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SOME ISSUES OF DESIGNING A HYBRID ELECTRIC MACHINE

S.A. Khanahmedova [1] S.Y. Shikhaliyeva [2] S.J. Alimamedova [1] S.M. Kerimova [1]

1. Power Faculty, Azerbaijan State Oil and Industry University, Baku, Azerbaijan
samira1009@mail.ru, sara_elimemmedova@mail.ru, saidakerimova77@mail.ru
2. Power Faculty, Mingachevir State University, Mingachevir, Azerbaijan, saadaasmar@mail.ru

Abstract- The scientific article discusses some issues in the design of a single-machine (hybrid) system. Taking into account the limits of the change in the speed of rotation of the armature of the new system, the method of reducing overall dimensions and weight with increasing engine speed, improving the cooling process is analyzed. The prospect of the development of electric machines used in the electrical equipment system is determined by the requirements of increasing the resource, reducing weight and size indicators, improving the manufacturability of structures and expanding functionality, using the latest achievements of science and technology, progressive technology. Design, calculations, comparison of operational and operational characteristics are performed for the starting speed and checked for the generator mode. The equation of motion of the unit "single-machine system-crankshaft" is given. To compile the equation of motion, the rotating system is described by generalized angular coordinates. The equivalent scheme, replacement circuit of a mechanical circuit, and the generator mode of a hybrid complex are investigated.

Keywords: Hybrid Complex, DC Machine, Single-Machine System, Electromagnetic Moment, Armature Speed, Rotation Speed.

1. INTRODUCTION

According to the theory of electric machines, it is known that every electric machine is capable of operating in both motor and generator modes. In this case, there is an interest in the fundamental consideration of the use of a hybrid electric car on board transport systems [5, 6, 8]. In modern on-board systems, a DC machine performing the function of a starter in a very short time does not work for a long time and leads to the non-use of materials consumed to perform the design. Naturally, the utilization rate of these materials becomes very low. If these materials are used to create a generator mode, the issue of saving expensive materials and non-ferrous metals with high costs in such mass production will become obvious.

The analysis of chronological studies, the increase in the number of on-board equipment and the requirements for increasing the volume for their placement, the savings put forward for the materials used, the generalization of the above features of the two-machine system consider it necessary to switch to a single-machine hybrid system [7, 9, 10, 12]. To solve this problem, it was decided to create a complex based on a DC machine. Comparison of all research works, feasibility studies of the complex are conducted based on a DC machine that currently performs the function of a starter.

In modern systems, the starter torque is fed to the crankshaft by one pair of gears [11, 13, 14]. The optimal transmission number is assumed to be within 8÷13. Naturally, an increase in the number of gears would lead to an increase in the frequency of rotation of the armature and eventually the overall dimensions would decrease. The accepted transfer number is an extreme number in the direction of increase.

2. DETERMINATION OF THE OPTIMAL ROTATION SPEED

Let's consider the solution of the problem in a different direction. According to the principle of designing electric machines with a constant value of current density (Δ) and induction, the following relations are determined between power, rotational speed, and linear size (l) [2]: $P_i/n \sim l^4$.

$$l \sim \sqrt[4]{P_i/n} \sim \sqrt[4]{M} \tag{1}$$

where, P_i is estimated capacity of the machine; and $M \sim P_i/n$ is electromagnetic moment of the machine.

The mass of the electric machine G is proportional to the volume, i.e., to the degree of a cube of linear dimensions:

$$G \sim l^3 \left(\sqrt[4]{P_i}\right)^3 \sim \sqrt[4]{P_i^3} \tag{2}$$

Assuming the rotation frequency is not constant, taking into account expressions (1) and (2), we can write:

$$l^3 \sim G \sim \sqrt[4]{P_i^3/n^3}$$

This means that with the constant power of the machine, an increase in the speed of rotation leads to a decrease in overall dimensions and weight:

$$l^3 \sim G \sim l/\sqrt[4]{n^3} \tag{3}$$

In fact, a decrease in overall dimensions and weight with an increase in the speed of rotation occurs at a higher speed. After the nominal speed of rotation, determined by the Equation (3), the cooling process improves and this makes it possible to increase the induction B and the current density Δ, which makes it possible to slightly reduce the overall dimensions and weight.

