Improving the Control Quality of Gas Diesel Engine as Part of Autonomous Electric Power System

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***Abstract*—The paper solves the problem of increasing the gas-diesel engines revolutions stablility and, accordingly, the voltage frequency in the network of autonomous electric power systems, which can vary in the range from 45 Hz to 55 Hz. The frequency instability causes fluctuations in active power and has a negative impact on the quality of electricity. The structure of the test bench was developed, which made it possible to get static characteristics and determine the range of active power exchange fluctuations between gas-diesel generators. In this case, the uneven distribution of active power between generators can reach 57%. Based on an analysis of the reasons for the appearance of frequency oscillations and the design features of the gas-diesel unit, its dynamic model has been developed, taking into account the influence of the turbocharger on the appearance of low-frequency revolutions oscillations. The structure of the control system for a gas-diesel generator set with auto-tuning of the controller was proposed. Computer simulation of the operation of a gas-diesel generator set was carried out, which made it possible to solve the problem of optimizing the parameters of a gas-diesel engine revolutions Proportional–Integral–Derivative (PID) controller. In this research the method of active experimentation, the theory of probability and statistical data analysis, methods of automatic control theory and computer modeling are used. Using the obtained solution makes it possible to reduce the dispersion of gas-diesel revolutions fluctuations by up to 20%.**

***Index Terms*—gas diesel engine, control quality, frequency instability, Proportional–Integral–Derivative (PID) controller, optimization**

I. INTRODUCTION

Considerable attention is paid to the problem of improving the quality of operating Gas-Diesel-Generator Units (GDGU) as part of autonomous electric power systems (AEPS), which also include ship power plants. Gas-diesel generators produced by the Ukrainian enterprise TDV “Pervomayskdieselmash” have power from 315kW to 750kW and are often used as part of AEPS because the use of natural gas instead of diesel fuel, on the one hand, as shown in [1, 2], is more economical and reduces the cost of electricity generation. On the other hand, gas-diesel generators are characterized by lower emissions of carbon dioxide, so their use has less negative impact on the environment [3–5]. The quality of electricity, reliability and energy efficiency of the entire autonomous electric power system largely depends on the quality of GDGU operation. Despite a number of advantages that GDGUs are characterized, one of the main disadvantages of their operation is the instability of the rotation frequency which has a negative effect on the quality of electricity. A gas-diesel engine is typically either developed from a diesel engine or modified from one. It can utilize natural gas, such as methane, or liquefied hydrocarbon gases like propane and butane as its fuel source. The rebuilt engine also retains the ability to run on diesel fuel or a mixture of gas and diesel fuel (diesel fuel is added to improve the ignition process of the mixture). In this case, fluctuations in gas-diesel engine revolutions period are observed when operating on pure gas or when using a mixture of gas and diesel fuel. In the proposed research, the work of gas-diesel on a mixture of natural gas and diesel fuel was investigated in a ratio of 85% and 15%, respectively. Actually, the reason for the instability of the gas-diesel shaft rotation period is the lower calorific value of gas compared to diesel fuel, low mixture heterogeneity, as well as design features. Gas is supplied to the cylinders at different pressures – with higher pressure to those cylinders that are located closer to the point of entry of the fuel mixture into the gas-diesel engine. As the gas moves through the pipe to the cylinders, the pressure drops because part of the mixture enters the cylinders located closer to the intake manifold. During single operation of the gas-diesel generator, the voltage frequency instability has a negative effect on the load, in particular on transformers, asynchronous motors, increasing power losses and reducing energy conversion efficiency. Also, the frequency instability leads to voltage fluctuations at the output of semiconductor power generators. At the same time, the instability of gas-diesel revolutions can be caused by various factors, in particular, the quality of the fuel, namely its low heat-generating capacity, as shown in [6, 7], as well as the design features of a gas-diesel generator. In particular, it was stated in [8] that the reason

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for the instability of revolutions can be the discreteness of obtaining information about the revolutions of the diesel engine rotor. Another reason for the revolution fluctuations is that in operating modes close to no-loading, that is, at low loads, the power of exhaust gases is not enough to ensure stable operation of the turbocharger and ensure uniform gas supply with the same pressure to all cylinders [9].

With the parallel operation of several GDGUs on a common load, the instability of the rotation frequency leads to an uneven distribution and fluctuations of active power between the generators, which negatively affects the reliability and energy efficiency of the AEPS, because the generators work either in an underloaded or overloaded mode. In [10], the use of a special device for the distribution of active power between generators was proposed, the operation of which was based on the control of the angular positions of the rotors of the generators and the torques on the shafts of the drive motors. Problems also arise when synchronizing generators are enabled to work in parallel. Due to the instability of the voltage frequency of the generators, which is due to the instability of the revolutions of the driving gas diesels, the synchronization process can take a long time, which is critical in the case of an overload of the working generator and the need to quickly introduce reserve capacity. One of the possible solutions is the use of a fuzzy logic device in the generator synchronization system, as proposed in [11]. At the same time, the technical solutions proposed in [10, 11] did not solve the problem of improving the control quality of gas diesel generators. Improving the quality of gas-diesel generator operator by controlling the fuel mixture was considered in [12]. However, the disadvantages of the proposed solution are that it is not always technically possible to install additional and expensive equipment to ensure the control of the process of mixing natural gas and diesel fuel to ensure proper operation of the engine. In addition, the proposed solution was designed for low-power diesel engines (up to 5 kW). Another possible solution was to adjust the coefficients of the gas-diesel speed controller optimally, as done in [13].

