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STUDY OF A LOCAL SOURCE OF AUTONOMOUS POWER SUPPLY ON THE BASIS OF A DIESEL GENERATOR

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Abstract

A mathematical model of a local autonomous power supply source based on a diesel generator set is presented. The source of primary mechanical energy is a diesel internal combustion engine with an automatic speed controller, operating on the Polzunov-Watt's principle. The electric energy converter is an asynchronous motor operating in a generator mode with capacitor self-excitation. The complete set of such devices is carried out from the available and normally working components of technological, electrical and transport equipment. They are formed by the personnel of the relevant enterprises in the period preceding the accident, during its development or at the end of its active phase. Therefore, mathematical models of subsystems of a diesel engine, an asynchronous machine operating in a generator mode, capacitive self-excitation and a number of typical electricity consumers are represented by separate structural blocks with functional relationships and connected according to the principle of subordinate regulation. This form of representation makes it possible to carry out large-scale studies of the qualitative and quantitative indicators of the operation of diesel generator sets with various types of both internal combustion engines and asynchronous machines. The coincidence of the results of numerical simulation and full-scale experiments allows to judge the adequacy of the proposed mathematical model of a local autonomous power supply source with a diesel generator. The presented model combines algorithmic simplicity and high computational precision and will make it possible to determine the criteria for the trouble-free operation of autonomous power supply sources to provide energy to consumers of different categories.

Keywords: diesel generator, autonomous power supply system, internal combustion engine, asynchronous generator, electrical energy consumers.

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1. Introduction

Exceptional reliability in any operating conditions, stable parameters of the generated electric current, convenient control, low cost of electricity – according to all these parameters, diesel (gasoline) mini power plants (DPP) are the best solution for setting up a secondary power supply system [1]. They can be used for the main, backup or emergency power supply of any facilities, they comply with modern electrical equipment standards. DPP are indispensable where there is no possibility to connect to the central power supply, for example, in remote settlements, shift camps for builders, in mineral deposits. They are also needed at important social and industrial facilities – in hospitals, schools, hotels, financial institutions, telecommunications companies, in plants and factories as a backup source of electricity in case of failures in the main network. However, not all objects of the national economy, in particular state-owned social enterprises, have emergency backup power plants – relatively expensive electromechanical equipment that is in a state of hot reserve, and is used quite rarely [2]. Enterprises that have backup power stations, as a rule, underestimate their capacity many times over in comparison with the installed capacity of the enterprise itself and use it only for uninterrupted power supply of especially important and critical processes and mechanisms.

Almost any enterprise, as part of the standard equipment, contains power equipment with an electromechanical transmission, including an internal combustion engine (ICE) and an electric generator (EG) [3].

Thus, to power consumers in emergency situations, instead of DPP for a short period, local autonomous power supply sources (LAPS) formed according to the DPP principle can be used. In them, the internal combustion engine of self-propelled vehicles acts as the primary source of mechanical energy, and the asynchronous generator complex (AGC) is an electrical energy converter – an asynchronous motor with a squirrel-cage rotor operating in a generator mode with controlled capacitive self-excitation.

The issues of creating and studying the modes and operating conditions of the LAPS are most expediently solved on the basis of mathematical models. For a number of reasons, the existing mathematical models of DPP [4–7] as an object of regulation are not convenient for solving the tasks set, in particular, when connecting/disconnecting the load, when working in parallel with the network, etc., and their use is difficult due to their high difficulties. In addition, most of the mathematical models of internal combustion engines are models of specially designed internal combustion engines for high-power DPPs [8–10], which differ in design, for example, in the presence of a turbine. Or these are built-in ICE models of various mathematical software packages [11, 12], which do not allow changing some parameters or characteristics, for example, setting the real dependence of mechanical torque on the speed and fuel consumption. Also, a number of authors represent the internal combustion engine as a simplified model in the form of a first-order transfer function [13] due to the neglect of the influence of the characteristics of the EG on the characteristics of the internal combustion engine itself and the presence of an automatic speed controller, which is acceptable if the power of the internal combustion engine significantly exceeds the power of the EG. Therefore, the development of a universal mathematical model of LAPS based on DPP with sufficient precision for engineering calculations is the goal of this work.

2. Materials and methods

2. 1. Mathematical model of the internal combustion engine

The drive motor in LAPS is a source of mechanical energy. As the literature analysis has shown, in LAPS of low power, the use of internal combustion engines prevails as a source of mechanical energy.

A modern internal combustion engine is a set of interacting elements, which include a consumer, the engine itself, containing a block with combustion chambers, cylinder-piston groups and a crankshaft. The input coordinates of the engine itself are the cyclic fuel supply g_t, air GD and load N, and the output coordinates are ω_d (angular velocity of the crankshaft ω_n) and G_g (gas supply to the exhaust manifold). For fuel equipment, the cyclic fuel supply g_t is the output coordinate, and the position h of the rail control is the input coordinate. Since g_t of spool fuel pumps significantly depends on the angular velocity ω_n of the crankshaft, then ω_n is the second input coordinate of the fuel equipment [14].

The set of functional diagrams of elements makes it possible to draw up a functional diagram of a combined naturally aspirated internal combustion engine (**Fig. 1**).

The engine operating mode is characterized by the state during operation of a number of parameters, which include N_e is the effective power; M is torque; ω_d is the angular velocity of the crankshaft; g_e is the effective specific fuel consumption; η_e is the effective efficiency, etc.

The operation of the engine in steady state is possible only if the conditions of static equilibrium are met. So, for example, the constancy in time of the angular velocity ω_d in the equilibrium mode is possible if the condition [15] is fulfilled:

$$M - M_c = 0, \tag{1}$$

where M is the torque of the internal combustion engine; M_c is the moment of resistance created by the asynchronous generator (AG).

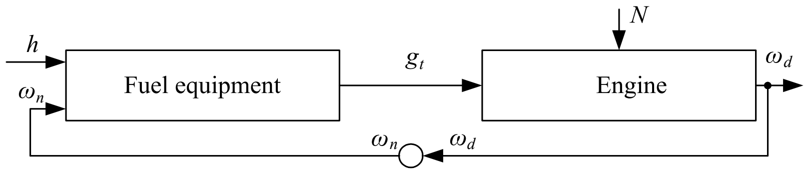


Fig. 1. Functional diagram of an internal combustion engine as a regulated object

The values of the parameters for possible steady-state operating modes of the engine are strictly limited by the strength, thermal and gas-dynamic capabilities. There are certain functional dependencies between the parameters of the engine operation in the steady-state, determined by the theory of engine working processes.When unsteady modes occur, the condition (1) of static equilibrium is violated, as a result of which an excess or insufficient amount of energy appears in the engine. Excess torque due to the violation of condition (1) causes an increase in the angular velocity ω_d, described by a differential equation compiled in accordance with the d'Alembert's principle:

$$J d\omega_d / dt = M - M_c, \tag{2}$$

where J is the reduced moment of inertia of the engine and connected parts.