In transition to a hybrid system, the above arguments occupy the main place. Internal ignition engines installed on cars have a rotational speed in the range of 1:6. If the connection with the internal combustion engine is set to 2 for a single-machine system, the armature will have a rotation speed of 1:2 (Figure 1).

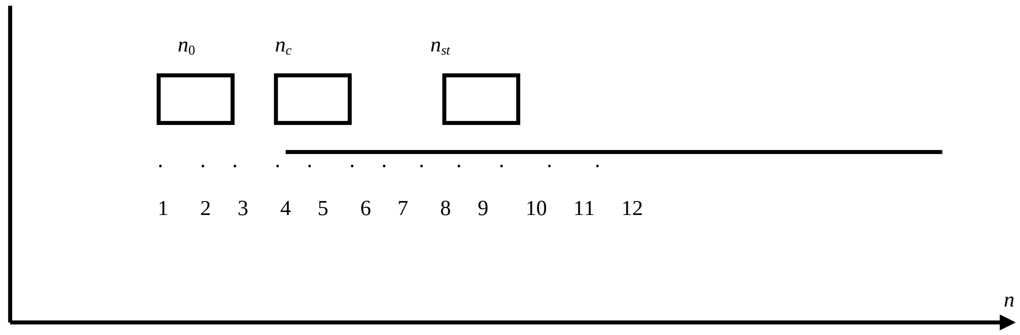

Figure 1. Limits of the change in the rotation frequency of the armature of a single-machine system

Corresponding to the idle speed of the armature speed n0 and about this mode, the on-board network is powered almost from the battery. Below the critical rotation frequency n_c of the armature, the induced electromotive force will be equal to the battery voltage. It is this rotation speed that is the minimum and from here the internal combustion engine starts to turn on useful work (nominal work).

One of the characteristic points in the field of the frequency of rotation of the hybrid complex is the frequency of rotation of the starting mode [1, 2, 3]. Design, calculations, comparison of operational and operational characteristics are carried out for this point and are checked for the generator mode. The start is carried out by means of a three-stage gearbox - a start-switching device (SSD). The transmission number of the gearbox is 15÷25, the belt transmission coefficient (a belt drive is used between the hybrid complex and the crankshaft) is assumed to be approximately equal to 2. As a result, the transmission number is in the range of 30÷50.

With a large number of total transmissions, the analysis of Equation (3) makes it possible to increase the rotation frequency of the armature of the DC machine, which can lead to a decrease in its total weight. Naturally, this makes it possible for the anchor to operate without problems in a wide range (1:2).

The coupled armature winding of the machine, due to the transition of the hybrid system to the generator mode, is adjusted to create a double electromotive force, which at values (0.3÷0.5) n_{st}, the on-board electrical network receives a nominal voltage and battery discharge is prevented. By entering a voltage regulator into the system, a nominal onboard voltage is created over the entire speed range [2, 8].

One of the constructive developments in solving the problem is the rejection of the collector-brush system, which is an unreliable node for a long generator mode. According to preliminary calculations, when switching to a new hybrid complex, it is possible to perform two modes at a modern level of reliability and consume materials half as much as in a two-machine system. The design is carried out in the direction of techno-economic justification, taking into account both modes.

Changing the operating mode of a hybrid car, including starting an internal combustion engine (ICE), switching to generator mode, a sharp change in the speed of rotation of the crankshaft of the internal combustion engine in one direction or another, etc. leads to the appearance of dynamic processes. In this case, fluctuations may occur when the moment changes in the motor mode [3, 14]. The cause of these fluctuations may be the start-up of the hybrid system current. At the same time, relatively small changes in one of the operating moments can cause alternating stresses in the shafts of the gearbox and the single-machine system. These stresses can lead to the destruction or rapid wear of one or another part of the complex.