However, the disadvantage of the work is that the non-linearity of the gas diesel generator was not taken into account and the proposed solution would ensure the stability of the work only at a given and constant load. The problem of instability of the voltage frequency in isolated (i.e., autonomous) power plants, which is due to the instability of the revolutions of the drive diesel generators, was also noted in [14]. At the same time, the optimization methods considered in [14] applied to diesel generators were mostly aimed at reducing the cost of electricity generation, reducing fuel consumption and reducing CO_2 emissions into the atmosphere. In [15], a numerical model for combustion research adapted to a hydrogen-natural gas (HNG)/diesel bi-fuel engine was developed to provide simulations over a wide range of loads and under different gas mixture compositions. However, the proposed model considers thermal energy processes in diesel, which allows precise control of the combustion sequence with detection of the beginning and end of each phase and the contribution to the overall rate of heat release. Therefore, this model, despite its high accuracy, does not allow to solve the problem of parametric optimization of the gas-diesel speed controller for a wide range of loads.

Recently, the use of gas-diesel generators as part of AEPS to power consumers in the event of blackouts has become particularly relevant in Ukraine. This is due not only to the increase in the cost of diesel fuel, as stated in [16], but also to the fact that there is an extensive network of gas pipelines, which allows gas-diesel generators to be installed in close proximity to consumers. During the operation of GDGU as part of AEPS, the load is constantly changing and therefore, for each operating mode of the gas-diesel generator, it is necessary to find the optimal values of the controller settings to ensure high control quality, taking into account the fact that the gas-diesel generator is a non-linear control object.

There are several known methods for tuning the Proportional–Integral–Derivative (PID) controller. Among them are such methods as manual tuning, Ziegler-Nichols, Tyreus Luyben, Cohen–Coon, Astrom-Haglund, SIMC and others [17, 18]. To use analytical tuning methods, it is necessary to know the exact mathematical model of the control object. GDGU are complex systems with numerous variables and interactions. In practice it is challenging to develop a reliable model that accurately represents real-world conditions. In addition, the GDGU is a nonlinear system, therefore specific settings of the PID controller provide acceptable control quality in a limited range of system operation. In this research the Ziegler-Nichols tuning method is used to determine PID controller coefficients for specific operating conditions of a gas-diesel engine.

So, there are a number of problems that arise not only with single, but also with parallel operation of GDGU due to significant fluctuations in gas-diesel revolutions, which leads to significant exchange fluctuations between generating units. The use of modern microprocessor PID controllers for speed stabilization does not fully solve this problem and allows to ensure sufficient quality of revolutions stabilization only in a very limited power range. The analysis of the literature showed that insufficient attention has been paid to the problem of increasing the stability of revolutions, and accordingly, the voltage frequency in AEPS with gas-diesel generators and this task remains unsolved. To eliminate this phenomenon, a more in-depth study of the static properties and dynamic characteristics of generating units based on experimental data is needed which will allow developing the necessary measures and hardware-software tools to ensure the stability of both single and parallel operation of GDGU in a wide range of loads.

To solve the task of improving the quality of GDGU operation, it is necessary to:

- Carry out a study of self-oscillating frequency processes of the gas-diesel unit based on the obtained experimental data, in order to study its dynamic properties, determine the causes of the occurrence and the possible range of active power fluctuations between GDGUs operating in parallel.
- Develop a model of a gas-diesel unit taking into

account its design features and justify the need to use an adaptive PID controller to stabilize its revolutions.

- Develop the structure of the control system with auto-adjustment of the controller to stabilize the revolutions of the gas-diesel unit and determine the optimal values of the coefficients of the gas-diesel revolution controller while working in different modes.
- Carry out model studies of the operation of a gas-diesel unit with optimized parameters of the controller and evaluate the efficiency of stabilization of the rotation frequency.

In order to achieve the goal, the methods of active experimentation, methods of probability theory and statistical data analysis, methods of automatic control theory and computer modeling are used.

II. IMPLEMENTATION OF THE GDGU CONTROL SYSTEM WITH AUTO-ADJUSTMENT OF THE CONTROLLER

A. *Development of a Test Bench for Obtaining Experimental Data*

For a detailed study of the dynamic properties of GDGU, the authors developed a hardware and software complex, which includes a portable personal computer, a multi-channel USB oscilloscope, a load control system as well as software for solving the tasks of collecting, processing information and controlling external switches. The structural diagram of the test stand is presented in Fig. 1. The main disadvantage of diesel engines is that they have difficulty starting at low temperatures. The problem lies with the diesel fuel itself. Using a sensor in the test bench, the temperature is monitored and, if necessary, additives are added to the fuel mixture to facilitate engine starting, and heating is also performed. After starting the gas-diesel generator, it takes some time for its steady state of operation to occur, including the temperature stabilizing. To do this, the temperature derivative is analyzed, and if it is less than a specified value, a delay is formed during which the thermal regime stabilizes. After this, the process of measuring fluctuations in the frequency of the output voltage, caused by fluctuations in the rotational speed of the gas-diesel engine shaft, is carried out.

