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STRUCTURAL DESIGN AND THEORETICAL STUDIES OF OPERATION OF A DRIVE HYBRID ELECTRIC MACHINE

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Abstract- This article is devoted to the study of a new vehicle, a hybrid electric machine installed on board and performing two functions, both a starter and a generator. General information is given about the design, its elements and the development of two designs of the device connecting the crankshaft of the hybrid electrical drive of the internal combustion engine. The article provides a constructive implementation, theoretical justification and the principle of operation of the gearbox. The mechanical developments of new designs are theoretically investigated and the specific features of the drive device in a wide range of generator operating modes are analyzed. The process of switching to the generator mode after starting an electric machine is considered. Mathematical studies of the start-up process are given, taking into account the basic laws of 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 design of the gear wheel, a system of excitation circuit equations can be written from the armature. Mathematical models of the main parameters of hybrid electric machine using Matlab/Simulink program are given. Next, a physical analysis of the start-up of a hybrid electric machine is given, taking into account the fact that the power of a hybrid electric machine for the voltage of the on-board network is not small, then when evaluating the mode, it is impossible not to take into account both the electromagnetic and electromechanical flow of processes. In cases where the time of electromagnetic processes in a hybrid electric machine is commensurate with the time of electromechanical processes.

Keywords: Hybrid Electric Machine, Simulink model, Gear, DC Motor, Shaft, Gear Wheels, Internal Gear, Brake Disc, Freewheel Clutch, Gear Block, Torque.

1. INTRODUCTION

On board autonomous objects, one power element is usually installed - internal combustion engines (ICE), which is started by starters receiving energy from a battery. To provide the on-board network with electricity, it is planned to install a second electric machine - a high-frequency alternator.

These electric machines by their design and all technical and economic indicators are at a modern level and perfectly perform their functions. However, given that they do not perform their function at the same time, they can be replaced by one electric machine [1]. The introduction of a hybrid electric machine into a constructive object gives great savings in non-ferrous metals, insulation and free space in the internal combustion engine compartment.

Taking into account the mass production of vehicles and the use of non-ferrous metals in the production of electrical equipment elements, as well as the increase in electromagnetic loads to the limit in operating electric machines, combining the functions of a starter and a generator and using one hybrid electric leads to savings of expensive metals [2, 5, 9]. On the other hand, when solving this problem, it becomes possible to increase the rotation speed of such a machine, which will also lead to an additional reduction in material consumption. The purpose of this work is the design of the main connecting hybrid electric machine with the crankshaft of the internal combustion engine gearbox, and the development of the functional features of the entire complex.

2. THE OVERALL LAYOUT OF THE COMPLEX AND FUNCTIONS

The object for this purpose is a DC electric machine that is mechanically connected to the crankshaft of the internal combustion engine by means of a gearbox (start-switching device) and a belt drive. In the starter mode, the DC machine operates as a DC motor with a complete design. In the generator mode, it functions as an alternating current generator, with a frequency of a wide range (40-250 Hz) being released from the brush collector assembly. When creating one whole structure with a DC machine, the reducer must perform the following functions [3, 4, 7, 8]:

Creation of a starter (motor) mode for a hybrid electric car, in order to start the internal combustion engine, to reduce the high speed of the DC motor (2500-4000 rpm, depending on the project) to a low (starting) speed of the crankshaft:

- Gearbox protection & DC motor elements in start-up mode;
- Performing a smooth transition to generator mode (without low mechanical shocks and overloads in the elements of the entire structure of the device);

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- Creation of a reliable mechanical connection between the shaft of a hybrid electric machine and the crankshaft with a sharp change in the rotational speed of the crankshaft of the internal combustion engine, taking into account the extreme permissible mechanical stresses of the parts;
- Protection of the elements of the entire structure of the starter generator in the event of the command "Start" during the operation of the internal combustion engine;
- Provision of generator mode over the entire range of rotation speed of the crankshaft of the internal combustion engine. Setting up the generator mode when the internal combustion engine stops.

In this article, the constructive implementation, theoretical justification and the principle of operation of the two developed gearboxes fulfilling the above requirements are given [2, 3, 4, 5, 21].