The moment M_c of the consumer depends on the angular velocity ω_d and the parameters N of the consumer (for example, the power of the AG and the parameters of the load connected to its terminals, the value of the excitation capacitance, etc.), so:

$$M_c = f(\omega_d; N). \tag{3}$$

The torque of the combined engine is determined by the cyclic supply of fuel g_t and the completeness of its combustion. The latter depends on the amount of air entering the combustion chamber. Since in this case the diesel engine is naturally aspirated, the air intake system is selected from the condition of air supply to the cylinders at nominal mode. The amount of air in this case is chosen sufficient for complete combustion of the fuel, as a result of which the engine torque is practically independent of the pressure in the intake manifold in all operating modes. Since the cyclic fuel supply is determined by the position h of the control (rail, throttle) and the angular velocity ω_d of the crankshaft, then:

$$M = f(h; \omega_d). \tag{4}$$

In general, functions (3) and (4) are non-linear, however, for small values of $\Delta\omega$, such a characteristic can be approximated by a linear section by expanding the dependences in a Taylor series. Subsequent linearization makes it possible to obtain dependencies [14]:

$$\Delta M_c = (\partial M_c / \partial\omega_d)\Delta\omega_d + (\partial M_c / \partial N)\Delta N, \tag{5}$$

$$\Delta M = (\partial M / \partial h)\Delta h + (\partial M / \partial\omega_d)\Delta\omega_d. \tag{6}$$

Substituting expressions (5) and (6) into equation (2), one can obtain:

$$J d\omega_d / dt + F_D \Delta\omega_d = (\partial M / \partial h)\Delta h - (\partial M_c / \partial N)\Delta N, \tag{7}$$

or

$$T_D d\phi / dt + k_D \phi = \theta_h \chi - \theta_N \alpha_D, \quad (8)$$

where $F_D = \partial M_c / \partial \omega_d - \partial M / \partial \omega_d$ is the stability factor determined by the imbalance ΔM of the ICE torque and the AGC torque at a given deviation $\Delta\omega_d$ of the angular velocity: if F_D>0, the ICE operation mode is stable, if F_D<0, it is unstable; $\phi = \Delta\omega_d / \omega_{0d}$; $\chi = \Delta h / h_0$; $\alpha_d = \Delta N / N_0$ is the change of the coordinate basis, rel. units; T_D is the time constant of the internal combustion engine; k_D, θ_h, θ_N are dimensionless coefficients.

2. 2. Mathematical model of an all-mode controller

The differential equation of the engine (8) shows that the control element χ of the internal combustion engine can be acted upon using an automatic speed controller (SC). It is possible to measure the change in the controlled parameter itself, i.e. ϕ, and, depending on its value, influence χ – the Polzunov-Watt's principle [14].

Automatic regulators of indirect action contain the following elements: a sensitive element, amplifying and auxiliary elements [15, 16]. At all loads, it is necessary to ensure the exact maintenance of the specified mode, which implies the use of an isodromic regulator with flexible feedback (**Fig. 2**).

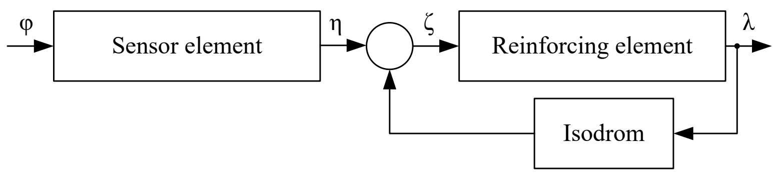


Fig. 2. Functional diagram of an indirect-acting controller with isodromic feedback

2. 2. 1. Servo motor

The equation of motion of the servomotor rod establishes a relationship between the displacements of the control spool ξ and the servomotor rod λ:

$$T_c d\lambda / dt = \xi, \quad (9)$$

where T_c is the time constant of the servomotor, characterizing its inertia (proportional to the working area of the rod). Then the transfer function of the servomotor is:

$$W^{\xi}(p) = 1 / T_c p. \quad (10)$$

As can be seen from equation (10), the servomotor cannot ensure stable operation of the regulator, since at the slightest displacement of the spool from the middle position, the servomotor rod moves to one of its extreme positions until it stops. Therefore, servomotors in regulators are supplemented with stabilizing connections.

2. 2. 2. Mechanical connection: coupling and spool

The dependence between the displacements of the clutch η and the spool ξ has the form:

$$\xi = i_1 \eta, \quad (11)$$

where i_1 is the gear ratio of the lever mechanism from the clutch to the spool.

If the clutch is directly connected to the spool, then $i_1 = 1$.

2. 2. 3. Mechanical connection: servomotor and rail

The dependence between the movements of the servomotor rod λ and the rail of the fuel pump χ:

$$\lambda = -i_2\chi, \tag{12}$$

where i_2 is the gear ratio between the movements of the rack and the servomotor rod.

The «–» sign means that with a positive displacement of the servomotor rod (this correlates with the increase in speed when the load is shed), the rail will move in the direction of decreasing the fuel supply.

2. 2. 4. Isodrom

The dependence between spool displacement ξ and axle box displacement ψ:

$$c^{-1}d\psi / dt(\nu + F_B^2 k^{-1}) + \psi = F_B F_{iz} k^{-1} c^{-1} \lambda d\lambda / dt, \tag{13}$$

or in operator form:

$$(T_{iz} p + 1)\psi = T_{iz} k_{iz} p\lambda,$$

where c – the isodrom spring stiffness; v_{is} – the coefficient of viscous friction; F_B – the area of the axle box; F_{iz} – the area of the driving piston of the isodrom; k – the coefficient of proportionality; T_{iz} – the isodrom time constant; k_{iz} – the coefficient of connection between the displacement of the servomotor rod and the isodrom rod.

2. 2. 5. Sensing element

In the steady state of operation of the internal combustion engine, the governor clutch occupies a certain equilibrium position η_0, corresponding to the frequency of rotation of the governor shaft ϕ_0. At the same time, two equal and oppositely directed forces act on it – restoring E and supporting $A\phi^2$, as well as viscous forces $F_g = -\nu d\eta / dt$ and dry $F_c = -Qd\eta / dt$ friction. The forces of viscous and dry friction have a sign opposite to the speed of the clutch.

All forces are projected onto the selected positive direction and let's write down the equation of motion of the regulator clutch [14]:

$$md^2\eta / dt^2 = A\phi^2 - E - \nu d\eta / dt - Qd\eta / dt, \tag{14}$$

where m is the reduced mass of the sensitive element.

The non-linear force functions (14) are expanded into a Taylor series in the vicinity of the equilibrium point of the clutch η_0 and, leaving only the linear terms of the expansion, let's obtain:

$$md^2\eta / dt^2 + (2E_0)^{-1}\nu d\eta / dt + F_p\eta = 2A_0\phi_0^2\phi - Qsign(d\eta / dt) - E(t), \tag{15}$$

where $F_p = (dE / d\eta)_0 - (dA / d\eta)_0 \phi_0^2$ is the stability factor of the sensing element; $E_0 = A_0\phi_0^2$ is the equilibrium condition.

From the clutch equilibrium condition, there is $2A_0\phi_0^2 = 2E_0$. Index «0» means equilibrium. Dividing both parts of the equation by $2E_0$, the equation for the movement of the governor clutch is obtained:

$$\begin{aligned}(2E_0)^{-1} md^2\eta / dt^2 + (2E_0)^{-1}\nu d\eta / dt + (2E_0)^{-1} F_p\eta = \\ = \phi - (2E_0)^{-1} Qsign(d\eta / dt) - (2E_0)^{-1} E(t),\end{aligned} \tag{16}$$

or in operator form:

$$T_p^2 p^2\eta + T_k p\eta + \delta_z\eta = \theta_\omega\phi - \theta_p\alpha_p,$$

where T_p – the time constant of the sensitive element; T_k – the time constant of the cataract, which characterizes the forces of hydraulic friction of the regulator; δ_z – local level of unevenness;

η – movement of the coupling of the sensitive element; ϕ – the speed of the crankshaft of the internal combustion engine; α_p – movement of a slat of the control lever; θ_p – amplification factor for setting the speed mode; $\theta_{\omega is}$ – the coefficient of connection between the displacement of the clutch and the rotational speed.

The block diagram of the system of automatic speed control (ACS) of rotation of the internal combustion engine is shown in **Fig. 3**.

