Methods of information systems synthesis

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PARAMETRIC SYNTHESIS OF THE DIGITAL REGULATOR OF THE DIESEL GENERATOR SET FOR INDUSTRIAL PURPOSE

Abstract. The object of research is the dynamic processes of high-quality electric power generation by a diesel generator set (DGS) with a digital fuel supply regulator. **The subject of research** is the methodology of choosing varied parameters of the digital fuel supply regulator, which ensure high stability of the frequency of the generated voltage in conditions of a wide range of changes in the external load on the part of electric energy consumers. **The results obtained**. A mathematical model of the disturbed motion of the diesel generator set was developed and varied parameters of the digital fuel supply regulator were determined. With the application of the combined algorithmic optimization method, which is a combination of the Sobol grid method and the Nelder-Mead method, in the plane of the varied parameters of the regulator, the values of these parameters were found, which deliver a minimum to the integral quadratic functional, which is a quantitative indicator of the degree of non-uniformity of the digital fuel supply regulator of the DGS. **Conclusions.** The use of a digital electronic fuel supply regulator instead of a hydromechanical regulator in a diesel of DGS significantly improves the quality of generated electricity relative to the stability of the three-phase voltage frequency at the output of the diesel generator set.

Keywords: diesel generator set; digital fuel supply regulator of diesel; frequency of three-phase voltage; Sobol grids; set of allowable values of varied parameters of regulator.

Introduction

Literary review and problem statement. The widespread use of small energy in the economy of various countries has led to the intensive production of mini-power plants, among which diesel generator sets (DGS) predominate Used in individual farms, rotational camps, as well as in emergency situations when there is a sudden cessation of power supply to populated areas and social facilities due to natural disasters or military operations, stationary and mobile mini-power plants usually have a power ranging from 50 to 1000 kW. The most widely represented on the world market are diesel generator sets from Matari (Japan), DG and Wilson (UK), Gummins Power and Caterpiller (USA), WFM (Italy), Benza (Spain), Kipor and Ming Powers (China), Dalga Kiran and TEKSAN (Turkey). A wide range of diesel generator sets is offered by the company Diesel System (RF), which uses YaMZ, TMZ and MMZ transport diesel engines with power from 12 to 600 kW in its diesel generator sets. Ukraine is represented on the global diesel generator market by the companies Darex Energy and Centaur, which use Chinese-made Ricardo diesel engines with a capacity from 12 to 1200 kW in their mini-power plants, as well as by the State Enterprise "Malyshev Plant", which produces stationary and mobile mini-power plants DGU-200 and DGU- 315 based on deforced tank diesel engines 5TDF and 6TD-1, respectively [1].

The rated power of the 5TDF diesel engine is 515 kW, and the rated power of the 6TD-1 diesel engine is 735 kW at an angular speed of the crankshaft of 293 s^{-1}. The maximum angular velocity of the crankshaft of both diesel engines is 314 s^{-1}, which corresponds to a rotation speed of 50 Hz. The difference between the nominal and maximum angular speed of the crankshaft is due to the use of a hydromechanical all-mode fuel supply regulator with a centrifugal sensing element on 5TDF and 6TD-1 diesel engines. Such a regulator has a high degree of unevenness, determined by the angle of inclination of the regulatory characteristic of the serial 5TDF diesel engine (Fig. 1).

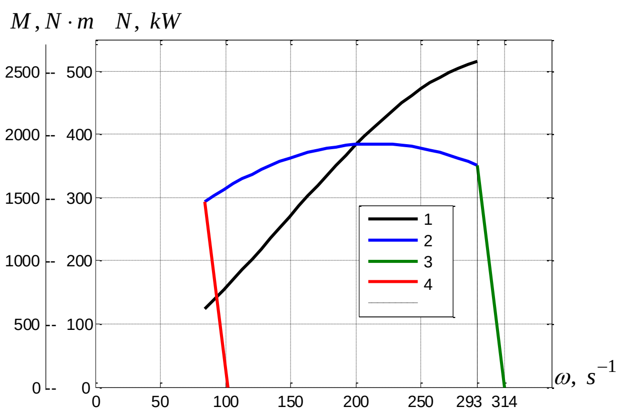

Fig. 1. Characteristics of the serial 5TDF diesel engine: 1 – external power characteristic; 2 – external moment characteristic; 3 – limiting regulatory characteristic; 4 – characteristic of idle speed

The nominal angular speed of the crankshaft $\omega_N = 293\, rad \cdot s^{-1}$ corresponds to the point of maximum power $N_{\max} = 515\, kW$, and the maximum permissible angular speed of the crankshaft, determined by the setting of the all-mode fuel regulator, is $\omega_{\max} = 314\, rad \cdot s^{-1}$.

Then the degree of unevenness of the hydromechanical fuel supply regulator, determined by the formula [2] $\delta = \frac{\omega_{\max} - \omega_N}{\omega_N}$ is $\delta = 0,07$.