3. DESIGN FEATURES OF THE GEARBOX OF THE NEW DESIGN

This design of the device mainly consists of two components, a gear unit (gearbox) and a brake element. The gear unit is the main unit that creates a favorable condition for the motor mode of a hybrid electric machine. The gear unit is created by two sets of gears (Figure 1); wheels 2 and 3 are connected by two radii with certain transmission numbers [1, 2, 3].

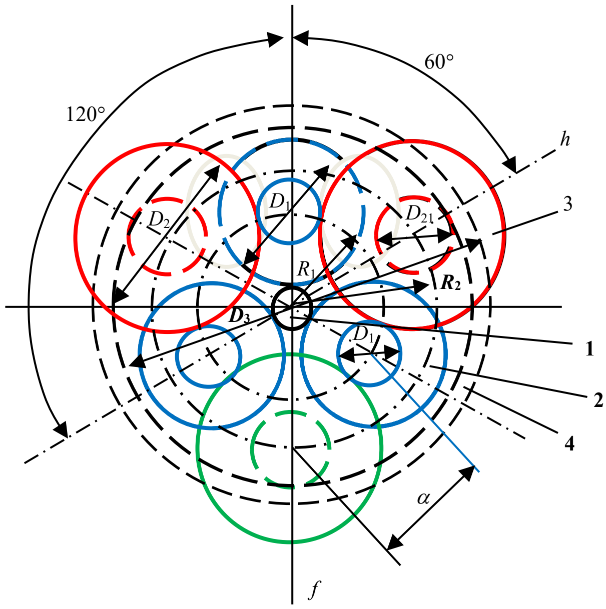

Figure 1. The layout of the gears, 1) gear part of the DC motor shaft; 2 and 3) gear wheels; 4) internal gear wheel

There is an angle of 120° between the axes of the gears located at the same radius. In order to reduce the overall dimensions of the gearbox and the inertia moments of the rotating elements, the gears located on the second radius are connected to two wheels. When designing this gearbox in compliance with the accepted rules for identical gears, the following special conditions are met [10, 16]:

1. Due to the fact that the gear wheels of the first radius has a connection with the gear wheel of the DC motor shaft at an angle of 1200, the number of its teeth must be divided by three; to obtain small dimensions of the block, the gear wheel of the shaft must have a small diameter, with an increase in the value of this size, the diameter of D_3 also increases, respectively, this affects the increase in overall dimensions, (diameter D_3 is simultaneously the inner diameter of the large gear wheel 4); this gear wheel, with the help of its shaft, transfers the torque to the belt drive pulley);
2. Radius R_2 and diameter D_{12} should be chosen in such a way that the following disequilibrium is fulfilled:
$R_2 + 0.5D_{12} < 0.5D_3$
3. There should be the following correspondence between the diameters D_{11}, D_{12} and the size "a":
$$\frac{1}{2}\left(D_{11} + D_{12}\right) < a$$
4. The angle between the f and h axes should strictly remain equal to 60°.

The arrangement of gears with two radii makes it possible to obtain a wide range of transmission speed control, and in the gearbox mode to provide one-way rotation, drive and driven shafts. Indeed, the resulting block is a gearbox with a large number of gears, the input and output shafts are on the same axis and have rotation in the same direction (the gear transmission number, where i_1, i_2 and i_3 are the number of gears of individual gear pairs); Such a solution is necessary because when starting and then, in generator mode, the crankshaft of the internal combustion engine has one direction of rotation.

The use of three gears on each radius makes it possible to create a symmetrical system of the influence of moments, reducing the width of the wheels, vibration and the moment of each tooth. The use of bevel-toothed wheels will lead to a significant reduction in noise and vibration [8, 11, 12, 17]. The frequency of rotation of the armature shaft of a DC machine using the gear numbers of two sets of gears is reduced to the starting speed of the crankshaft of the internal combustion engine:

$$\omega_n = \omega_1 \frac{1}{K}$$

where, $K = K_g K_b$ is total number of transfers; $K_g = i_{12} \cdot i_{23} \cdot i_{34}$ is gear transmission number; i_{12} is the number of gears between the armature and gearbox shafts; i_{23} is number of gears between gears 2 and 3; i_{34} is number of gears between gears 3 and 4; K_b is belt transmission number.