This complex refers to mechanisms with a sequential connection of elastic links operating in conditions of free movement of all elements. The movement of these elements is described by a complex system of differential equations, the solution of which is difficult even with the help of mathematical machines. For this reason, from the numerous elements and connections between them, the main ones are distinguished, determining the basic nature of the movement, and for convenience of calculations, they operate with systems reduced to one of the elements, for this case, to a DC motor.

3. THE EQUATION OF MOTION OF THE NODE "HYBRID SYSTEM-CRANKSHAFT"

To compile the equation of motion, a rotating system can be described by generalized angular coordinates. The derivation of the equation of motion can be performed using the D'alembert principle. According to the D'alembert principle, the dynamic equilibrium condition can be made taking into account the elements of the calculation system connected by elastic bonds [1, 2, 3]:

$$M_{e_{n-1}} - J_n \frac{d_2\alpha_c}{dt^2} + M_n - M_{e_n} \quad (4)$$

where, $\frac{d\alpha}{dt} = \omega$ is angular rotation speed; α is generalized coordinate defining the motion of the system; $M_{e_{n-1}}$ is the moment acting on the nth inertial link, transmitted through the n–1st elastic bond, from the element on the left; M_{e_n} is the moment of resistance forces from the side of the n+1 inertial link transmitted through the n^{th} elastic coupling from the element on the right; J_n is the moment of inertia of the link; α_n is the generalized angular coordinate.

On the other hand, the moment of elastic forces can be expressed in terms of stiffness C and angular coordinates α, since the deformation in the non-inertial link, taking into account the translation into the static system, is linear and obeys Hooke's law:

$$M_{e_{n-1}} = C_{n-1}\left(\alpha_{n-1} - \alpha_n\right) \quad (5)$$

$$M_{e_n} = C_n\left(\alpha_n - \alpha_{n+1}\right) \quad (6)$$

Taking into Equations (5) and (6), the Equation (4) can be written as follows [2]:

$$J_n \frac{d\alpha_n}{dt^2} = M_n - C_{n-1}\left(\alpha_{n-1} - \alpha_n\right) - C_{n-1}\left(\alpha_n - \alpha_{n+1}\right) \quad (7)$$

Taking the differentiation symbol $p=d/dt$ for the calculation system, we can write a system of equilibrium equations:

$$\left.\begin{aligned} &J_1 p^2\alpha_1 = M_1 - C_1\left(\alpha_1 - \alpha_2\right) \\ &J_2 p^2\alpha_2 = M_2 + C_1\left(\alpha_1 - \alpha_2\right) - C_2\left(\alpha_2 - \alpha_3\right) \\ &J_3 p^2\alpha_3 = M_3 + C_2\left(\alpha_1 - \alpha_3\right) - C_3\left(\alpha_3 - \alpha_4\right) \\ &J_4 p^2\alpha_4 = M_4 + C_3\left(\alpha_3 - \alpha_4\right) \end{aligned}\right\} \quad (8)$$

In general, the equation of motion of in-line calculation systems of an electric drive, taking into account elastic mechanical connections, is written in the following form [1, 5, 16]:

$$\sum_{i=1}^{n}\left(A_i p^{2i}\alpha_1\right) + \alpha_1 = \sum_{i=1}^{n}\left(B_i M_i\right) + f\left(M_1, ..., M_{n-1}\right) \quad (9)$$

where, n is number of degrees of freedom.

The left part included in Equation (9) is the sum of even derivatives of the desired coordinate with coefficients A_i depending on the moments of inertia and stiffness of elastic links and coordinates α_1. The right part consists of two parts: the first part is the sum of all the moments acting in the system with coefficients also depending on the moments of inertia and stiffness. The second part is a function of the sum of even derivatives of the acting moments with coefficients. For a hybrid system, Equation (9) can be written as follows [2, 3]:

$$\begin{aligned} &A_4 p^8\alpha_1 + A_3 p^6\alpha_1 + A_2 p^4\alpha_1 + A_1 p^2\alpha_1 = \\ &= B_3 p^6 M_1 + B_2 p^4 M_1 + B_1 p^2 M_1 + \\ &+ C_2 p^4 M_2 + C_1 p^2 M_2 + D p^2 M_3 + \\ &+ M_1 + M_2 + M_3 + M_4 \end{aligned} \quad (10)$$

where, A_1 is single-machine system; A_2 is start-up switching device; A_3 is belt drive; and A_4 is crankshaft.