This means that the frequency of the voltage generated by the diesel generator set can decrease by an amount of Δf with increasing electrical load, and

$$\Delta f = f_N \cdot \delta = 3,5\ Hz .$$

One of the main requirements for the quality of electrical energy is the stability of the frequency of the generated alternating current voltage. It is clear that serial tank diesel engines 5TDF and 6TD-1 with a hydromechanical all-mode fuel supply regulator with a high degree of unevenness cannot be used in special diesel generator sets used to supply power to medical institutions, where high quality electricity is required for power of high-precision medical equipment, for power supply to industrial facilities that use complex technological equipment in the production process, or social facilities with complex household appliances.

At the end of the last century, a prototype of an analog electronic all-mode fuel supply regulator was created at the Kharkov Engine Design Bureau for engines of the TD family, which was installed on experimental tank diesel engines 5TDF and 6TD-1 [3]. Sea trials of the T-80UD tank with the experimental 6TD-1 diesel engine showed a significant increase in the traction and fuel-economic characteristics of the tank, the diesel engine of which was equipped with an electronic fuel supply regulator. This increase is primarily due to the fact that a diesel engine with an electronic fuel supply regulator has a very low degree of unevenness, the value of which is $\delta = 0,01$ and even lower. This means that when using a diesel generator set with an electronic fuel supply regulator, an increase in the electrical load causes a decrease in the frequency of the generated voltage to no more than 49.5 Hz, which is quite acceptable.

In addition to the degree of unevenness of the fuel supply regulator of diesel as part of a diesel generator set, the quality of the generated electricity is influenced by the magnitude of the delay between the time of the start of an increase or decrease in the electrical load at the output of the diesel generator set and the time of the start of the corresponding change in the traction torque of the diesel engine [4,5].

The service life of tank diesel engines 5TDF and 6TD-1 is 500–600 hours before major overhaul. This is clearly not enough for use in diesel generator sets with a long service life. In this regard, these engines are deforced in terms of developed torque by 2.5 times, which makes it possible to extend their service life to 1200–1500 hours before major overhaul. Thus, in the DGU-200, the developed power of the deforced 5TDF diesel engine is 200 kW, and in the DGU-315, the power of the deforced 6TD-1 diesel engine is 315 kW. The characteristics of the deforced 5TDF diesel engine with electronic fuel supply regulator are shown in Fig. 2.

From the analysis of Fig. 2 it follows that the regulatory characteristics of a diesel engine with an electronic fuel supply regulator are almost vertical, which means high accuracy in maintaining the nominal angular velocity of the diesel crankshaft

$$\omega_N = 314\ rad \cdot s^{-1}$$

and, consequently, the frequency of the voltage generated by the diesel generator set.

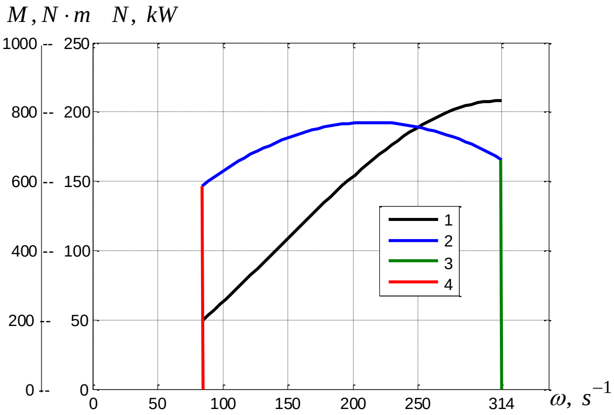

Fig. 2. The characteristics of the deforced 5TDF diesel engine with electronic fuel supply regulator: 1 – external power characteristic; 2 – external moment characteristic; 3 – limiting regulatory characteristic; 4 – characteristic of idle speed

The purpose of this article is to select the optimal values of the varied parameters of the digital fuel supply regulator, ensuring the minimum deviation of the frequency of the generated voltage from its nominal value under conditions of changes in the electrical load at the output of the diesel generator set.

Main material

Functional diagram of the diesel generator set. The functional diagram of the digitally controlled diesel generator set is shown in Fig. 3. The control object is a diesel generator set, which is a combination of diesel engine 1 with a fuel pump rack 2 and a synchronous generator 3, and the diesel crankshaft is rigidly fixed to the generator rotor. Synchronous generator 3 contains the winding of independent excitation 5. The automatic control system of the diesel generator set is double-circuit, containing internal and external control loops. The internal circuit contains a voltage sensor 17 and a voltage regulator 4, designed to regulate the output voltage of the synchronous generator 3 when the consumer's electrical load changes by changing the current value in the excitation winding 5. The external circuit contains a position sensor 7 of the control handle 6, sensor 8 of angular rotation speed of the crankshaft of diesel 1 and rack position sensor 9 of fuel pump 2 of diesel 1, digital control unit 10 and executive body of diesel generator set 11, which is a series connection of electromagnet 12 and a hydraulic servomotor with hydraulic pump 13, spool valve 14 and hydraulic cylinder 15. Executive body of diesel generator set 11 designed to stabilize the rotation speed of the diesel crankshaft 1 by changing the position of the fuel pump rack 2 when the load on the diesel crankshaft, transmitted from the rotor of the synchronous generator 3, changes when the consumer's electrical load changes. Both control loops operate independently of each other.