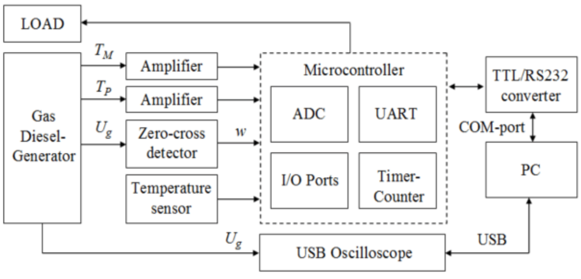


Fig. 1. Structural diagram of the test bench.

When measuring voltage frequency, difficulties arise due to the instability of the analog-to-digital converter sampling frequency. Over a certain number of periods of the measured voltage, the error accumulates, and as a result, a single error occurs in determining the frequency in one period. Using a digital Finite Impulse Response (FIR) or Infinite Impulse Response (IIR) filter will greatly affect the measured frequencies. Using a median filter will eliminate a single error, but will not affect other values.

To determine the GDGU parameters, both the single and double acceleration methods have been used [19]. The method of single acceleration consists in the fact that the engine is accelerated together with the consumer (generator) when the generator is disconnected from the load in a given range of changes in the shaft frequency Δn, or its angular speed $\Delta\Omega$. The moment of inertia of the GDGU is determined based on the known torque, which is chosen as average M_{avg} or nominal M_{rt}, and the experimentally determined start-up time (acceleration time) T_{st} according to the ratios [20]:

$$J_{\text{rt}} = \frac{T_{\text{st}}\, M_{\text{avg}}}{\Delta\Omega}, \quad J_{\text{rt}} = \frac{T_{\text{st}}\, M_{\text{rt}}}{\Delta\Omega}.$$

The nominal torque of the diesel engine is equal to:

$$M_{\text{rt}} = \frac{P_{\text{rt}} \cdot 9550}{n_{\text{rt}}}$$

The average effective engine torque during acceleration:

$$M_{\text{avg}} \cong 0.95\, M_{\text{rt}}.$$

In order to equalize the values M_{rt} and M_{avg} in the studied interval, the initial revolutions are chosen from a value that is from 15% to 20% of the nominal. The value $\Delta\Omega$ is found from the expression:

$$\Delta\Omega = \frac{\pi(n_{\text{rt}} - n_{\text{st}})}{30}.$$

The given equations are used to specify the calculated value of the moment of inertia of the engine J_d and generator J_g.

The moment of inertia of the engine J_d is related to the moment of inertia of the flywheel J_{fw} by approximate ratios:

$$J_d \approx \frac{1.2}{1.3} J_{\text{fw}}, \quad J_{\text{fw}} = \frac{mD_{\text{fw}}^2}{2}, \quad J_g = \frac{mD_g^2}{4}.$$

In most cases, the moment of inertia of the generator is given by the manufacturer. In this case, there is an additional, known mass attached to the diesel engine, which allows you to use the double acceleration method. The main equations used in this case are given below:

$$J_d \frac{\Delta\Omega}{T_{\text{da1}}} = M_t, \quad (J_d + J_g)\frac{\Delta\Omega}{T_{\text{da2}}} = M_t.$$

By equating the left sides of the equations, we get:

$$J_d \frac{\Delta\Omega}{T_{\text{da1}}} = (J_d + J_g)\frac{\Delta\Omega}{T_{\text{da2}}}.$$

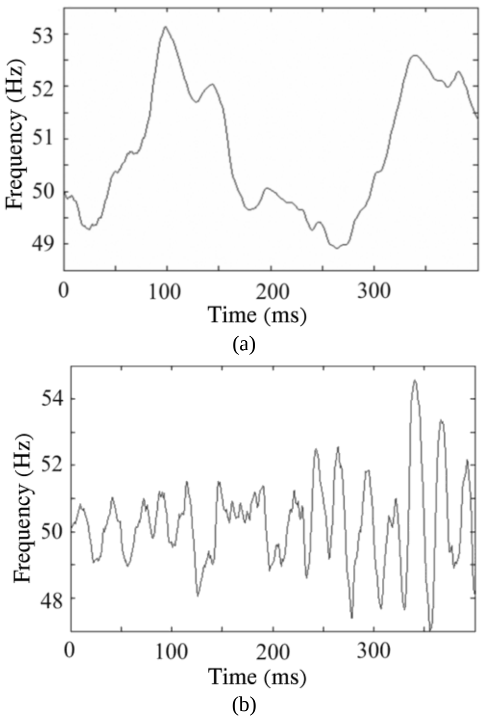
Hence

$$J_d = \frac{J_g}{T_{\text{da2}}}\left(\frac{T_{\text{da1}} T_{\text{da2}}}{T_{\text{da2}} - T_{\text{da1}}}\right).$$

The start-up mode makes it possible to identify the dynamic model of the gas-diesel generator unit based on the control effect, using reference curves of transient processes. The time T_{da} is determined until the moment when $\Delta\Omega \leq 0.02\ \Omega_{rt}$.

Based on the above equations, an algorithm for conducting start-up tests of a gas-diesel generator unit has been developed. The test algorithm consists in successively increasing the load by 20% from the nominal, starting from 20% of the generator load. After setting the process, when the GDGU revolutions differ from the constant value by no more than 2%, the next process of load increase is prepared. Since the transient process usually ends completely after a time interval equal to 10 T_{MAX} (T_{MAX} is the maximum time constant of the dynamic system), the time interval for this group of diesel engines is rigidly set and is equal to 1 min.

In Fig. 2(a) and Fig. 2(b) the processes of the output voltage frequency fluctuations of the gas-diesel generator unit GDVG-1A-630 at different loads (40% and 80% of the nominal) are shown.