Taking into account this distribution of typical design schemes, the design scheme refers to a four-mass elastic system, which is used in the study of electromechanical systems of automated electric drive-in rare cases when there is a need for a more detailed analysis of the conditions of movement of their mechanical part. To solve the problem in such cases, mathematical modeling on computers is usually used [1, 2]. The moments of rigidity and moments of inertia of the links included in this calculation scheme are given taking into account the transmission coefficients and angular displacements and the equilibrium equations of a system with two degrees of freedom will be:

$$\left.\begin{aligned} &J_1 p^2\alpha_1 = M_1 + C_{p1}\left(\alpha_1 - \alpha_2''\right) \\ &J_2'' p^2\alpha_2'' = M_2'' + C_p\left(\alpha_1 - \alpha_2''\right) \end{aligned}\right\} \quad (11)$$

where, J_2'', M'', C_p are the values of the moment of inertia, the moment of resistance and the stiffness of the elements, respectively, are given on the shaft of a hybrid electric machine. The joint solution of system (8) with respect to α_1 gives the equations of this two-mass system:

$$\frac{J_1 J_2''}{C_p} p^4\alpha_1 + \left(J_1 + J_2''\right) p^2\alpha_1 = M_1 + M_2'' + \frac{J_2''}{C_p} p^2 M_1 \quad (12)$$

For this case of writing the equation, it is easy to find the sum of partial derivatives of the desired coordinate with coefficients A_i acting in a system of moments with inertia and stiffness coefficients included in the general Equation (12) of the drive.

In the obtained differential equations, all the main parameters of all four nodes participate implicitly, which makes them difficult to compare. In order to substantiate this assumption, the method of electromechanical analogy was used to derive the equation of moments acting on the same shaft of the starter-generator complex. This method is widely used in the theories of electromechanical oscillations and electrical devices. To begin with, the vector value of the periodic force acting on the body of the mechanism is determined [1, 3]:

$$F = F_0\left(\cos\omega t + j\sin\omega t\right) = F_0 e^{j\omega t}$$

Similarly, for linear motion, we write the following expression: $V = V_0\left(\cos\omega t + j\sin\omega t\right) = V_0 e^{j\omega t}$.

If we keep in mind that the speed value is expressed in the following form:

$$\dot{V} = j\omega\left(V_0 e^{j\omega t}\right) = j\omega t \text{ and } V = \dot{V}/j\omega$$

and we get:

$$\dot{V} = j\omega\left(j\omega V_0 e^{j\omega t}\right) = j\omega\dot{V}\left(j\omega\right)^2 V = -\omega^2 V; \; \dot{V} = j\omega\dot{V}$$

According to the D'alembert principle, the sum of velocities and forces acting on individual nodes [1]:

$$\dot{V} - \dot{V}_m - \dot{V}_r - \dot{V}_k = 0; \; F - F_m - F_r - F_k = 0$$

where, the indices m, r and k are parameters providing inertia, friction and elasticity. We will write the velocity expression in the following form:

$$\dot{V}_m = \frac{F_m}{m} \text{ or } \dot{V}_m = \frac{1}{m}\int F_m dt = \frac{F_m}{pm}$$

where, $p=d\omega/dt$. Then,

$$\dot{V}_r = \frac{F_r}{r};\ V_k = \frac{F_k}{k} \text{ or } \dot{V}_k = \frac{1}{k} = \frac{dF_k}{dt} = \frac{pF_k}{k} \quad (13)$$

Let 's write down this expression:

$$\dot{V} - \frac{F_m}{pm} - \frac{F_r}{r} - \frac{pF_k}{k} = 0$$

and the values of the forces F_m, F_r and F_k will have the following form:

$$F_m = m\dot{V} = j\omega\dot{V};\ F_r = r\dot{V}; F_k = kV = \frac{k}{j\omega}\dot{V}$$