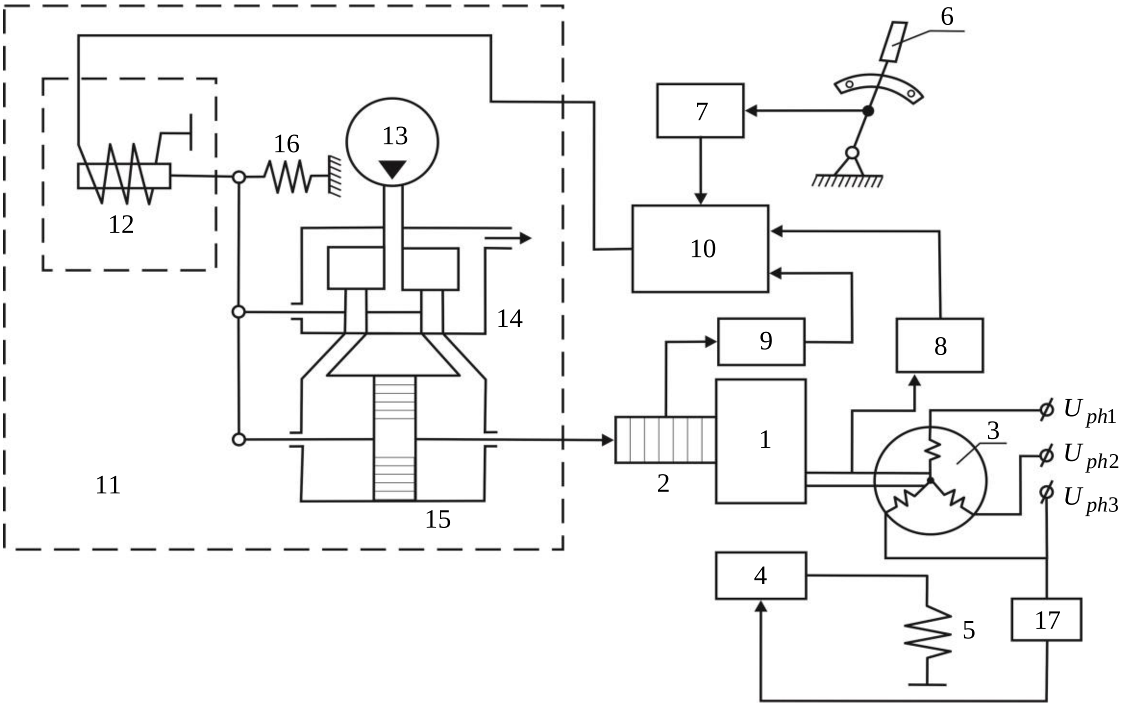

Fig. 3. Functional diagram of the digitally controlled diesel generator set: 1 – diesel 5TDF or 6TD-1; 2 – fuel pump rack; 3 – synchronous generator; 4 – voltage regulator; 5 – winding of excitation; 6 – fuel supply control lever; 7 – handle position sensor; 8 – crankshaft angular speed sensor; 9 – fuel pump rack position sensor; 10 – digital control unit of the diesel generator set; 11 – executive body; 12 – electromagnet; 13 – hydraulic pump; 14 – spool valve; 15 – hydraulic cylinder; 16 – fixing spring; 17 – voltage sensor

Mathematical model of perturbed motion of closed-loop control system of diesel generator set. The control object of the external loop is the diesel engine, the mathematical model of which is considered in works [6,7] and is written in the form

$$I\frac{d\omega(t)}{dt} = M_D\left[\omega(t), h(t-\tau)\right] - M_L(t), \qquad (1)$$

where $\omega(t)$ is the angular speed of rotation of the crankshaft; $h(t)$ – position of the fuel pump rack; $M_D\left[\omega(t), h(t-\tau)\right]$ – active torque developed by the diesel engine; $M_L(t)$ – load moment on the crankshaft; I – moment of inertia of the moving parts of the diesel engine and synchronous generator brought to the crankshaft. Torque $M_D\left[\omega(t), h(t-\tau)\right]$ for each of the engines under consideration is determined by the following relations [8, 21]

$$M_D\left[\omega(t), h(t-\tau)\right] = \\ = -1,23\cdot 10^5\left[h(t-\tau) - 0,024\right]\times \\ \times\left[1 + 0,33\cdot 10^{-2}\omega(t) - 0,11\cdot 10^{-4}\omega^2(t)\right]; \qquad (2)$$

$$M_D\left[\omega(t), h(t-\tau)\right] = \\ = -1,76\cdot 10^5\left[h(t-\tau) - 0,024\right]\times \\ \times\left[1 + 0,33\cdot 10^{-2}\omega(t) - 0,11\cdot 10^{-4}\omega^2(t)\right]. \qquad (3)$$