(a)

(b)

Fig. 2. Oscillograms of frequency fluctuations of the GDGU output voltage at different loads: (a) 40% of the nominal value; (b) 80% of the nominal value.

The oscillograms were obtained by processing the experimental results of the real output voltage followed by digital filtering of quantization noise. The signal sampling frequency in the oscilloscope used is 40 kHz. Then, at a generator voltage frequency of 50 Hz, there are 800 samples per voltage period. By counting the number of samples per period of generator voltage, the process of frequency changes of the output voltage, and, accordingly, fluctuations in gas-diesel revolutions, is measured. In this case, the measurement error is 0.125%.

Since the controller parameters are adjusted to the nominal mode of operation with the specified requirements for dynamic parameters, an increase in the amplification factor contributes to an increase in the fluctuation index.

In order to build an adequate GDGU model, it is necessary to determine the statistical characteristics of rotation fluctuations. Table I shows the obtained values of the statistical characteristics of the signals for different GDGU loads. It can be seen that the standard deviation of the frequency instability decreases if the load of a gas-diesel generator unit increases. This can be explained by the fact that the GDGU is a nonlinear system, the gain of which increases with decreasing load, and vice versa. Since the controller parameters are adjusted to the nominal operating mode, an increase in the gain contributes to an increase in the oscillation coefficient.

TABLE I: NUMERICAL VALUES OF STATISTICAL CHARACTERISTICS OF FREQUENCY FLUCTUATIONS

Load (kW)	**Average, f_{avg}, Hz**	**Max, f_{max} (Hz)**	**Min, f_{min} (Hz)**	**Difference, f_{max}-f_{min} (Hz)**	**Standard deviation**
100	50.55	55.3	46.62	8.672	1.648
150	50.02	51.29	48.78	2.507	0.4247
200	49.73	51.03	48.64	2.39	0.4117

A detailed analysis of the results obtained shows that in the general case the process of frequency oscillations is nonstationary with changing standard deviation (and dispersion). In this case, there is a tendency for the standard deviation to decrease with increasing GDGU load. This can be explained by the fact that the generator plays the role of additional flywheel mass, and as the load increases, an additional torque occurs, which leads to a decrease in the the gas-diesel engine revolutions instability. Moreover, at the rated load, which is usually 80% of the maximum, speed fluctuations almost disappear. This is due to the fact that the GDGU is designed to operate at rated load most of the time. Therefore, the speed controller settings are made precisely for this operating mode, which is what is observed in practice.

The autocorrelation function of the process can be calculated according to the equation:

$$r_{11}(j) = \frac{1}{N}\sum_{n=0}^{N-1} x_1(n)x_1(n+j),$$

where N is the number of counts.

For most of the load range, the random process can be described by an exponential correlation function:

$$r(\tau) = \sigma^2 \exp(-\alpha|\tau|),$$

which the spectral density corresponds:

$$S(\omega) = \sigma^2 \frac{\alpha}{\alpha^2 + \Omega^2},$$

for a sufficiently large time constant α for the load range $P=(0.4 \div 1)P_{rt}$; $\alpha = 0.3 \div 0.4$ s. In the load range P from 0 to $0.4P_{rt}$, the correlation function can more likely be approximated by the following expression:

$$r(\tau) = \sigma^2 \exp(-\alpha|\tau|)\cos\Omega\tau,$$

and the spectral density is approximated by the expression:

$$S(\omega) = \sigma^2 \frac{\alpha}{\alpha^2 + (\omega - \Omega)^2}.$$

The detailed analysis of the obtained results shows that, in general, the process of frequency fluctuations is non-stationary with mathematical expectation and changing variance. Oscillograms in Fig. 2 illustrates significant voltage frequency fluctuations (and therefore diesel engine revolutions), which can vary in the range from 45 Hz to 55 Hz, which will lead to significant fluctuations in active power. Fig. 3 presents the possible static characteristics of gas diesel generator in the presence of rotational speed fluctuations.

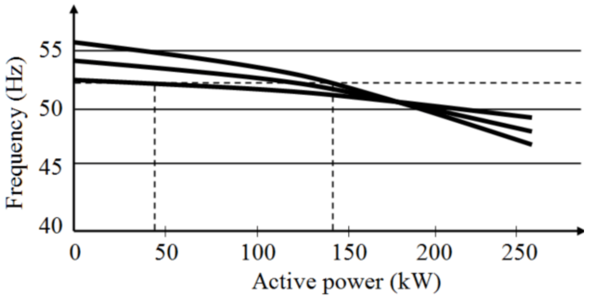


Fig. 3. A set of static characteristics of GDGU.

The diesels work with the Heinzmann DG...2-01 microprocessor-based speed stabilization system, which implements the functions of a PID controller and is adjusted for each diesel separately. A magnetic sensor is used as a speed sensor, which reads information about the angular position of the shaft from the toothed crown of the flywheel. The frequency of the output pulses of the sensor is determined by the equation:

$$f = \frac{n \cdot t \cdot z}{60}. \tag{1}$$

where n (rpm) is the rotation frequency of the diesel engine shaft; z is the number of teeth of the toothed crown of the flywheel and is usually within 12kHz (for controllers DG162-01, DG302-01, DG402-01, DG6.2-01, DG.6V.2-01, DG-10.2-01) .