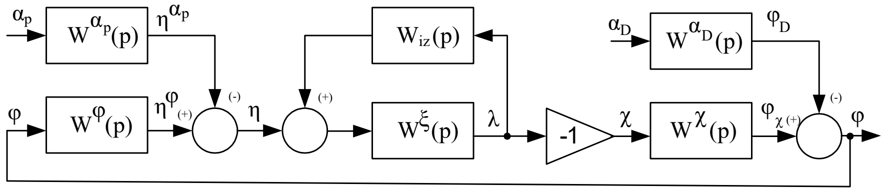


Fig. 3. Structural diagram of the automatic control system of the internal combustion engine

2. 3. Mathematical model of an asynchronous generator complex

The voltage equilibrium equations for the windings of the stator and rotor phases of an asynchronous machine in matrix form have the form [17–21]:

$$d[\Psi_s]/dt=[u_s]-[R_s][i_s],$$

$$d[\Psi_r]/dt=[u_r]-[R_r][i_r]+j\omega[\Psi_r], \tag{17}$$

where $[u_s]=\begin{bmatrix}u_A & u_B & u_C\end{bmatrix}^T$, $[u_r]=\begin{bmatrix}u_a & u_b & u_c\end{bmatrix}^T$ are transposed matrices of instantaneous values of stator and rotor phase voltages, respectively; $[i_s]=\begin{bmatrix}i_A & i_B & i_C\end{bmatrix}^T$, $[i_r]=\begin{bmatrix}i_a & i_b & i_c\end{bmatrix}^T$ are the transposed matrices of instantaneous values of currents in the stator and rotor phases, accordingly; $[\Psi_s]=\begin{bmatrix}\Psi_A & \Psi_B & \Psi_C\end{bmatrix}^T$, $[\Psi_r]=\begin{bmatrix}\Psi_a & \Psi_b & \Psi_c\end{bmatrix}^T$ – transposed matrices of full flux linkages of phase windings of the stator and rotor, accordingly;

$$[R_s]=\begin{bmatrix}R_s & 0 & 0\\ 0 & R_s & 0\\ 0 & 0 & R_s\end{bmatrix}$$

– the matrix of active resistances of the stator windings;

$$[R_r]=\begin{bmatrix}R_r & 0 & 0\\ 0 & R_r & 0\\ 0 & 0 & R_r\end{bmatrix}$$

– the matrix of active resistances of the rotor windings; ω – electrical rotation frequency.

The expressions for the stator flux are:

$$\begin{aligned}\psi_A&=L_Ai_A+M_{AB}i_B+M_{AC}i_C+M_{Aa}i_a\cos\gamma+M_{Ab}i_b\cos(\gamma+2\pi/3)+M_{Ac}i_c\cos(\gamma-2\pi/3),\\ \psi_B&=L_Bi_B+M_{BA}i_A+M_{BC}i_C+M_{Bb}i_b\cos\gamma+M_{Bc}i_c\cos(\gamma+2\pi/3)+M_{Ba}i_a\cos(\gamma-2\pi/3),\\ \psi_C&=L_Ci_C+M_{CA}i_A+M_{CB}i_B+M_{Cc}i_c\cos\gamma+M_{Ca}i_a\cos(\gamma+2\pi/3)+M_{Ab}i_b\cos(\gamma-2\pi/3),\end{aligned} \tag{18}$$

for the rotor:

$$\begin{aligned}\psi_a&=L_ai_a+M_{ab}i_b+M_{ac}i_c+M_{aA}i_A\cos\gamma+M_{aC}i_C\cos(\gamma+2\pi/3)+M_{aB}i_B\cos(\gamma-2\pi/3),\\ \psi_b&=L_bi_b+M_{ba}i_a+M_{bc}i_c+M_{bB}i_B\cos\gamma+M_{Ba}i_A\cos(\gamma+2\pi/3)+M_{bC}i_C\cos(\gamma-2\pi/3),\\ \psi_c&=L_ci_c+M_{cb}i_b+M_{ca}i_c+M_{cC}i_C\cos\gamma+M_{cB}i_B\cos(\gamma+2\pi/3)+M_{cA}i_A\cos(\gamma-2\pi/3),\end{aligned} \tag{19}$$

where γ – the angle between the axes of the windings «A» and «a»; L_A, L_B, L_C – inductance of the stator phases; L_a, L_b, L_c – rotor phase inductances; M_{AB}, M_{AC}, ... – mutual inductances between the stator windings; M_{ab}, M_{ac}, ... – mutual inductances between the rotor windings; M_{Aa}, M_{Ba}, ... – mutual inductances between the stator and rotor windings.

According to the accepted assumptions about the symmetry of the rotor and stator windings, the expression will take the form:

$$R_A = R_B = R_C = R_s;\; R_a = R_b = R_c = R_r;\; L_A = L_B = L_C = L_s;$$

$$L_a = L_b = L_c = L_r;$$

$$M_{AB} = M_{BA} = M_{BC} = M_{CB} = M_{CA} = M_{AC} = M_1;$$

$$M_{ab} = M_{ba} = M_{bc} = M_{cb} = M_{ca} = M_{ac} = M_2;$$

$$M_{Aa} = M_{aA} = M_{Ba} = ... = M_{12}.$$

Taking into account the symmetry condition of the stator currents, the magnetic flux of phase A (only a part of the total flux associated with the stator phase is considered in the case when the stator windings are open):

$$\psi_A = L_s I_A + M_1(I_B + I_C) = I_A(L_s - M_1) = I_A(L_{s\sigma} + L_{s\mu} - M_1) = L_s I_A, \tag{20}$$

where $L_{s\sigma}$, $L_{s\mu}$ – inductance of the stator phase winding from the stray field and the main flow field; $M_1 = L_{s\mu}\cos(2\pi/3) = L_{s\mu}/2$ – mutual inductance between any two stator windings (taking into account their spatial position); $L_s = L_{s\sigma} + 3L_{s\mu}/2$ – total equivalent inductance of the stator phase, including the inductance from the stray field and from the main flux created by the current of the stator winding itself.

Similarly for phases B and C of the stator:

$$\psi_B = L_s I_B,\; \psi_C = L_s I_C, \tag{21}$$

and for the phases of the rotor:

$$\psi_a = L_r I_a,\; \psi_b = L_r I_b,\; \psi_c = L_r I_c, \tag{22}$$

where $L_r = L_{r\sigma} + 3L_{r\mu}/2$ – the total equivalent inductive inductance of the rotor phase, including the inductance from the stray field, from the main winding created by the current and from the flows arising under the action of the currents of the other two rotor windings.

Taking into account the reduction of the rotor winding to the number of turns of the stator winding, the equation will take the form:

$$3L_{s\mu}/2 = 3L_{r\mu}/2 = 3M_{12}/2 = L_\mu, \tag{23}$$

where L_μ – the equivalent mutual inductance.

To take into account the saturation of the magnetic circuit, the dependence of the mutual inductance parameter $L_{s\mu}$ from the magnetizing current i_μ:

$$L_\mu = 1/(a + b i_\mu^2), \tag{24}$$

where a, b – the approximation coefficients of the magnetization curve.

The magnetizing current i_μ of the AGC is determined through the components $i_{\mu A}$, $i_{\mu B}$, $i_{\mu C}$ along the corresponding axes of the stator phases:

$$i_\mu = \sqrt{2(i_{\mu A}^2 + i_{\mu B}^2 + i_{\mu C}^2)/3}, \tag{25}$$

where

$$i_{\mu A} = i_A - (i_B + i_C)/2 + 3i_a/2,\ i_{\mu B} = i_B - (i_A + i_C)/2 + 3i_b/2,$$

$$i_{\mu C} = -i_{\mu A} - i_{\mu B} = i_C - 3(i_A + i_B) - 3(i_a + i_b)/2.$$

To implement the AGC excitation mode, capacitors are included in the stator circuit. Therefore, as the voltage $[u_s]$ of the power supply, the voltage drop through the capacitors for all three phases of the generator stator should be substituted [22]:

$$[u_s] = (-1/C)\int_0^t [i]dt + [u_0], \tag{26}$$

where $[i] = [i_{cA} \quad i_{cB} \quad i_{cC}]^T$ is the transposed matrix of the instantaneous values of the currents that flow in the capacities; $[u_0] = [u_{0A} \quad u_{0B} \quad u_{0C}]^T$ is the transposed matrix of instantaneous values of phase voltages at the initial moment of time $t = t_0$; C – the capacitance of the excitation capacitors.