For internal combustion engines, the starting speed is different: for diesel internal combustion engines, the starting speed is 100÷200 rpm; for carburetor internal combustion engines, 40÷70 rpm. The rotational speed data is taken as an input parameter for the design. Preliminary studies show that the number of gears of the gearbox in the drive device can be varied within 15÷25, taking into account the belt drive, the range is doubled, i.e., K=30÷50.

This design for performing the start-switching operation, consisting of hypoid and helical gears, is released from the freewheel clutch. It makes it possible to significantly increase the torque transmitted from the DC motor to the crankshaft of the internal combustion engine [8, 9, 19, 13]. The elements of the device with a DC motor are shown in Figure 2.

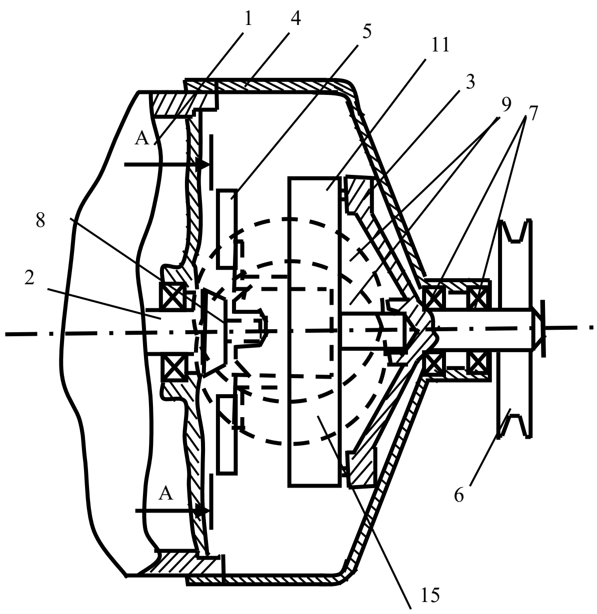

Figure 2. The design diagram of the drive device for hybrid electrical drive, 1) DC motor; 2) drive shaft; 3) driven shaft; 4) cover; 5) brake disc; 6) pulley; 7) bearings; 8) small gear hypoid gear; 9) large gear hypoid gear; 10) gear helical gear; 11) screw wheel

4. ANALYSIS OF THE ELECTRICAL CIRCUIT

Switching of electrical circuits is performed sequentially in two modes (starter and generator). it is performed without problems, both with regard to electrical connections and mechanical overloads [17, 18, 22]. Three windings participate in the conversion of accumulative electrical energy into mechanical, then mechanical into electrical: armature and two excitation windings, parallel and serial. The anchor winding is made of two identical windings in order to create a favorable condition when changing the operating range conditions. According to the degree of complexity and severity of the transition process in the starter mode, it is necessary to investigate the starting mode. Despite the short turn–on time, the starter generator is exposed to an increased value of the starting current, electrodynamic shock and quite possibly thermal exposure [2, 3, 20].

Consider the start-up and at the same time we will take into account some assumptions: the transient process is completed in the excitation circuit, i.e., Φ=constant; given the supply of the excitation system with a sequential winding, we consider the network to be sufficiently powerful (U=constant). Saturation of the magnetic circuit is neglected and the influence of eddy currents is not taken into account. We start under load at a constant statistical torque M. After switching on (i_a=0 is the moment of switching on) the current instantly increases to $i_a = I_a$, which provides the moment of starting $M_E = C_E \Phi i_a = M$. To study the start-up, it is necessary to refer to the voltage equations of the armature winding circuits [3, 20]:

$$\left.\begin{aligned} U &= C_E \Phi n + R_{a1} i_{a1} + L_a \frac{di_{a1}}{dt} \\ U &= C_E \Phi n + R_{a2} i_{a2} + L_a \frac{di_{a2}}{dt} \end{aligned}\right\} \qquad (1)$$

where, P is number of pole pairs; $C_E = \frac{PN}{a}$ is EMF coefficient; N is number of rotor winding conductors; n is rotation speed, expressed in revolutions per second; and a is number of parallel branches.