Force acting on the shaft:

$$F = \left(r + \frac{k}{j\omega} + j\omega m\right)\dot{V} = r + j\left(\omega m - \frac{k}{\omega}\right)\dot{V} = z$$

where, z is mechanical resistance in linear motion

$$z = \frac{F}{V} = r + j\left(\omega m - \frac{k}{\omega}\right)$$

Similarly, according to the scheme shown in Figure 2, we write the following expressions [1]:

$$M_j = J\dot{\zeta} = j\omega J\dot{\zeta};\ M_\rho = \rho\dot{\zeta};\ M_\chi = \chi\zeta = \frac{\chi}{j\omega}\dot{\zeta}$$

$$z = \frac{M}{\dot{\zeta}} = \rho + j\omega J + \frac{\chi}{j\omega} = \rho + j\omega\left(J - \frac{\chi}{\omega^2}\right) M_\chi = \chi\zeta = \frac{\chi}{j\omega}\dot{\zeta}$$

According to the mechanical circuit replacement scheme (Figure 2b)

$$\dot{\zeta} = \frac{M(t)}{\chi + j\omega J + \frac{\chi}{j\omega}} = \frac{M(t)}{\rho + j\omega\left(J - \frac{\chi}{\omega^2}\right)}$$

For a four-mass system:

$$\dot{\zeta}(t) = \frac{M(t)}{z_1 + z_2 + z_3 + z_4} =$$

$$= \frac{M(t)}{\rho_1 + \rho_2 + \rho_3 + \rho_4 + j\omega\left(J_1 + \ldots + J_4 - \frac{\chi_1 + \chi_2 + \chi_3 + \chi_4}{\omega^2}\right)}$$

For the angular velocity of rotation through the moment of rotation $M(t)$ and the mechanical resistance z_m, we obtain the following analytical expression:

$$\dot{\zeta} = \frac{M(t)}{z_m} = \frac{M(t)}{\rho_{14} + j\omega\left(J_{14} - \chi_{14}\frac{1}{\omega^2}\right)}$$

where, $\rho_{14} = \rho_1 + \rho_2 + \rho_3 + \rho_4$ take into account the friction resistance of the nodes M_1, M_2, M_3 and M_4; $\chi_{14} = \chi_1 + \chi_2 + \chi_3 + \chi_4$ take into account the elastic forces of the nodes; and $J_{14} = J_1 + J_2 + J_3 + J_4$ are the total moment of inertia of the nodes, which is directly proportional to the sum of the masses: $m_{14} = m_1 + m_2 + m_3 + m_4$.

As, $\rho_2 + \rho_3 + \rho_1 + \rho_4$, $J_2 + J_3 << J_1 + J_4$ and $\chi_2 + \chi_3 << \chi_1 + \chi_4$, then:

$$\dot{\zeta}(t) = \frac{M(t)}{\rho_1 + \rho_4 + j\omega\left(J_1 + J_4 - \frac{\chi_1 + \chi_4}{\omega^2}\right)}$$

From the conditions we obtain an analytical expression for the resonant part [2, 3]:

$$\omega_0 = \frac{1}{\sqrt{\left(J_1 + J_2\right)\left(\frac{1}{\chi_1 + \chi_2}\right)}} \quad (14)$$

The denominator of Equation (14) is rather larger, so resonance is possible at low frequencies $\omega=\omega_0$.

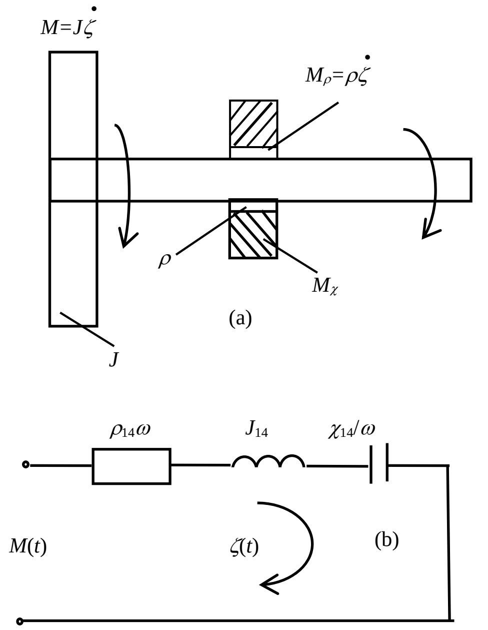

Figure 2. (a) Equivalent circuit of a single-mass mechanical device, (b) a mechanical circuit replacement circuit