The equation of motion of the AGC has the form:

$$d\omega_m / dt = (M - M_G)/J, \tag{27}$$

where ω_m is the mechanical frequency of rotation of the AGC (determines the electrical frequency of rotation of the rotor $\omega = p\omega_m$, where p is the number of pairs of poles); J is the moment of inertia of the part; M, M_G is the torque of the internal combustion engine and the electromagnetic torque of the AGC. Electromagnetic moment of AGC:

$$M_G = pL_\mu[(i_{\mu B} - i_{\mu C})i_A + (i_{\mu C} - i_{\mu A})i_B + (i_{\mu A} - i_{\mu B})i_C]/\sqrt{3}. \tag{28}$$

The general view of the developed model in the Matlab package is shown in **Fig. 4**. In more detail, all the components of the LAPS, according to the above equations, are shown in **Fig. 5–9**. The «Diezel» subsystem contains a mathematical model of the internal combustion engine itself (**Fig. 5, *a***), as well as a mechanical interface system with the shaft of an asynchronous generator (**Fig. 5, *b***).

The subsystem «AG» (**Fig. 6**) implements a mathematical model of an asynchronous machine in three-phase coordinates, operating in a generator mode.

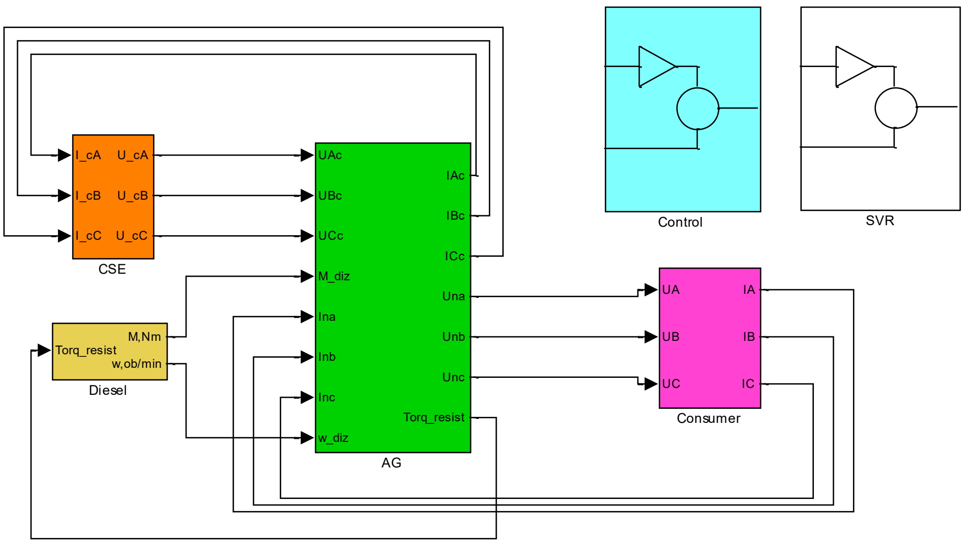


Fig. 4. General view of the mathematical model of a local autonomous power supply source in the Matlab package

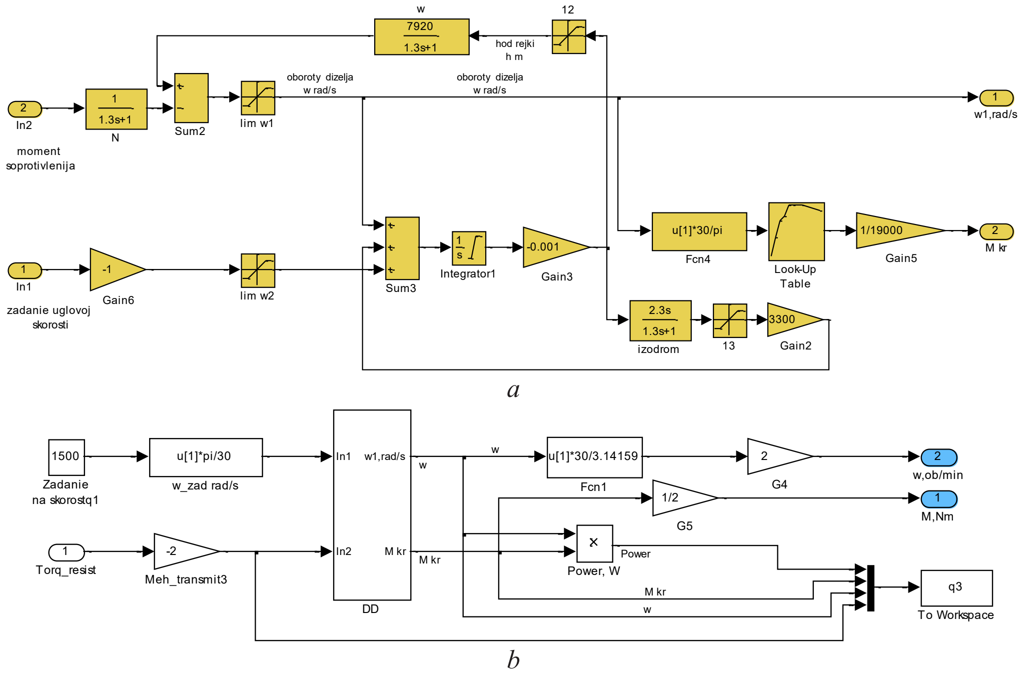


Fig. 5. «Diesel» subsystem: drive engine: *a* – internal combustion engine; *b* – mechanical interface with the shaft of an asynchronous generator