From the output of the code-to-analog converter (CAC) of the digital control unit 10, the control signal $u(t)$ is supplied to the winding of the electromagnet 12. In this case, the change in the electric current in the winding 12 is determined by the differential equation

$$L_w\frac{di_w(t)}{dt} + r_w i_w(t) = u(t), \qquad (4)$$

where L_w and r_w are the inductance and active resistance of the electromagnet winding 12, respectively.

The disturbed movement of the armature of the electromagnet 12 is described by the equation

$$m\frac{d^2 z(t)}{dt^2} + f\frac{dz(t)}{dt} + cz(t) = k_M i_w(t), \qquad (5)$$

where $z(t)$ – movement of the electromagnet armature; m – mass of armature; f – coefficient of fluid friction when moving the armature; c – coefficient of rigidity of the fixing spring 16; k_M – gain of the electromagnet.

The differential equation of the perturbed motion of the fuel servomotor is written as [9]

$$T_s\frac{dh(t)}{dt} + h(t) = k_s z(t), \qquad (6)$$

where k_s and T_s are the gain and time constant of the servomotor, respectively. In accordance with work [5], we introduce into consideration a function $\Delta M_D(t)$ that satisfies the differential equation

$$\tau^2 \frac{d^2 \Delta M_D(t)}{dt^2} + 2\tau \frac{d\Delta M_D(t)}{dt} + \Delta M_D(t) = = \left(\frac{\partial M_D}{\partial h(t-\tau)} \right)_0 \Delta h(t), \quad (7)$$

where $\left(\frac{\partial M_D}{\partial h(t-\tau)} \right)_0$ – derivative of functions (2) or (3), calculated at point $\omega_0 = \omega_N$. Let us linearize the nonlinear equation (1) in the vicinity of the point $\omega = \omega_N$:

$$I \frac{d\omega(t)}{dt} = \left(\frac{\partial M_D}{\partial \omega} \right)_0 \Delta\omega(t) + \Delta M_D(t) - \Delta M_L(t), \quad (8)$$

where $\left(\frac{\partial M_D}{\partial \omega} \right)_0$ – derivative of functions (2) or (3), calculated at point $\omega = \omega_N$, $h = h_0$. The value h_0 is determined by the load moment M_{L0} on the diesel crankshaft and is in the range $0,01 \le h_0 \le 0,024$ for 5TDF and 6TD-1 diesel engines. It is in this interval that the steady-state value of the variable $h(t)$ is located at a constant electrical load of the diesel generator set. Thus, in the vicinity of the point $\omega = \omega_N$, the mathematical model of the perturbed motion of the continuous part of the DGS is described by linear differential equations (4)-(8).

The discrete part of the diesel generator set control system is the digital electronic control unit 10, which processes signals from sensors 8 and 9, as well as generating a control algorithm. Structural and logical diagram of block 10 is shown in Fig. 4.

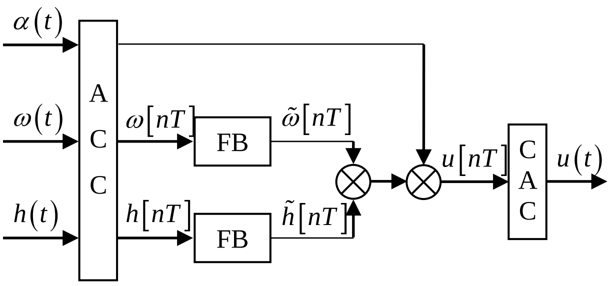

Fig. 4. Structural and logical diagram of the digital control unit of the diesel generator set

The control algorithm implemented by the digital control unit in accordance with Fig. 4, we write it in the form

$$u[nT] = k_\omega \tilde{\omega}[nT] + k_h \tilde{h}[nT] + k_\alpha \alpha_{\max}, \quad (9)$$

where $\alpha_{\max}$ – position of the control handle corresponding to setting the fuel supply regulator to the maximum (nominal) crankshaft rotation speed ω_N ; k_ω , k_h – varied parameters of the electronic control unit.

The output signals of sensors of the angular velocity of the crankshaft 8 and the rack position of the fuel pump 9 are supplied to the inputs of the analog-to-code converter (ACC), and then in the form of lattice functions $\omega[nT]$ and $h[nT]$ are supplied to the inputs of digital low-frequency Butterworth filters, where high-frequency interference is filtered, and then control algorithm (9) is formed, where $\tilde{\omega}[nT]$ and $\tilde{h}[nT]$ denotes the corresponding functions filtered from high-frequency interference caused by torsional vibrations of the crankshaft and vibrations of the fuel pump [10].