4. MATHEMATICAL STUDY OF THE STARTUP PROCESS

In general, from the generalized theory of electric machines, in accordance with the principle of operation of a uniaxial machine with fixed switching brushes located along the transverse axis and an excitation winding oriented along the longitudinal axis without taking into account the gear structure of the armature, it is possible to write a system of equations of the excitation circuit [2, 10, 15]:

$$U_{ab} = R_b i_b + L_b \frac{di_b}{dt} \quad (15)$$

where, U_{ab} is battery voltage. Equation of armature winding circuit voltages:

$$\left.\begin{aligned} U &= C_E \Phi_n + R_{a1} i_{a1} + L_a \frac{di_{a1}}{dt} \\ U &= C_E \Phi_n + R_{a2} i_{a2} + L_a \frac{di_{a2}}{dt} \end{aligned}\right\} \quad (16)$$

where, $C_E = PN/a$ is EMF coefficient; P is number of pole pairs; N is number of armature winding conductors; a is number of parallel circuits; and n is rotation speed, expressed in revolutions per second.

The equation of motion of the armature:

$$\left.\begin{aligned} C_M \Phi i_{a1} + M_1 = 2\pi J \frac{dn}{dt} \\ C_M \Phi i_{a2} + M_2 = 2\pi J \frac{dn}{dt} \end{aligned}\right\} \quad (17)$$

where, $C_M = \dfrac{C_E}{2\pi}$ is torque coefficient.

Resistances R_b, R_{a1}, R_{a2} and inductance L_b, L_a are assumed to be constant; M_1 and M_2 are the moments on the shaft from currents i_{a1}, i_{a2}, are the moment of inertia J of the rotating masses, brought to the armature axis. The starter mode is mainly of a transient nature of the process flow, and therefore its study is important for assessing the electromagnetic and mechanical action of the starter generator; collectively, the electromechanical transient process is mainly being studied.

The start-up process, taking into account the above analytical studies, can be analyzed by the following analytical explanations. Considering that the power of the hybrid machine for the voltage of the on-board network is not small, it is impossible not to take into account both the electromagnetic and electromechanical flow of processes when evaluating the mode. In cases where the time of the electromagnetic processes in the starter generator is commensurate with the time of the electromechanical processes, it is necessary to take into account the influence of the electromagnetic inertia of the anchor chain. The process of changing the armature current is not instantaneous at all, its increase depends on the speed of the electromagnetic process. The time that the armature current reaches the value required to create the starting moment will be significantly small compared to conventional motors that are powered by a powerful source [1, 8].

The starter generator is powered by the onboard electrical network, the only source of which is a rechargeable battery with a large internal resistance. For this reason, when starting the internal combustion engine, the starting current of the armature will be affected by this resistance, and it is physically impossible to equate the starting current at t=0 to the short-circuit current (Figure 3). After the start time t_t has elapsed, the anchor begins to rotate.

It is associated with numerous processes of electromechanical and electromagnetic phenomena, and one of them can be the pronounced rocking of the crankshaft of the internal combustion engine. At a low speed of rotation of the crankshaft, when the ignition moments in the cylinders are relatively long, the rotation speed may be unstable; despite the presence of a flywheel on the shaft and the use of a belt drive between the flywheel shafts, and at the beginning of the movement several times there is an imperceptible swing of the armature rotation frequency within narrow limits; this instability almost does not affect the armature current due to the smallness of the swing amplitudes and its rapid repayment. On the other hand, for transient electromechanical processes, the assumption is within (5÷10)% doesn't have a big impact on calculations and physical analyses if these processes are determined in time in fractions of seconds.