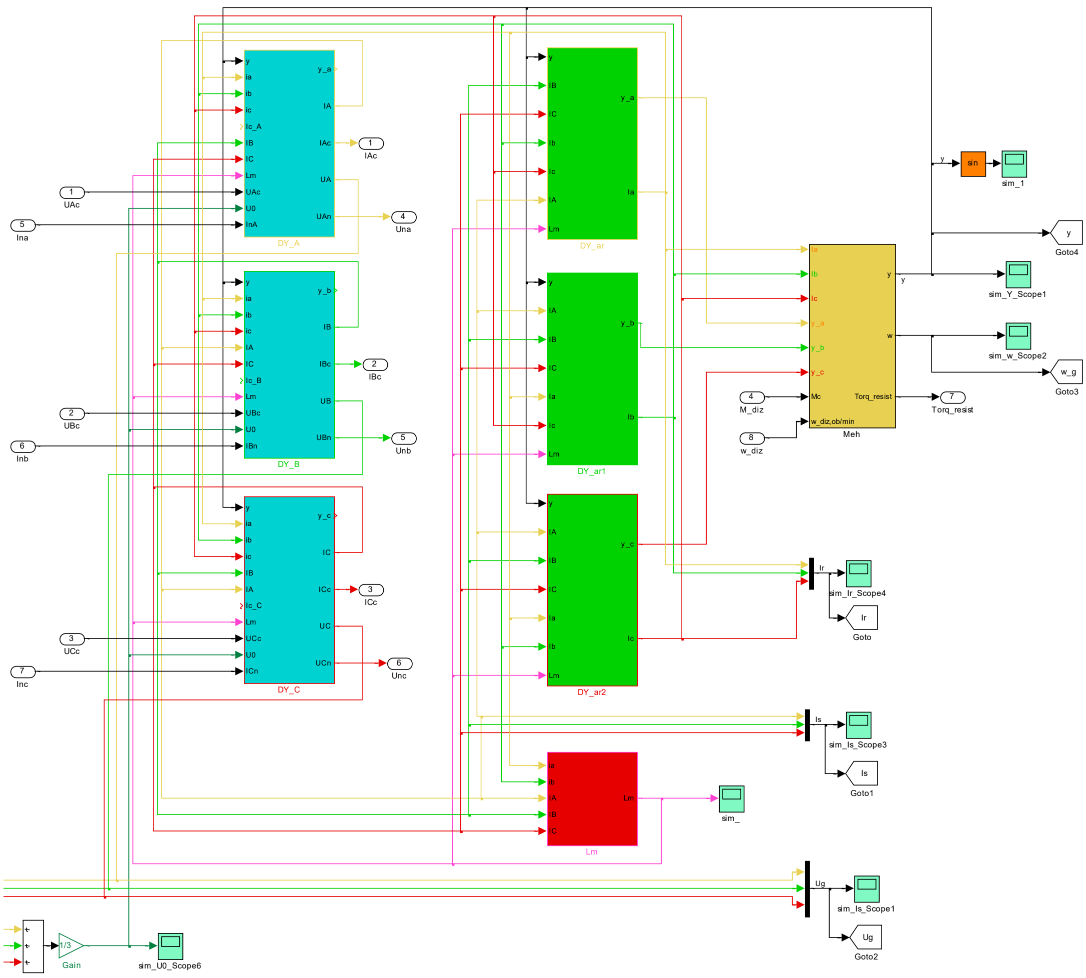


Fig. 6. «AG» subsystem: asynchronous generator

The «CSE» subsystem (**Fig. 7**) contains a mathematical model of a capacitor bank, which makes it possible to implement the self-excitation mode of an asynchronous machine and thereby transfer it to the generator mode.

In the «Consumer» subsystem (**Fig. 8**), it is possible to connect to the terminals of the AGC various types of consumers, both AC and DC, connected through converters. The connection of consumers can be both single and group, which has already been presented by the authors in [22–26].

The «Control» subsystem (**Fig. 9**) was created for the convenience of visualizing the calculation procedure and consists of Matlab package oscilloscopes grouped into two blocks – characteristics of an asynchronous generator with capacitive self-excitation «GENERATOR» and characteristics of connected consumers «LOAD».

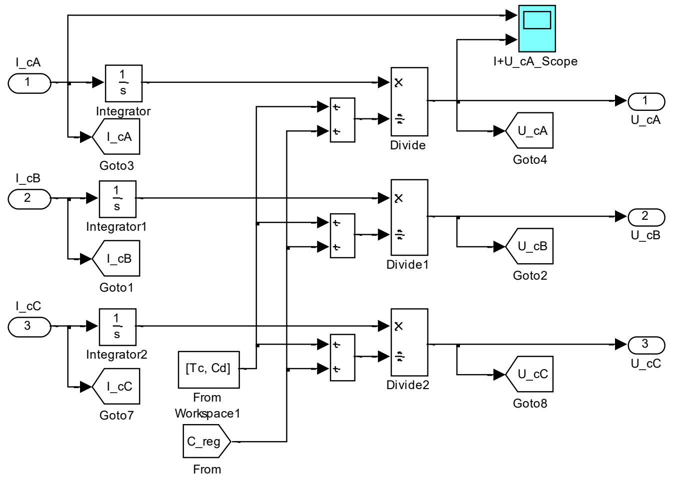


Fig. 7. «CSE» subsystem: generator self-excitation capacitances

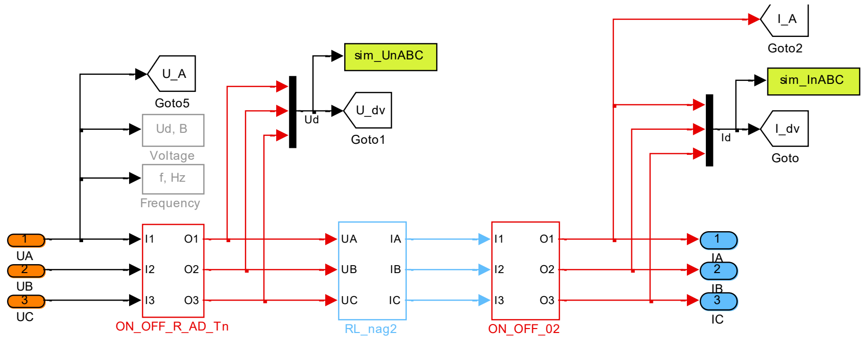


Fig. 8. «Consumer» subsystem: connection/disconnection of various kinds of consumers

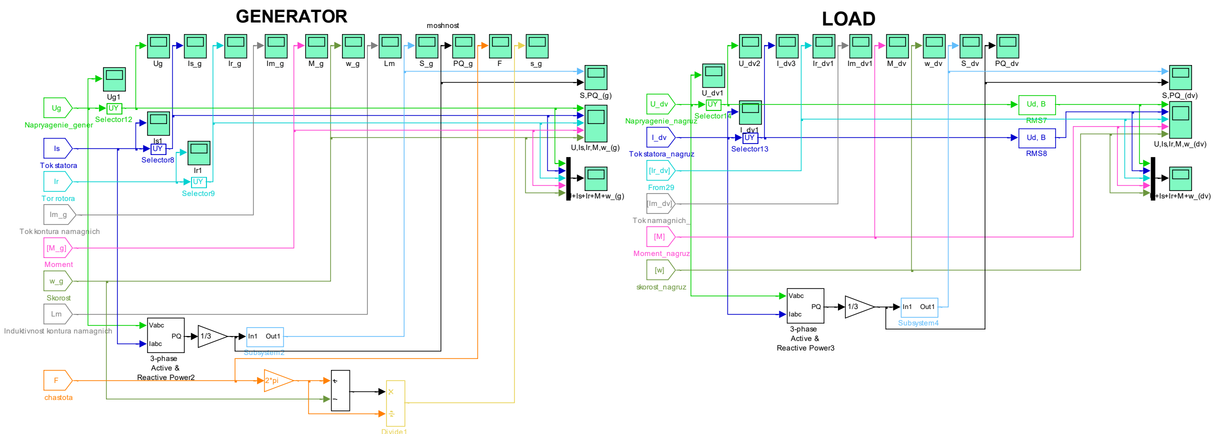


Fig. 9. «Control» subsystem: visualization of calculation processes

3. Results and discussion

The mathematical model of the AGC output voltage stabilization system («SVR» subsystem) is not given, since both its mathematical description and technical implementation are described in detail in [23].

When modeling the operating modes, an internal combustion engine was used, which is used in DALGAKIRAN DJ diesel generator power plants with the parameters given in **Table 1**. As a source of electrical energy, an asynchronous motor of the AIR120A4 type was used (**Table 2**), operating in a generator mode with an initial capacitive self-excitation $C = 30$ μF.

Table 1

Specifications DE

Model	DJ 4000 DG–ECS
Type	Air-cooled single cylinder
Max Power	7.0 kVA
Rotation frequency	3000 rpm
Volume	418 cm^3
Power reserve – tank capacity	240 g/kW – 16 l

Table 2

Parameters of an asynchronous machine type AIR120A4

Parameter	Meaning
Nominal power, P_G	1200 W
Nominal voltage, U_g	220 V
Nominal speed, n_n	2900 rpm
Nominal current, I_s	2.9 A
Stator active resistance, R_s	9.37 ohm
Stator inductive reactance, X_s	7.03 ohm
Reduced active resistance of the rotor, R_r	5.13 ohm
Reduced inductive resistance of the rotor, X_r	6.5 ohm

In **Fig. 10−12** the characteristics of LAPS obtained with the help of the developed mathematical model are presented. **Fig. 10** shows the dynamic characteristics of the internal combustion engine (**Fig. 10**, ***a***) when the load (**Fig. 10**, ***b***) is connected – AGC with subsequent connection to it of a consumer with an RLC character. At the sixth second after the start of the internal combustion engine, the connection of the AGC to the internal combustion engine shaft by means of an absolutely rigid coupling was simulated. At time $t_{on} = 7$ s, the mode of connection to the terminals of the RLC-load generator was simulated, and at time $t_{off} = 12$ s, the load was switched off. In **Fig. 10**, the following designations are adopted: power P_{dizel}, rotational speed ω_d, diesel engine torque M_{kr}, and drag moment M_G. Characteristics in **Fig. 10** are shown on the following scales: $P_{dizel} = 1/100$; $\omega_d = 1/8$; $M_{cr} = 1/2$; $M_c = 1/1$.