The code-to-analog converter converts the lattice control function (9) into a piecewise constant function in accordance with the algorithm

$$u(t) = \begin{cases} u[nT] & for \ nT \le t < (n+1)T; \\ u[(n+1)T] & for \ (n+1)T \le t < (n+2)T, \end{cases} \quad (10)$$

where T is the quantization period of the digital electronic unit.

Relations (9), (10) represent a mathematical model of the discrete part of the diesel generator set, which, together with differential equations (4)-(8), forms a mathematical model of the closed-loop automatic control system of the diesel generator set.

Solution of the problem of parametric synthesis of the digital regulator of the diesel generator set. The choice of varied parameters of the digital fuel supply regulator will be made based on the condition of high accuracy of maintaining the nominal value of the angular velocity of the diesel crankshaft in the mode of its nominal value. The operation of the fuel supply regulator over the time interval (0, *r*) can be assessed quantitatively by the value of the integral quadratic functional

$$I(k_\omega, k_h) = \int_0^r \Delta\omega^2(t)\,dt, \quad (11)$$

calculated on the solutions of the mathematical model of the perturbed motion of the closed-loop fuel supply system of the diesel generator set (4)-(10). The smaller the value of the functional (11), the more stable the value of the frequency of the generated voltage.

Let us formulate the problem of parametric synthesis of a digital fuel supply regulator for a diesel generator set as follows. It is required to find the optimal values of the varied parameters of the digital fuel supply regulator k_ω and k_h , such that on the solutions of the mathematical model of the closed-loop fuel supply system of the diesel generator set (4)-(10) the integral quadratic functional (11) reaches a minimum.

To solve the problem, we will use the algorithmic combined method of parametric synthesis of dynamic systems, set out in works [11,12]. This method is a sequential combination of two optimization methods – the Sobol grids method [13] and the Nelder-Mead method [14]. Well-known computational methods of optimization make it possible to find the local minimum of the optimality criterion closest to the starting point. The Sobol grids method allows one to derive the starting point in the vicinity of the global minimum point of the quality functional. At the second stage of the computational process of optimization, the starting point is selected at the

Sobol grid node, where the value of the functional is the smallest. This starting point is located near the global minimum point and, when using the Nelder-Mead method, tends along the trajectory of steepest descent [15, 16].

The main problem when using the algorithmic combined method of parametric synthesis of dynamic systems is the problem of finding a set of allowable values G_K for the components of the vector of varied parameters $K: K \in G_K$.

In this case, if the controller of a dynamic object is analog, then it is natural to take as the set G_K the stability region of a closed-loop system in the space of varied parameters of the controller. For a digital controller, constructing a stability region in the space of varied constants of the control algorithm is a rather complex task. In work [13] it is shown that the stability region of a dynamic object with a digital controller $\tilde{G}_K$ is inside the stability region of the same object with an analog controller $\tilde{G}_K \in G_K$.

The quantization period of modern digital regulators of technical objects is $T = (0,01 \div 0,001)\ s$. As the quantization period of the digital controller decreases, the stability region of the closed-loop system indefinitely approaches the stability region of the closed-loop system with an analog controller. Therefore, the stability region of a closed-loop analog system can be used as a set of allowable values of varied parameters of a digital controller. To construct the stability region of a closed-loop automatic control system of a diesel generator set with an analog fuel supply regulator, we assume that the analog regulator implements the control law in the form

$$\Delta u(t) = k_\omega \Delta\omega(t) + k_h \Delta h(t)\ , \tag{12}$$

where $\Delta h(t)$ – deviation of the current position $h(t)$ of the fuel pump rack from the position h_0 corresponding to the steady-state equilibrium mode

$$\Delta h(t) = h(t) - h_0\ .$$

Depending on the magnitude of the electrical load of the diesel generator set, the value h_0 can vary within $h_0 = (0,01 \div 0,024)\ m$. Linearization of the mathematical model of the diesel generator set is carried out in the vicinity of the point of steady-state equilibrium (ω_N, h_0). If the value ω_N is constant, then each value h_{0i}, $(i = \overline{1,m})$ has its own point of steady-state equilibrium and, therefore, its own region of stability (its own set of allowable values) $G_K(h_{0i})$, $(i = \overline{1,m})$. The intersection of these sets determines the set of allowable values of varied parameters of the controller [17,18]

$$G_K = G_K(h_{01}) \cap G_K(h_{02}) \cap ... \cap G_K(h_{0m})\ . \tag{13}$$

For the 5TDF diesel engine we will build the set of G_K. To do this, we substitute formula (12) into the right side of equation (4), and solve system (4)-(8) with respect to the highest derivatives