Switching to generator mode is a special operation and should be considered separately, since two freely acting electromotive forces (generator and battery) are combined into one system, i.e., into the electrical network of the on-board power supply.

5. GENERATOR MODE OF A HYBRID ELECTRIC MACHINE

In the generator mode, the armature windings are released from the battery voltage and being under the influence of the magnetic flux created by the poles, they induce an electromotive force. Each winding turns into a source of electromotive force [3]. Three-phase electromotive forces e_1 and e_2 are transmitted to rectifier units mounted on a plastic disk. Each rectifier unit serves as an anchor winding separately. Depending on the project, these blocks can be connected in series or in parallel.

Since two sources of rectifying electromotive force e_1 and e_2 have been created, the angle value between them can be $0÷180^0$. The coincidence of the angles e_1 and e_2 can have a pulsating curve with a large amplitude (Figure 4), where α=0. If we equate the angle $\alpha\pi/2$, then the pulsation will decrease significantly and the value of the rectified electromotive force will increase by ΔE, that is, $E_0+\Delta E$.

The change in the value of depends on many factors: the number of poles, collector plates, etc. To adjust the value of the angle α, we can change the contact points of the three-phase clamps with the collector plates [2, 3, 18, 19]. Immediately after being released from the starter mode, the voltage between the brushes will differ from the battery voltage, since depending on the starter mode, the two sources may not have an electrical connection.

Despite this, the rapid intervention of the voltage regulator, the transient process created by the short time of the discrepancy cannot create any problems when connecting two electrical machines. When designing a specific object, the coordination of the constant time of the voltage regulator with the parameters of the transient process should be clarified.

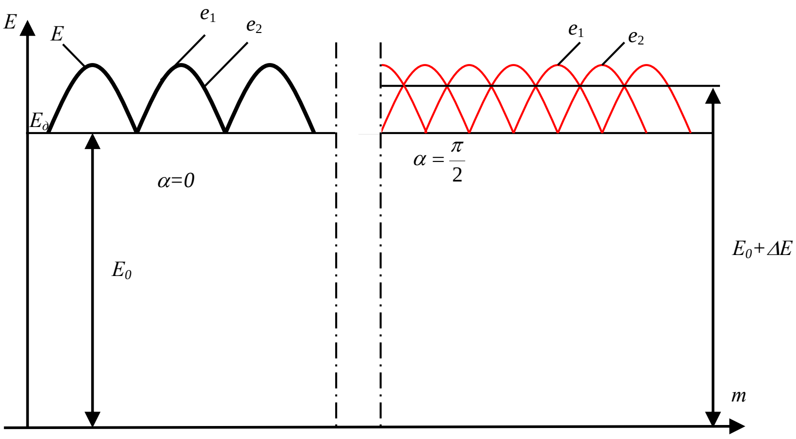

Figure 3. Rectifying electromotive forces

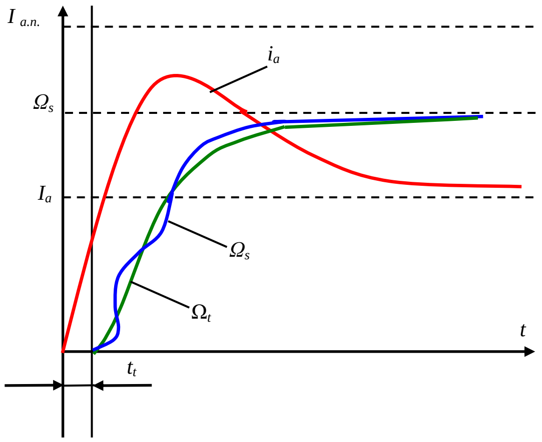

Figure 4. Changes in current (i_a) and rotational speed (Ω_C) depending on the start-up time Ω_s is rotational speed, taking into account the influence of swing; Ω_t is also, without taking into account

6. CONCLUSION

Dynamic processes, causes of friction and vibrations are investigated, problems for their elimination are solved. Using the method of electromechanical analogy, differential equation systems are obtained that do not take into account the parameters of belt transmission systems. It was found out that the new design makes it possible to bring a four-mass assembly "hybrid electric machine - crankshaft" into a two-mass elastic system. Thus, the derivation of the equation of motion can be performed using the D'alembert principle. According to this principle, the dynamics of the system is represented as a static problem, moments and forces are added to the moments or forces acting in the calculation system due to the inertia of moving concentrated masses. Therefore, to compile the equation of motion, the record is made in static.