Fig. 11 shows the characteristics that demonstrate the operation of the diesel speed controller, where ω_z, ω_d are the set and actual speeds of the internal combustion engine, h is the stroke of the internal combustion engine fuel rail. Characteristics in **Fig. 11** are presented in the following scales: $\omega_z = 1/8$; $\omega_d = 1/8$; $h = 1500/1$.

An analysis of the obtained characteristics showed that the RFD fully compensates for the static error of speed control.

Fig. 12, **13** show the effective and instantaneous voltage values (scale: $U_g = 1/30$) and currents flowing in the AGC at idle and connected to 0.7 s consumers with active (**Fig. 12**, $R_d = 30$ Ohm) and active-inductive (**Fig. 13**, R_d = 30 Ohm L_d = 15 μH) of the load, as well as the disconnection of these consumers at times t = 1.2 with active and, in view of the longer transition process, t = 1.5 with active-inductive load characteristics.

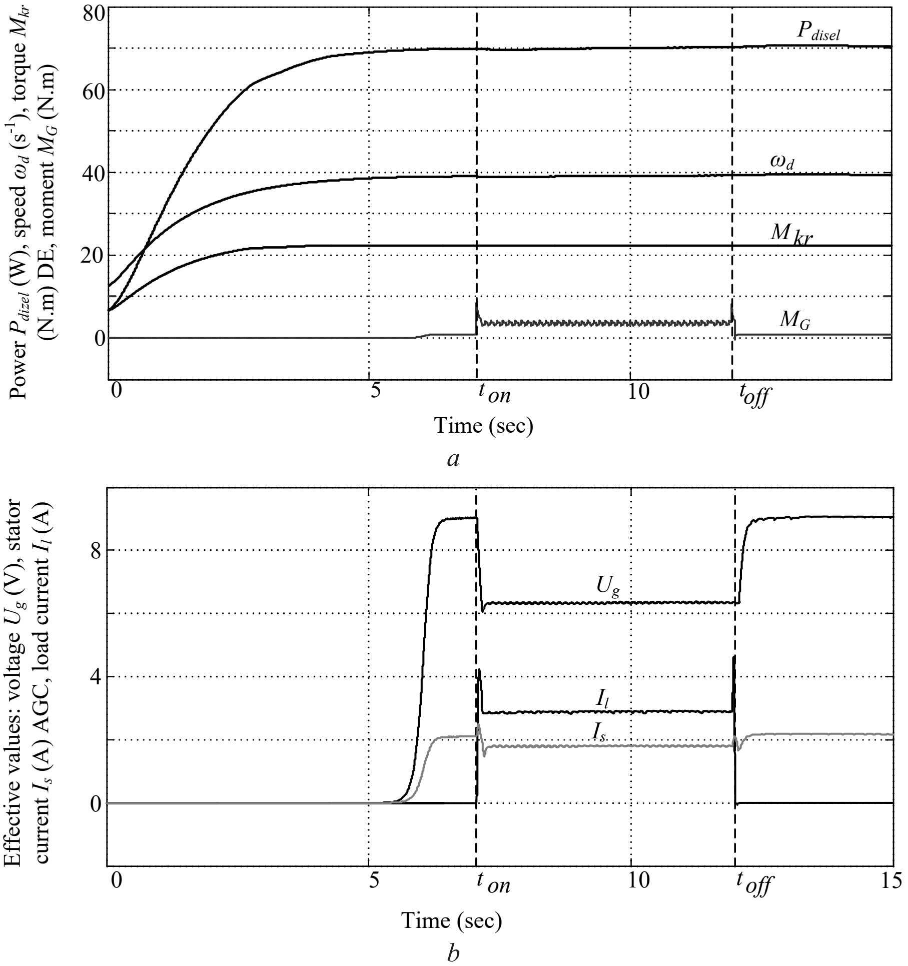


Fig. 10. Dynamic characteristics of a local autonomous source of power supply: a – internal combustion engine; b – asynchronous generator complex with RLC load

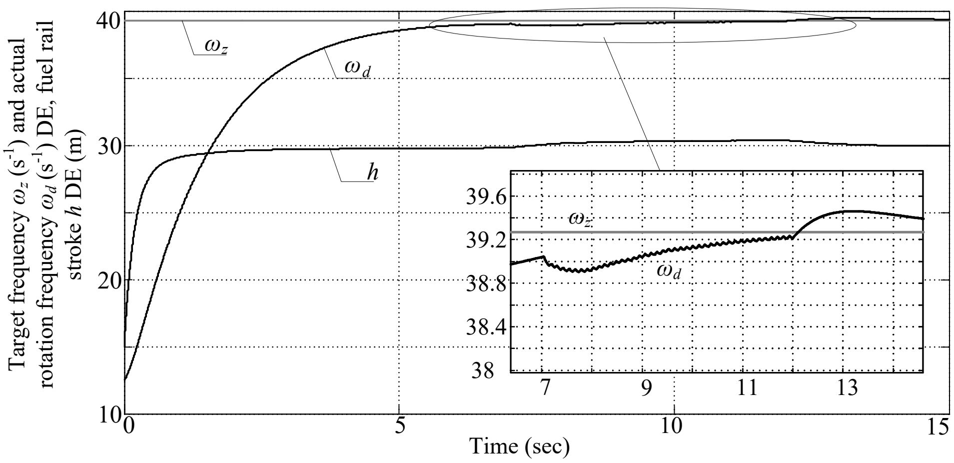


Fig. 11. Stabilization of the rotational speed of the internal combustion engine

An experimental study of the characteristics of an autonomous power supply built on the basis of an asynchronous motor operating in a generator mode was carried out on a laboratory facility, the appearance of which is shown in **Fig. 14**.