$$\begin{aligned}
&\frac{d\Delta\omega(t)}{dt} = \frac{1}{I}\left(\frac{\partial M_D}{\partial\omega}\right)_0 \Delta\omega(t) + \\
&\quad + \frac{1}{I}\Delta M_D(t) - \frac{1}{I}\Delta M_L(t); \\
&\frac{d^2\Delta M_D(t)}{dt^2} = -\frac{2}{\tau}\frac{d\Delta M_D(t)}{dt} - \frac{1}{\tau^2}\Delta M_D(t) + \\
&\quad + \frac{1}{\tau^2}\left(\frac{\partial M_D}{\partial h(t-\tau)}\right)_0 \Delta h(t); \\
&\frac{d\Delta h(t)}{dt} = -\frac{1}{T_s}\Delta h(t) + \frac{k_s}{T_s}\Delta z(t); \\
&\frac{d^2\Delta z(t)}{dt^2} = -\frac{f}{m}\frac{d\Delta z(t)}{dt} - \frac{c}{m}\Delta z(t) + \frac{k_M}{m}\Delta i_w(t); \\
&\frac{di_w(t)}{dt} = -\frac{r_w}{L_w}\Delta i_w(t) + \frac{1}{L_w}k_\omega\Delta\omega(t) + \frac{1}{L_w}k_h\Delta h(t).
\end{aligned} \tag{14}$$

Taking into account formula (2), we will find the partial derivatives on the right sides of the first two equations (14)

$$\begin{aligned}
&\left(\frac{\partial M_D}{\partial\omega}\right)_0 = -1,23\cdot 10^5\left[h_0 - 0,024\right]\times \\
&\times\left[0,33\cdot 10^{-2} - 0,22\cdot 10^{-4}\omega_N\right];
\end{aligned} \tag{15}$$

$$\begin{aligned}
&\left(\frac{\partial M_D}{\partial h(t-\tau)}\right)_0 = -1,23\cdot 10^5\times \\
&\times\left[1 + 0,33\cdot 10^{-2}\omega_N - 0,11\cdot 10^{-4}\omega_N^2\right].
\end{aligned} \tag{16}$$

The values of partial derivatives (15) and (16) are given in Table 1.

The values of the constant parameters of the diesel generator set are:

$$I = 82\ N\cdot m\cdot s^2;\ \tau = 0,015\ s;\ T_s = 0,05\ s;\ k_s = 1;$$
$$m = 0,098\ kg;\ f = 0,55\ N\cdot m^{-1}\cdot s;\ c = 100\ N\cdot m^{-1};$$
$$k_M = 1,5\ N\cdot A^{-1};\ L_w = 0,01\ H;\ r_w = 30\ \Omega.$$

Table 1 – **Partial derivative values (15) and (16)**

Coordinates of the stabilized state point	$\left(\frac{\partial M_D}{\partial\omega}\right)_0$, **N·m·s**	$\left(\frac{\partial M_D}{\partial h(t-\tau)}\right)_0$, **N**
ω_N =314 s^{-1}; h_{01} =0,012 m	-5,14	-2,4 · 10^5
ω_N =314 s^{-1}; h_{02} =0,017 m	-3,10	-2,4 · 10^5
ω_N =314 s^{-1}; h_{03} =0,022 m	-0,89	-2,4 · 10^5

Let us introduce the notation

$$a_i = \left(\frac{\partial M_D}{\partial\omega}\right)_0,\ (i = 1,2,3)$$

and substitute the above numerical values of the diesel generator set parameters into system (14). As a result, we obtain the mathematical model of the disturbed motion of the diesel generator set in the vicinity of the i-th point of the stabilized state:

$$\frac{d\Delta\omega(t)}{dt} = 0,0122 \cdot a_i \Delta\omega(t) + 0,0122 \cdot \Delta M_D(t); \qquad \frac{di_w(t)}{dt} = -306,12 \cdot \Delta i_w(t) + 100 k_\omega \Delta\omega(t) + 100 k_h \Delta h(t);$$

$$\frac{d^2 \Delta M_D(t)}{dt^2} = -133,3 \cdot \frac{d\Delta M_D(t)}{dt} - 4444,4 \cdot \Delta M_D(t) - 1,1705 \cdot 10^9 \Delta h(t); \qquad (17)$$

$$\frac{d\Delta h(t)}{dt} = -20 \cdot \Delta h(t) + 20 \cdot \Delta z(t); \qquad \frac{d^2 \Delta z(t)}{dt^2} = -5,61 \frac{d\Delta z(t)}{dt} - 1020,41 \cdot \Delta z(t) + 15,31 \cdot \Delta i_w(t).$$