The degree of uneven distribution of active power v_p can be calculated by the equation [21]:

$$v_p = \frac{P_1 - P_2}{P_1 + P_2} \times 100\% \cdot \tag{2}$$

Substituting experimentally obtained numerical values into Eq. (2), we obtain:

$$v_p = \frac{165 - 45}{165 + 45} \times 100\% = 57.1\% \cdot$$

If $P_2 \approx 0$, $v_P = 1$, all the load is accepted on the first generator. If $P_1 \approx 0$, $v_P = -1$, the entire load is accepted on the second generator, if $P_1 = P_2$, $v_P = 0$, the load is distributed evenly.

$$v_p = \frac{P_1 - P_2}{2P_N} \times 100\% = \frac{165 - 45}{2 \cdot 500} \times 100\% = 12\% \tag{3}$$

With this determination of the degree of unevenness, the absolute unevenness refers to a constant value $2P_N$. Therefore, with different total loads, the degree of unevenness is underestimated at low system loads and overestimated at high system loads.

The degree of non-uniformity of the distribution of active power at a given zone of adjustment inaccuracy 2Δ depends on the statism of the characteristic δ, with a large statism v_p decreases. The statism of the characteristic can be determined by the equation:

$$\delta = \mathrm{tg}\,\alpha = \frac{n_1 - n_2}{P_N}. \tag{4}$$

The maximum and minimum value of statism at the total load of generators up to 100 kW can be determined by Eq. (4), substituting numerical values of speed and power in relative units.

$$\delta_{\max} = \frac{1.122 - 1.078}{0.2} = 0.22, \quad \delta_{\min} = \frac{1.052 - 1.03}{0.2} = 0.11.$$

It is possible to determine the value in relative units from Fig. 2:

$$P_1 - P_2 = \frac{2\Delta}{\mathrm{tg}\,\alpha}. \tag{5}$$

By substituting this expression in (2), we get:

$$v_p = \frac{2\Delta}{\mathrm{tg}\,\alpha (P_1 + P_2)} \times 100\% \cdot \tag{6}$$

Eq. (6) makes it possible to determine v_p for different values of the 2Δ regulation inaccuracy zone, the statism of the characteristics and station loading. For the given characteristics, the value of the regulation inaccuracy zone is equal to:

$$2\Delta = \frac{56.1 - 52.7}{50} \times 100\% = 6.8\% \cdot$$

$$v_p = \frac{0.068}{0.22 \times (0.5 + 0.5)} \times 100\% = 30.9\% \cdot$$

The degree of unevenness of active power distribution increases sharply at given 2Δ and δ as the station loading P_1+P_2 decreases, and at given 2Δ and P_1+P_2 as δ decreases. A radical means for reduction v_p is the installation of a special automatic device for distributing active power between generators [10].

1) Development of a gas-diesel unit model

To build highly efficient GDGU control systems, it is necessary to determine the type and parameters of the dynamic GDGU model with sufficient accuracy for practice. The general dynamic model of GDGU contains both mechanical and electrical parameters. However, since electrical processes in the generator in the absence of disturbance control occur many times faster than mechanical ones, their general influence on the dynamics of the system can be ignored. This is also due to the fact that the active power is supplied by the generator to the power network:

$$P = \sqrt{3} U I \cos\varphi = M\Omega ,$$

where U and I are the operating current and voltage values of the generator, φ is the phase shift angle; M is the torque on the gas diesel shaft; and Ω is the revolutions of the gas diesel engine.

Even in those cases where there is disturbance regulation through Automatic Voltage Regulator (AVR) systems, the speed of the latter is at least an order of magnitude higher than the speed of mechanical systems [22, 23]. Therefore, taking into account the influence of the generator on the dynamics of the GDGU is carried out only by taking into account the inertial masses of the generator rotor. The dynamic properties of a diesel engine were described in the literature at different levels of complexity – from 9-th order systems to the first [24–27]. In most cases, the authors have built adequate models.

The GDGU does not contain such elements as a fuel rail, fuel pump, cataract, mechanical speed controller and the regulation of the gas-air mixture supply is carried out by a low-power reversible DC motor with a capacity of 100 W, which is controlled by a high-speed wide-pulse controller.

The dynamic model of the diesel engine itself, without taking into account the turbocharger for both disturbing and controlling effects, was described by the transfer function [27]:

$$W(s) = \frac{M(s)}{\lambda(s)} = \frac{1/D}{\frac{T_E}{D}s + 1}$$

where $M(s)$ is the torque developed by the engine on the shaft; $\lambda(s)$ is a parameter of the supplied fuel; D is a coefficient that takes into account the self-regulating properties of the primary engine; and T_E is the equivalent time constant of the engine, which takes into account the inertia of the flywheel masses of the engine itself and the generator rotor.

From the given equations it follows that the GDGU without a turbocharger in a wide power range is a nonlinear link with variable gain coefficient $1/D$ and equivalent time constant T_E/D. The fuel valve control engine, together with the valve itself, is presented in the form of a first-order aperiodic link, the input parameter of which is the signal from the output of the PID controller and the output is the amount of gas-air mixture λ. The gas diesel itself is presented in Fig. 4 in the form of two links. The amplifying link K_g, which reflects the transformation of the gas-air mixture flow at the torque on the shaft M, and the inertial link of the first order, which establishes the relationship between the revolutions on the shaft and the magnitude of the moment.