The Simulink model for systems of Equation (1) is shown in Figure 3

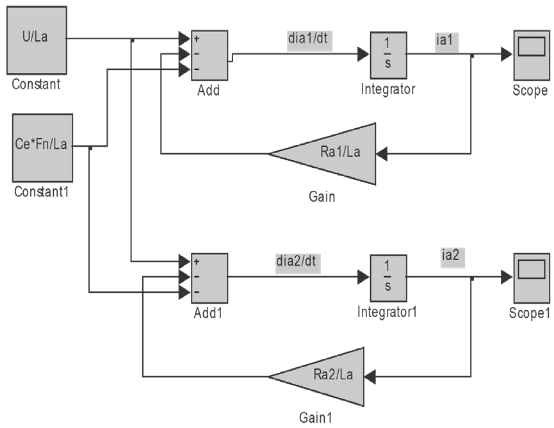

Figure 3. Simulink model for systems of equation (1)

The equation of motion of the anchor:

$$\left.\begin{aligned} C_M \Phi i_{a1} + T_1 &= 2\pi J \frac{dn}{dt} \\ C_M \Phi i_{a2} + T_2 &= 2\pi J \frac{dn}{dt} \end{aligned}\right\} \qquad (2)$$

where, $C_M = \frac{C_E}{2\pi}$ is torque coefficient; T_1 and T_2 are torques on the shaft from currents i_{a1}, i_{a2}; J is the inertia moment of the rotating masses, brought to the axis of the armature.

Considering that in Equations (1) and (2) the parameters for the two windings are identical (depending on the technology and the errors between these parameters, the deviations can be no more than 1-3%), they can be combined and the following equilibrium equations can be written [1, 2]:

$$U = C_E \Phi n + R_a i_a + L_a \frac{di_a}{dt} \qquad (3)$$

$$C_M \Phi i_a + T = 2\pi J \frac{dn}{dt} \qquad (4)$$

Simulink model for equations (3) and (4) is shown in Figure 4.

The process at n=0 and u=U in accordance with the solution of Equation (3) for the initial condition i_a=0 obeys the chain law of the RL circuits [3, 20]:

$$i_a(t) = I_a \left[1 - \exp(-\frac{t}{T_a}) \right] \qquad (5)$$

where, $i_a = U / R_a$ is armature current at stationary rotor (short circuit mode current); $T_a = L_a / R_a$ is time constant.

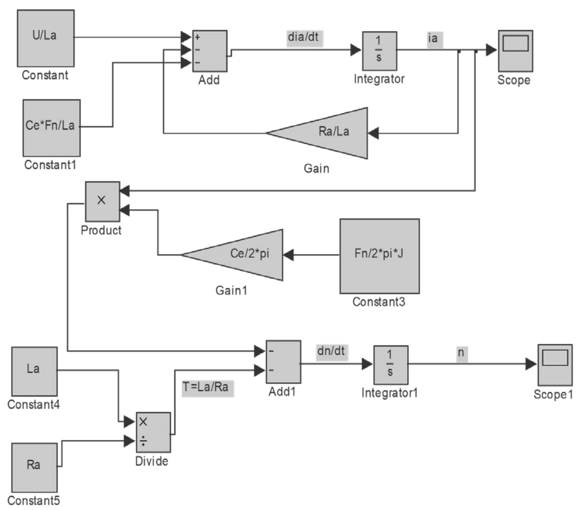

Figure 4. Simulink model for Equations (3) and (4)

If $t=t_0$ (5), then the current will be equal to $i_a(t_0)=I_a$. Since starting the starter generator is an electromechanical process, it is possible to take $t_0=0$. If we go to the angular velocity $\Omega=2\pi n$, the solution of a system of two linear differential Equations (3) and (4) of the first order with initial conditions $i_a(0)$ and $n(0)=\Omega(0)=0$ by any known method gives Equations (6) and (7) [20]:

$$i_a(t) = I_a + \left(I_{an} - I_a\right)\frac{\exp P_1 t - \exp P_2 t}{\sqrt{\Delta}} \tag{6}$$

$$\Omega(t) = \Omega_C\left(1 + T_a \frac{P_2 \exp P_1 t - P_1 \exp P_2 t}{\sqrt{\Delta}}\right) \tag{7}$$

The roots of the characteristic equation:

$$P_{1,2} = -\frac{1}{2T_a}\left(1 \mp \sqrt{\Delta}\right);\ \Delta = 1 - \frac{4T_a}{T_{EM}}$$

where, $T_{EM} = \dfrac{J\Omega_0}{M_E}$ is electromechanical time constant.

