. The given transient of start-up can not correspond to the second. Taking into account all these circumstances, it is possible researching in dynamics of start-up of the system of “starter-generator-cranked shaft”.

IV. CONCLUSIONS

The transitive process of the starter-generator taking into account changes of numbers of the belt drive is analyzed in this paper. Mathematical research of the basic parities used in calculations of regime questions, connected with the statistical moments, efforts and the inertia moments is considered. The differential equations describing movements of the mechanism of “starter-generator-cranked shaft” are also processed. Some recommendations about transition four-mass to two-mass elastic system of the mechanism and facilitating the decision with insignificant errors are proposed as the results.

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BIOGRAPHY

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