Let us reduce the mathematical model (17) to the normal Cauchy form, for which we introduce into consideration the state vector

$$X(t) = \left[\Delta\omega(t) \quad \Delta M_D(t) \quad \Delta\dot{M}_D(t) \quad \Delta h(t) \quad \Delta z(t) \quad \Delta\dot{z}(t) \quad \Delta i_w(t)\right]^T = \left[x_1(t) \quad x_2(t) \quad \dots \quad x_7(t)\right]^T.$$

As a result, we obtain

$$\dot{x}_1(t) = 0,0122 \cdot a_i x_1(t) + 0,0122 \cdot x_2(t); \qquad \dot{x}_2(t) = x_3(t); \qquad \dot{x}_5(t) = x_6(t);$$

$$\dot{x}_3(t) = -4444,4 \cdot x_2(t) - 133,3 \cdot x_3(t) - 1,1705 \cdot 10^9 x_4(t); \qquad \dot{x}_4(t) = -20 \cdot x_4(t) + 20 \cdot x_5(t); \qquad (18)$$

$$\dot{x}_6(t) = -1020,41 \cdot x_5(t) - 5,61 \cdot x_6(t) + 15,31 \cdot x_7(t); \qquad \dot{x}_7(t) = -306,12 \cdot x_7(t) + 100 k_\omega x_1(t) + 100 k_h x_4(t).$$

The eigenmatrix of the system (18) is written in the form

$$A = \begin{bmatrix} 0,0122a_i & 0,0122 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & -4444,4 & -133,3 & -1,1705 \cdot 10^9 & 0 & 0 & 0 \\ 0 & 0 & 0 & -20 & 20 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & -1020,41 & -5,61 & 15,31 \\ 100k_\omega & 0 & 0 & 100k_h & 0 & 0 & -306,12 \end{bmatrix}. \qquad (19)$$

The characteristic equation of the closed fuel supply system of the diesel generator set has the following form:

$$\det\left[A - E \cdot s\right] = 0, \qquad (20)$$

where E is a square identity matrix of size 7 × 7.

Let's use the MatLab software package [19,20] and construct stability regions of a closed-loop automatic control system of a diesel generator set with an analogue fuel supply regulator for various values of the constant value a_i, $(i = 1, 2, 3)$ given in Table 1. These regions are shown in Fig. 5 and are practically indistinguishable from each other, which indicates a very weak influence of the coefficient a_i on the boundary of the stability regions. Consequently, we can assume that the optimal values of the varied parameters are the same for any of the points of steady-state equilibrium of the diesel generator set, relative to which the linearization of the mathematical model (4)-(8) was carried out.

To solve the problem of parametric synthesis of the digital regulator of the diesel generator set, we select the region shown in Fig. 5 as the area of allowable values of varied parameters of algorithm (9) G_K using the algorithmic combined method of parametric synthesis of dynamic systems. Let us apply the Sobol grid with nodes marked with bold dots onto the area G_K and, using the Sobol algorithm given in [13], we calculate the minimum value of the integral quadratic functional (11), where

$$\Delta\omega(t) = \omega(t) - \omega_N .$$

To do this, we add one more differential equation to the mathematical model (4)-(9)

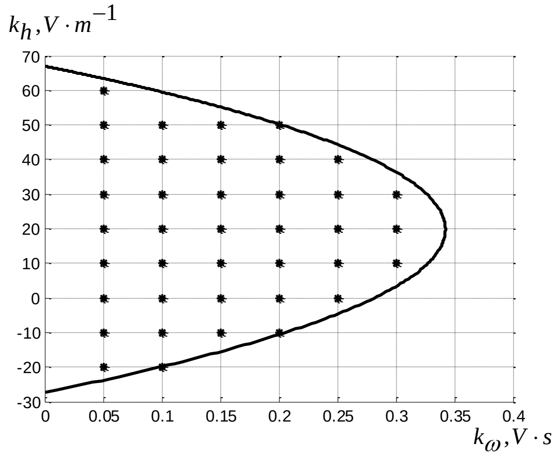

Fig. 5. Area of allowable values of varied parameters of the algorithm (9)

$$\dot{I}(t) = \left[\omega(t) - \omega_N\right]^2. \qquad (21)$$

As a result of the joint solution of the mathematical model (4)-(9) and equation (21), we obtain

$$I(k_\omega, k_h) = I(r).$$

For the problem under consideration, the functional (11) takes its minimum value at the Sobol grid node with coordinates $k_\omega^* = 0,2\ V \cdot s$; $k_h^* = 10\ V \cdot m^{-1}$ and amounts to $I(0,2;10) = 0,099744\ s^{-1}$. At the second stage of the optimization process, the resulting point $\left(k_\omega^*, k_h^*\right)$ is selected as the starting point of the computational process of the Nelder-Mead method, as a result of which the point of global minimum of the functional (11) is determined, the coordinates of which are $k_{\omega}^{**} = 0{,}198\ V \cdot s$; $k_h^{**} = 7{,}85\ V \cdot m^{-1}$. The value of functional (11) at this point is $I\left(k_{\omega}^{**}, k_h^{**}\right) = 0{,}099526\ s^{-1}$. In Fig. 6 shows the process of deviation of the frequency of the generated voltage $\omega(t)$ from the nominal value $\omega_N = 314\ s^{-1}$ during a pulsed change in the electrical load at the output of the generator.