Solving Equation (4) with respect to time, it is possible to explain the physical meaning of the time constant. If we accelerate the starter-generator armature idling, i.e., at $M=0$ with a constant dynamic moment $M_d = J\dfrac{d\Omega_0}{dt}$ from $\Omega = M_E = \text{const}$, 0 to the rotational speed of $\Omega_0=2\pi n_0$, we get the time of the artificial process of this acceleration:

$$t_p = J\int_0^{\Omega_0} \frac{d\Omega}{M_{En}} = \frac{d\Omega_0}{M_{En}} = M_{EM}$$

The electromechanical time constant is equal to the ratio of the largest kinetic moment ($M_k=J\Omega$) to the maximum electromechanical moment $M_{En}=C_M\Phi I_a$. Starters usually have a shaft power from 0.7 kW to 7.7 kW. For such capacities, the electromechanical time constant is $T_{EM}\approx0.05\div0.15$ sec. If we take into account that starter generators must capture this power range, then taking into account the fact that their anchor has a significantly low weight, the T_{EM} will have even lower values.

5. PHYSICAL STUDIES OF THE LAUNCH

Considering that the power of a hybrid electric machine for the voltage of the onboard network is not small, then when evaluating the mode, it is impossible not to take into account both the electromagnetic and electromechanical flow of processes [12, 13, 14]. In cases where the time of the electromagnetic processes in a hybrid electric machine is commensurate with the time of the electromechanical processes. The time constant T_a is determined by the armature inductance L_a and the resistance of the armature R_a (Figure 5). The change of the rotor current is not instantaneous at all; its increase depends on the electromagnetic process. The time that the current of the rotor to reach the value required to create the starting torque will be significantly less compared to conventional motors that are powered by a power source. The hybrid electrical drive is powered from the on-board electrical source, the only power supply of which is a rechargeable battery with a large internal resistance [16, 21].

For this reason, when starting the internal combustion engine of a hybrid electric machine, the starting current of the armature will be affected by this resistance. After the t_t start time has elapsed, the armature starts to rotate. 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 the starter generator, at the beginning of the movement, an imperceptible swing of the armature rotation frequency occurs several times 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)% does not have a big impact.

Switching a hybrid electric machine to a steady-state mode is a special action taking into account the influence of 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.

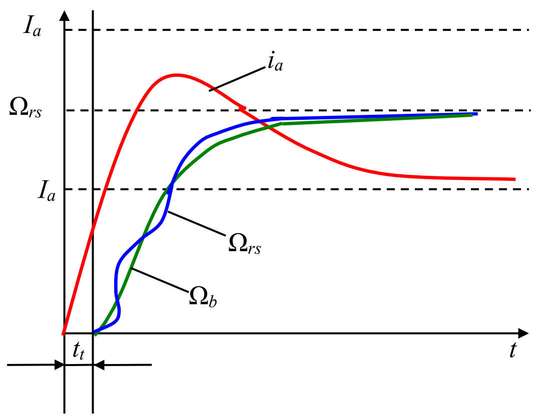

Figure 5. Changes in current (i_a) and speed (Ω_C) depending on the start-up time, Ω_{rs} is rotational speed, taking into account the influence of swing; Ω_b is also, without taking into account

6. CONCLUSION

Based on the analytical studies of mechanical developments of both designs, the specific features of these drive devices, changing in time within a wide range of the generator mode, are determined by the following actions:

- The transition to the generator mode after the starter is carried out without any outside interference;
- The transition to generator mode is performed without any mechanical overload, the transfer is performed with a soft mechanical connection;
- According to the specifics of the generator mode in case of sudden transients, the mechanical disconnected and the connection between the drive and driven shafts is carried out automatically depending on the speed of rotation;
- If the "Start" command is given during normal operation of the internal combustion engine, there are no mechanical overloads or an emergency situation between the crankshaft of the internal combustion engine and the starter generator;
- When the internal combustion engine is not working, the drive device is set to generator mode; any mechanical starting process can be performed using methods provided for modern designs.

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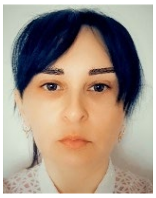
BIOGRAPHIES



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