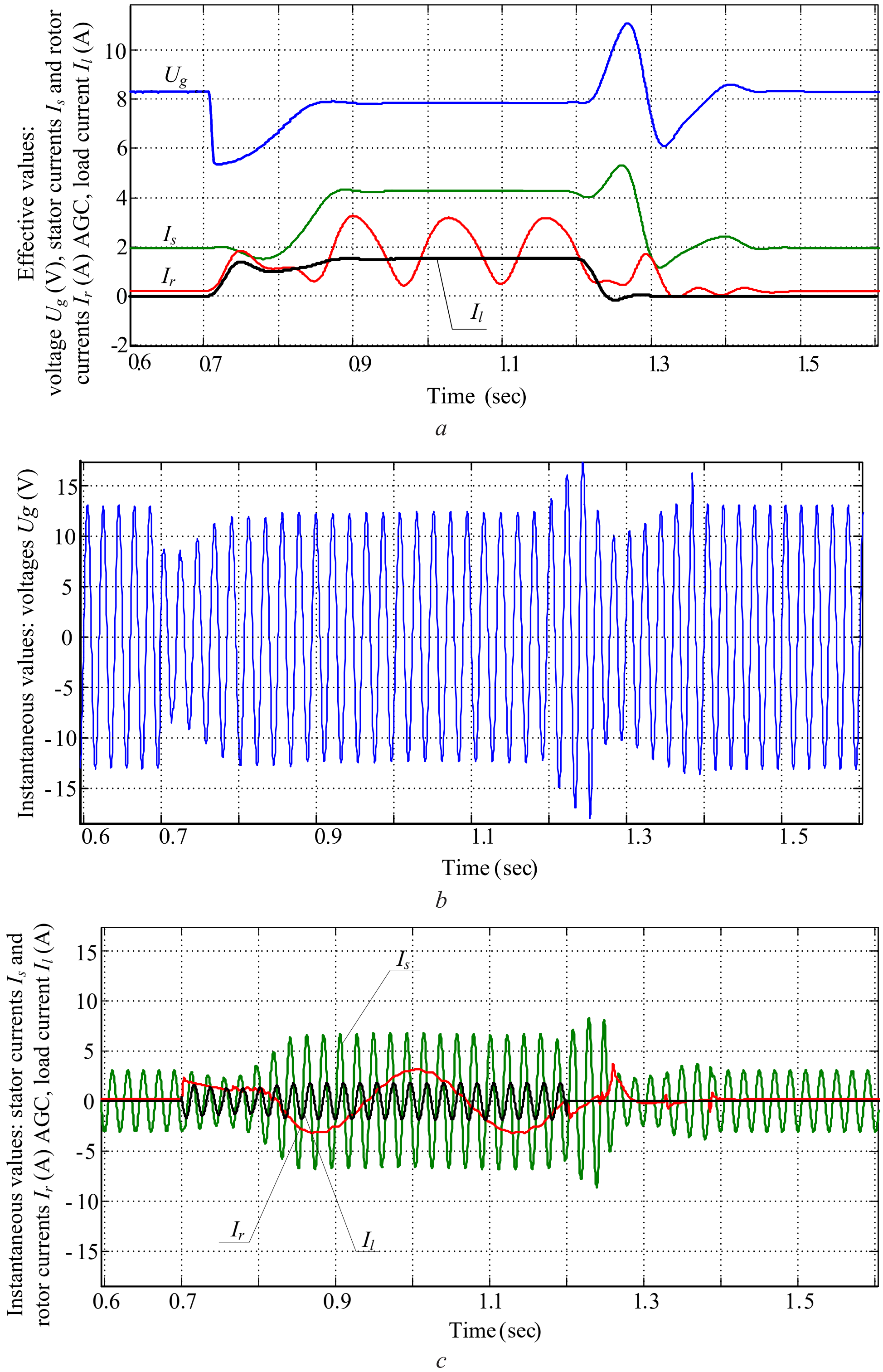


Fig. 12. Time diagrams of voltage, stator and rotor currents of AGC and a consumer with an active nature of the load for: *a* – effective values; *b, c* – instantaneous values voltage and currents

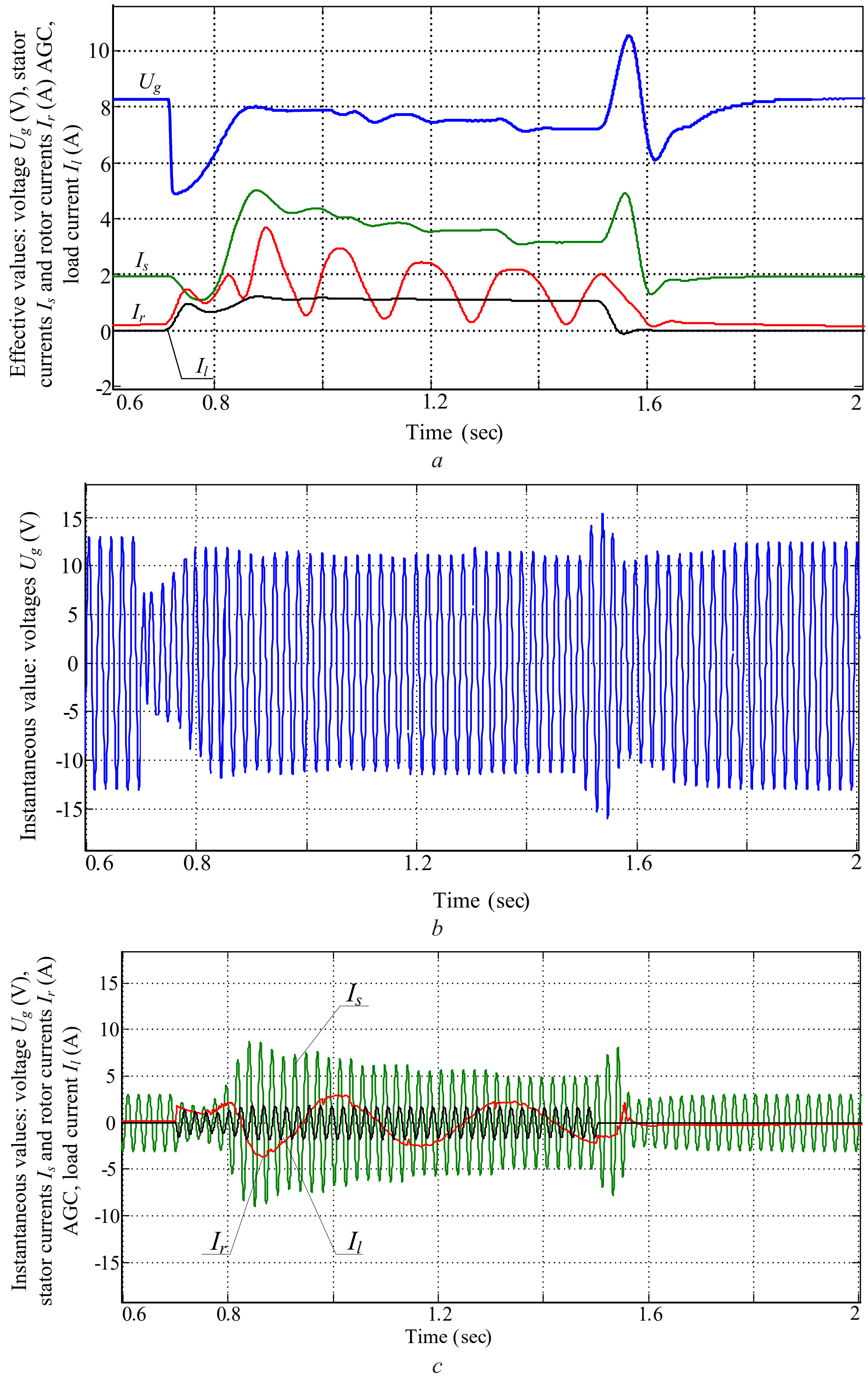


Fig. 13. Time diagrams of voltage, currents of the stator and rotor of the AGC and the consumer with an active-inductive nature of the load (cosϕ = 0.9) for: *a* – effective values; *b*, *c* – instantaneous values voltage and currents

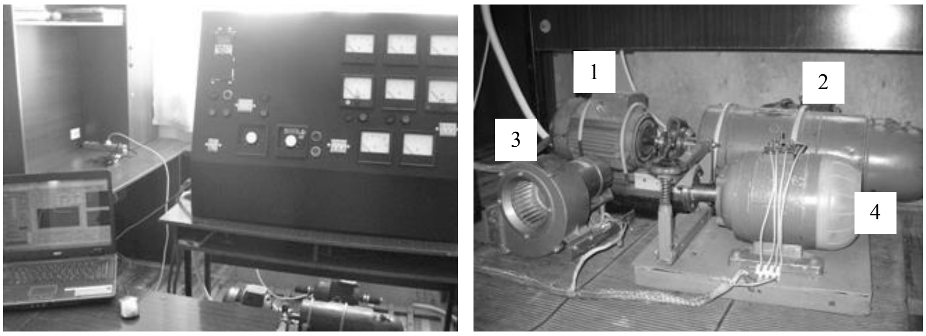
The main part of the facility is an asynchronous machine and a drive motor mounted on a frame. A three-phase asynchronous motor (1) was used as a generator, the nominal parameters of which are given in **Table 2**. A DC motor (2) with independent excitation was used as a drive motor. The change in the speed of rotation of the AGC rotor was carried out by changing the supply voltage of the DC by a thyristor converter. The facility provides for connection to the AGC of various consumers of AC and DC electricity:

– a consumer with an active load – lighting devices (not shown in **Fig. 14**);

– motor load – asynchronous motors (**Fig. 14**, ***b*** – 3 and 4) of various power with active and fan resistance moments on the shafts;

– rectifier load of two types – a resistor with adjustable resistance and a DC with an active resistance moment on the shaft (on **Fig. 14**).