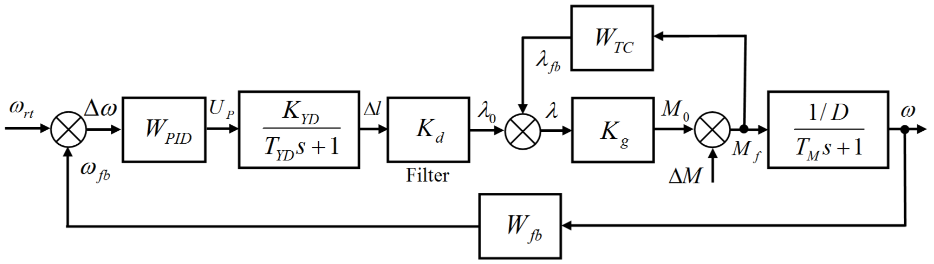


Fig. 4. Structural diagram reflecting the peculiarity of gas diesel operation.

A special feature of this dynamic model is the consideration and explanation of the influence of the turbocharger on the operation of the machine. In the considered dynamic structure, the turbocharger is presented in the form of an aperiodic link of the first order with a low gain coefficient, which covers the first link of the diesel engine with positive feedback. The selection of power in the form of torque is carried out directly after the link. Such a simplified structural diagram of the connection between the turbocharger and the diesel engine eliminates any influence of the engine revolutions on the operation of the turbocharger. At the same time, the influence of the torque is obvious. The increase in torque is equivalent to the increase in the intensity of exhaust gases and the acceleration of the turbine revolutions, which is adequate to the additional opening of the gas-air valve. A decrease in torque is, on the contrary, equivalent to a partial closing of the air valve.

Processes take place slightly differently with sudden changes in the load (moment). When the load increases, the torque $M_f = M_0 - \Delta M$ is momentarily selected, which is supplied to the last link, as a result of which the engine revolutions decrease according to the time constant (T_E/D). A decrease in torque M_f will lead to a decrease in signals λ_{fb} and, accordingly λ, which leads to an additional decrease of M_0. This strengthens the transition process. Therefore, the revolutions ω continue to decrease until, with the help of the main feedback, the appropriate opening of the valve Δl and an increase in the amount of gas-air mixture is ensured.

When the load decreases, the reverse process takes place – the process of increase $M_f = M_0 + \Delta M$. The engine revolutions start to increase. At the same time, an increase of M_f leads to a growing λ_{fb} and, accordingly, $\lambda = \lambda_0 + \lambda_{fb}$. This corresponds to an additional increase of M_f and, accordingly, engine revolutions ω.

According to the control effect, the transfer function of the engine W_{Tg}, taking into account the turbocharger W_{TC} in the positive feedback circuit, takes the following form:

$$W_{\text{Tg}} = \frac{k_g}{1 - k_g W_{\text{TC}}}.$$

If we take into account that the turbocharger is usually presented in the form of an aperiodic link:

$$W_{\text{TC}} = \frac{k_{\text{TC}}}{T_{\text{TC}} s + 1}.$$

Then,

$$W_{\text{Tg}} = \frac{k_g}{1 - \frac{k_g k_{\text{TC}}}{T_{\text{TC}} s + 1}} = \frac{k_g}{1 - k_g k_{\text{TC}}} \cdot \frac{T_{\text{TC}} s + 1}{\frac{T_{\text{TC}}}{1 - k_g k_{\text{TC}}} s + 1}. \quad (7)$$

It follows from Eq. (7) that this link contains a fast-acting differentiating component with a time constant T_{TC} and an integrating component with a time constant $T_{\text{TC}} / (1 - k_g k_{\text{TC}})$. Since under the condition of stability $k_g k_{\text{TC}} < 1$, the time constant can approach the equivalent time constant of the GDGU flywheel masses.

In the presence of disturbing influences on the system, the parameters of the PID controller must be selected in such a way as to ensure such a degree of system damping that excludes the appearance of fluctuation processes in the output parameter. For this purpose, an analysis of the possible reduction of the system fluctuation index m_c and its numerical values was carried out for various parameters of the controller.

It is necessary to estimate the possible decrease of m_c in comparison with m_0 in the presence of a PI controller with a transfer function:

$$W_{\text{PI}}(s) = k_p \frac{(T_I s + 1)}{T_I s} = k_p \left(1 + \frac{1}{T_I s} \right),$$

where k_p is the gain coefficient of the controller, T_I is the time constant of integration.

The transfer function of a closed system with a PI controller at $W_{fb} = 1$ is as follows:

$$W = \frac{W_{\text{PI}}(s) W_O(s)}{1 + W_{\text{PI}}(s) W_O(s)}.$$

The characteristic equation is obtained when $s = m_c \omega \pm j\omega$:

$$1 + W_{\text{PI}}(m_c, j\omega) W_O(m_c, j\omega) = 0.$$

The following calculation equation can be obtained from the following equation:

$$k_p = \frac{1}{A_0} \left(\omega T_I \left(m_c^2 + 1 \right) \sin \varphi_0 \right) = \frac{1}{A_0} \left(m_c \sin \varphi_0 - \cos \varphi_0 \right),$$

from which is obtained:

$$m_c = \frac{k_p A_0 + \cos \varphi_0}{\sin \varphi_0} = \sqrt{\frac{A_0 k_p}{\omega T_I \sin \varphi_0} - 1},$$

where the magnitude-frequency characteristic of the object is as follows:

$$A_0 = \sqrt{\left[\text{Im}_0 (m_0 \omega)_0 \right]^2 + \left[\text{Re}_0 (m_0, \omega) \right]^2} - \frac{k_0}{\left(1 - \omega^2 T_0 \right)^2 + \left(2 \xi \omega T_0 \right)^2}$$

phase-frequency characteristics:

$$\varphi_0 = \frac{\text{arctg} \left(\text{Im}_0 (m_0 \omega) \right)^2}{\text{Re}_0 (m_0 \omega)}.$$