After being released from the starter mode, the voltage between the brushes will differ from the battery voltage, since depending on the starter mode, the two sources may not have an electrical connection. Despite this, the rapid intervention of the voltage regulator, the transient process created by the short time of the discrepancy cannot create any problems when connecting two electrical machines.

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BIOGRAPHES

Name: **Samira**
Middle Name: **Alkhadi**
Surname: **Khanahmedova**
Birthday: 09.10.1967
Birth Place: Baku, Azerbaijan
Bachelor: Electrical Engineering, Department of Electrical Signal and Automation of Industrial Installations, Faculty of Energy, Azerbaijan State University of Oil and Industry, Baku, Azerbaijan, 1988
Master: Electrical Engineering, Department of Electric Machines, Azerbaijan State University of Oil and Industry, Baku, Azerbaijan, 1990
Doctorate: Ph.D., Department of Electromechanics, Azerbaijan State University of Oil and Industry, Baku, Azerbaijan, 2014
The Last Scientific Position: Assist. Prof., Department of Electromechanics, Azerbaijan State Oil and Industry University, Baku, Azerbaijan, 2016
Research Interests: Control of Asynchronous Electric Drives, Alternative Energy Sources, Management of Various Technological Processes Using Programmable Logic Controllers
Scientific Publications: 60 Papers, 14 Books, 22 Theses

Name: **Saadat**
Middle Name: **Yashar**
Surname: **Shikhaliyeva**
Birthday: 29.09.1973
Birth Place: Sheki, Azerbaijan
Bachelor: Electrical Power Systems and Networks, Faculty of Power Engineering and Mechanics, Mingachevir State University (Mingachevir Polytechnic Institute), Mingachevir, Azerbaijan, 1997
Master: Electrical Power Systems and Networks, Faculty of Power Engineering and Mechanics, Mingachevir State University (Mingachevir Polytechnic Institute), Mingachevir, Azerbaijan, 1999
Doctorate: Electrotechnical Systems and Complexes, Department of Electromechanics, Faculty of Energy, Azerbaijan State Oil and Industry University, Baku, Azerbaijan, 2016
The Last Scientific Position: Lecturer, Department of Energy, Faculty of Engineering, Mingachevir State University, Mingachevir, Azerbaijan, Since 2012
Research Interests: Control of Asynchronous Electric Drives, Use of Alternative Energy Sources; Methods for Ensuring the Efficient Operation of Power Lines, Electrical Machines, Switching Devices
Scientific Publications: 32 Papers, 1 Patent, 16 Theses

Name: **Sara**
Middle Name: **Javanshir**
Surname: **Alimamedova**
Birthday: 09.09.1982
Birth Place: Goy-Gol, Azerbaijan
Bachelor: Faculty of Agricultural Engineering, Azerbaijan Agricultural University, Baku, Azerbaijan, 2000
Master: Electrical Engineering, Faculty of Agricultural Engineering, Azerbaijan Agricultural University, Baku, Azerbaijan, 2021
Research Interests: Control of Electric Drives, Alternative Energy Sources, Management of Various Technological Processes Using Programmable Logic Controllers
Scientific Publications: 6 Papers

Name: **Saida**
Middle Name: **Maarif**
Surname: **Kerimova**
Birthday: 07.06.1977
Birth Place: Baku, Azerbaijan
Bachelor: Physics, Faculty Physics, Tusi Azerbaijan State Pedagogical University, Baku, Azerbaijan, 1998
Master: Electrical Engineering, Azerbaijan Technical University, Baku, Azerbaijan, 2022
Research Interests: Control of Electric Drives, Alternative Energy Sources, Management of Various Technological Processes Using Programmable Logic Controllers
Scientific Publications: 7 Papers