To visualize the dynamic processes occurring in the DC-AGC-consumer system, the experimental laboratory setup is equipped with a block of current and voltage sensors based on the Hall effect and a data acquisition device of the National Instruments USB 6009 type with the ability to connect to a personal computer (**Fig. 14**, ***a***).



a *b*

Fig. 14. Experimental laboratory setup: *a* – appearance of the front panel of the setup; *b* – the main electrical machines of the facility

The adequacy of the developed mathematical model is confirmed by direct comparison of the results of the calculated characteristics (**Fig. 15**, ***a***) with the experimental ones (**Fig. 15**, ***b***) of the AGC self-excitation process (scale: U_g = 1/30).

In **Fig. 15** the results of mathematical modeling are fully confirmed by experimental machine diagrams both in the steady state (amplitude values of the voltage) and in transient modes (the nature of the flow and the time of the transient process) are shown. In contrast to the calculated characteristic of the AGC voltage, fluctuations in the amplitude values are observed on the experimental curve U_g. This is due to the influence of the AGC parameters on the characteristics of the drive DC, which operates without a speed stabilization system. In addition, during the tests, six out of eight channels of the USB 6009 data acquisition device were used, which required a significant reduction in the frequency of polling the module channels and, accordingly, led to the presence of distortions in the current and voltage signals (**Fig. 15**, ***c***).

Fig. 16 shows the experimental curve of the output voltage of one phase of the AGC when a load is connected in the form of lighting devices with a power of 300 W.

The resulting curve confirms the results of the previously given mathematical modeling **(Fig. 12)** on the presence of damped voltage oscillations. Due to their attenuation, the effect of partial restoration of the AGC voltage after the connection of electrical energy consumers is observed.

The model of a diesel engine makes it possible to study modes at a variable speed and can be integrated into any model of an autonomous energy complex to search for and develop effective control algorithms. This provides the required stabilization of the rotational speed, power output and reduction in fuel consumption. The model of an asynchronous generator complex allows to explore the modes of self-excitation, load modes of operation in both normal and emergency modes. This makes it possible to determine the overload capacity, qualitative and quantitative indicators of the generated electricity, as well as to develop systems for reactive power compensation and stabilization of the output parameters of the complex.

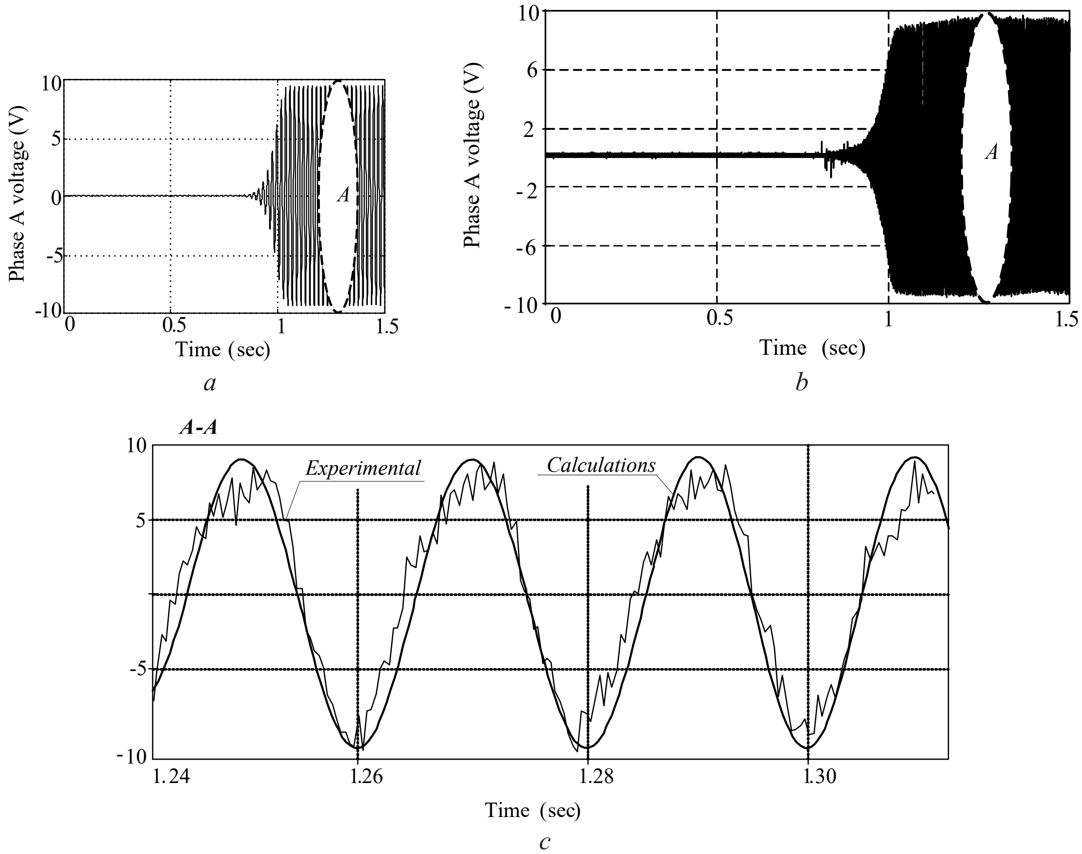


Fig. 15. Instantaneous voltage values of an asynchronous generator complex during self-excitation: *a* – mathematical calculations; *b* – experimental studies; *c* – combined range A

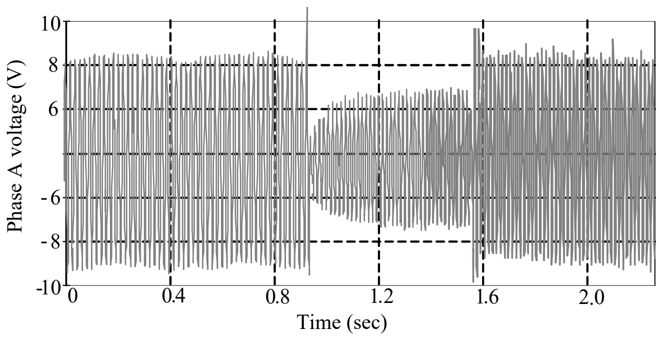


Fig. 16. Experimental voltage curve at the AGC clamps when connecting/disconnecting the load

The constructed mathematical model of the autonomous power source being formed on the basis of a diesel generator set provides an adequate reproduction of the performance characteristics of all its components. The model allows to perform research for various types of diesel engines of non-turbocharged vehicles, as well as three-phase asynchronous general purpose machines with a rigid connection of their shafts, as well as various consumers of electrical energy connected to the terminals of an electric generator. The created model is convenient for solving optimization problems and developing control systems, monitoring and diagnosing the state of electrical equipment, as it combines algorithmic simplicity and high computational precision.

4. Conclusions

A mathematical model of a diesel generator set is proposed, which with sufficient precision for designing displays the processes in an asynchronous generator with capacitor self-excitation.

The model of the drive internal combustion engine is supplemented with an automatic shaft speed controller and a block for setting the dependence of the mechanical torque on the speed and fuel consumption for a specific type of engine. The use of a three-phase coordinate system in the synthesis of a mathematical model of an asynchronous generator complex made it possible to unify the mathematical representation of various types of consumers that are connected to its terminals. The adequacy of the proposed mathematical model with sufficient precision for engineering calculations was confirmed by a direct comparison of the simulation results and full-scale tests on a laboratory facility.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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