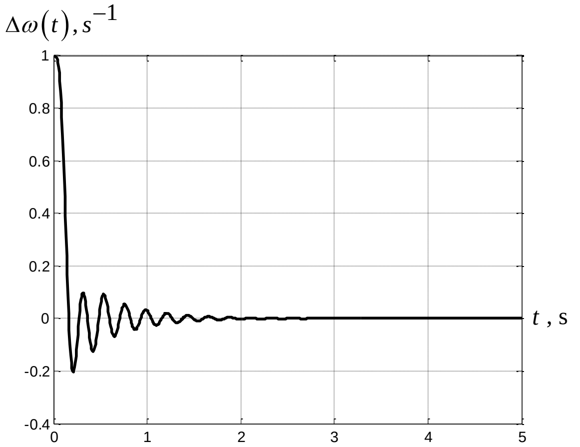

Fig. 6. Deviation of the frequency of the generated voltage from the nominal value during a pulsed change in the electrical load at the generator output

The process is rapidly damping with a high damping decrement and a duration not exceeding 1 s.

Conclusions and recommendations

In most industrialized countries of the world, serial production of mini-power plants has been established, mainly on the basis of diesel generator sets (DGS) for power supply of equipment for geological exploration expeditions, logging, remote farms, as well as for power supply of industrial enterprises, medical institutions and social facilities in the conditions of emergency situations, natural disasters and military conflicts. The main requirement for a diesel generator set is the quality of the generated electricity, namely, the stability of the amplitude and frequency of the generated voltage. The stability of the amplitude of the output voltage of a synchronous generator is ensured by a voltage regulator by changing the excitation current of the generator depending on the change in the electrical load at the generator output. The stability of the frequency of the generated voltage is ensured by the fuel supply regulator of diesel of diesel generator set.

Domestic DGU-200 with a power of 200 kW and DGU-315 with a power of 315 kW are built using tank diesel engines 5TDF and 6TD-1, deforced in terms of developed torque. Diesel generator sets are characterized by high reliability and durability, but are equipped with hydromechanical fuel supply regulators with a significant degree of unevenness, which leads to significant deviations of the generated voltage frequency from its nominal value. To improve the quality of the generated voltage, it is proposed: firstly, instead of the serial hydromechanical fuel supply regulator with a centrifugal sensing element in 5TDF and 6TD-1 diesel engines, use an electronic fuel supply regulator; secondly, to develop a mathematical model of the perturbed motion of the closed-loop fuel supply system of the diesel generator set, taking into account all the dynamic properties of the control object and the regulator, first of all, to take into account the delay between the movement of the fuel pump rack of diesel and the implementation of the corresponding change in the active torque of the diesel engine; thirdly, to carry out the targeted selection of optimal values of varied constants of the control algorithm, ensuring the minimum deviation of the current value of the frequency of the generated voltage from its nominal value.

As a result of applying the algorithmic combined method of parametric synthesis of dynamic systems, previously developed by the authors, optimal values of the varied parameters of the digital regulator of the diesel generator set were obtained, ensuring high quality of the generated electrical energy.

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Параметричний синтез цифрового регулятора дизель-генераторної установки промислового призначення

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Анотація. Об'єктом досліджень є динамічні процеси генерації електричної енергії високої якості дизель-генераторною установкою (ДГУ) з цифровим регулятором паливоподавання. **Предметом досліджень** є методологія вибору варійованих параметрів цифрового регулятора паливоподавання, які забезпечують високу стабільність частоти генеруємої напруги в умовах широкого діапазону зміни зовнішнього навантаження з боку споживачів електричної енергії. **Отримані результати**. Розроблена математична модель збуреного руху ДГУ і визначені варійовані параметри цифрового регулятора паливоподавання. Із застосуванням комбінованого алгоритмічного методу оптимізації, який представляє собою комбінацію методу сіток Соболя і методу Нелдера-Міда, в площині варійованих параметрів регулятора знайдені значення цих параметрів, які доставляють мінімум інтегральному квадратичному функціоналу, що є кількісним показником ступеня нерівномірності цифрового регулятора паливоподавання ДГУ. **Висновки**. Застосування цифрового електронного регулятора паливоподавання замість гідромеханічного регулятора в дизелі ДГУ значно підвищує якість виробляємої електроенергії щодо стабільності частоти трьохфазної напруги на виході ДГУ.

Ключові слова: дизель-генераторна установка; цифровий регулятор паливоподавання дизеля; частота трьохфазної напруги; сітки Соболя; множина допустимих значень варійованих параметрів регулятора.