The analysis of the obtained expressions shows that the value of the fluctuation index m_c cannot be reduced in comparison with m_0. This also follows from the analysis of the logarithmic magnitude-frequency characteristics of the open system (Fig. 5(a)):

$$W_P = W_P W_O = \frac{k_p T_I s + 1}{T_I s} \frac{k_0}{T_0^2 s^2 + 2 \xi T_0 s + 1},$$

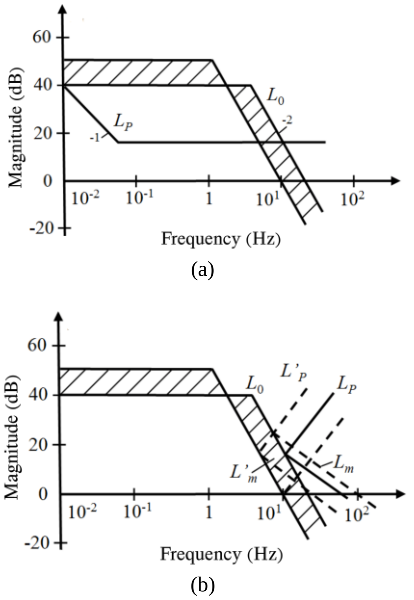
from which it follows that it is fundamentally impossible in such a structure to provide the desired logarithmic magnitude-frequency characteristics with a section of –20 dB/dec.

It is obvious that the same picture will be observed for the proportional controller with $W_p = k_p$. The characteristic equation of the system in this case is as follows:

$$T_0^2 s^2 + 2 \xi T_0 s + (k_p k_0 + 1) = 0.$$

From the last equation, it is easy to establish the relationship between indicators of the fluctuation of the system m_c and the object m_0:

$$m_c = m_0 \sqrt{k_0 k_p \left(1 + m_0^2 \right)} + 1.$$



(a)

(b)

Fig. 5. (a) Bode magnitude plot of the open-loop system and (b) Bode magnitude plot taking into account the change in gas diesel parameters.

In Fig. 5 the following notations are used to designate LFCs: L_0 is the control object, L_p is the ideal controller, L'_p is the adjusted controller, L_m is the control object taking into account changes in gas-diesel parameters, L'_m is the control object taking into account changes in gas-diesel parameters and adjusted controller parameters.

Thus, when $m_c < m_0$ fluctuation processes can only increase. At the same time, the frequency of fluctuations

$$\omega_0 = \frac{1}{T_0}\sqrt{1 + k_0 k_p - \xi^2} \,.$$

herewith, $k_0 k_p > 1$ also increases.

Next, we consider the possibility of reducing the degree of flunctuation of the system for the case of an ideal PD controller with a transfer function:

$$W_{\text{PD}}(s) = k_p(1 + T_D s) \,.$$

where T_D is the time constant of differentiation.

The characteristic equation for this case is the following:

$$T_0^2 s^2 + (2\xi T_0 + k_0 k_p T_D)s + k_0 k_p + 1 = 0 \,.$$

from which there is a connection between the setting parameters T_D, k_p and m_c, m_0.

$$m_c = \frac{\dfrac{T_D}{2\xi T_0} k_0 k_p + 1}{\sqrt{\left(\dfrac{m_0^2 + 1}{m_0^2}(k_0 k_p + 1) - \left(\dfrac{T_D}{2\xi T_0} k_0 k_p + 1\right)^2\right)}} \,. \qquad (8)$$

From the last expression, as a result of the analysis, you can see that the parameter can increase, that is, the fluctuation process in the system will decrease.

The relationship between the parameters can be established from the obtained expression or from the construction of the desired logarithmic magnitude-frequency characteristic taking into account the change in gas-diesel parameters (Fig. 5(b)).

From the analysis of the logarithmic magnitude-frequency characteristic, it follows that the adjustment of the controller should be carried out not at the nominal power of the gas-diesel, but at the minimum power. In this case, an increase in the load due to a decrease in the gain coefficient will lead to an increase in the stability margin.

To ensure an aperiodic transient process, when $m_c = \infty$, from Eq. (8), we obtain the following ratio:

$$\frac{m_0^2 + 1}{m_0^2}(k_0 k_p + 1) = \frac{T_{\text{D}}}{2\xi T_0} k_0 k_p + 1 \,.$$

which allows finding the necessary relationship between the parameters of the controller and the object.

Fig. 6 shows a dynamic model of a gas diesel engine with set parameters close to the physical ones for the considered units.

It can be seen from the figure that the gas-diesel itself is represented by three sequentially connected links. The positive feedback link takes into account the effect of the turbocharger. The parameters of the gas-diesel dynamic model are determined by using identification methods and further adjustment for the adequacy of transient processes of decreasing/increasing of loading, as well as for control.

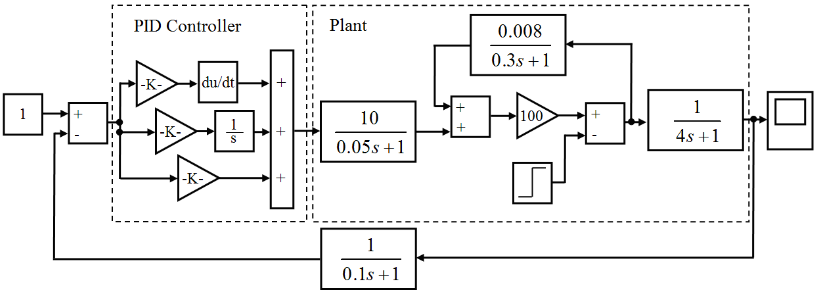


Fig. 6. Dynamic model of gas diesel.

A functioning of the GDGU can be considered as an ideal machine, which is affected by additive noise. Additive noise in the form of a destabilizing function f_ω is applied to the output. The transfer function of the system is described by the expression:

$$W_{\text{K}}(s) = W_{\text{PID}}(s) W_{\text{TC}}(s) W_{\text{Tg}}(s) W(s) \,.$$

The interference level $f_{\omega\text{CL}}$ at the output of a closed-loop system is

$$W_{\omega\text{CL}} = \frac{f_\omega}{1 + W_K} = f_\omega \frac{1}{1 + W_K} = f_\omega W_{\text{CL}} \,.$$

The spectral density of interference at the output of a closed-loop system is

$$S_{\omega\text{CL}}(\omega) = S_\omega \cdot \left|W_{\text{CL}}(j\omega)\right|^2 = S_\omega \cdot \left|\frac{1}{1 + W_{\text{K}}(j\omega)}\right|^2 .$$

From the above expression, taking into account the nature of the LFC of the stable system for the region of effective interference suppression, where $|W_K| >> 1$, we have

$$S_{\omega\text{CL}}(\omega) \approx S_\omega \frac{1}{\left|W_{\text{K}}(j\omega)\right|^2} ,$$

$$S_{\omega \mathrm{LC}}(\omega)=S_{\omega}\frac{\left(\dfrac{T_I}{K_E}j\omega\right)^2}{1+\left(\dfrac{T_I}{K_E}\right)^2\omega^2}.$$

Since in a real system the PID controller is adjusted to only one point in the operating range, there is reason to believe that the proposed control algorithm will significantly increase the stability of gas-diesel engine revolutions period throughout the entire range of load power changes.

B. Optimization of Gas-Diesel Unit Controller Parameters

Fig. 7 shows the structural diagram of the control system, which includes a self-adjusting controller.

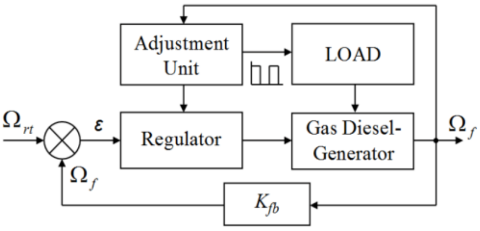


Fig. 7. Structure of the GDGU control system with auto-adjustment of the controller.

In Fig. 7 the following is marked: Ω_{rt} is set rotation frequency, Ω_f is actual rotation frequency, ε is error signal. The basis of the system is a digital PID controller.

In order to avoid the influence of measurement noise on the control process and to prevent the infiltration of high-frequency components, to which the differential link of the controller reacts particularly strongly, the feedback signal is digitally filtered. In this case, a low-pass filter with a cutoff frequency of 60 Hz is used, since, it has been found experimentally, the maximum frequency of the output voltage of the GDGU does not exceed this value. The approach used to solve problems of digital signal filtering was considered in [28].

The adjustable controller works as follows. The operator sets the requirements for the system. The controller setting unit generates a pulse signal that controls the connection and disconnection of the load to the GDGU. The value of the load increases from 0 to 100% of the generator power in steps of 20%. At the same time, for accurate adjustment of the controller (reduction of the influence of measurement error), connection and disconnection of the load is performed for each point a specified number of times. The identification of the control object is performed according to the experimental transient characteristic.

The next stage in the creation of a real GDGU rotation stabilization system should be the search for optimal parameters of the PID controller coefficients and their practical implementation to ensure the stable operation of the engine in a wide range of load changes. For the considered case of using GDGU in AEPS, a criterion is selected as an optimization criterion, according to which the maximum speed recovery of nominal revolutions with an acceptable over-regulation should be ensured, which, in accordance with the standards for the voltage quality of autonomous electric power systems, should not exceed 5%.

To solve the problem of optimizing the parameters of the PID controller coefficients, the method of dynamic optimization is used during simulation modeling by using the Nonlinear Control Design (NCD) application program package, which is part of the BlockSets Simulink tools.

Having the given structure of the control object and the known uncertainties of its parameters, it is necessary to find the values of the coefficients K_p, K_i and K_d. The values of the coefficients K_p, K_i and K_d of the controller are chosen in accordance with the Ziegler-Nichols method, intended for optimal adjustment of PID controllers. Since the gas-diesel-generator unit is characterized by high instability of the rotation frequency, which in turn depends on the load of the generator (moment on the shaft of the gas-diesel), it is necessary to adjust the coefficients of the controller depending on the power of the load P_L, which is connected to the generator and causes the failure of the revolutions of the gas-diesel generator.

On the basis of the conducted experiment, the values of the controller coefficients have been obtained, which at a given load power provide the best transition process in dynamic modes. The values of the coefficients are given in Table II, Table III and Table IV at different values of the gas diesel power ΔP (in no-loading mode; at ΔP = 15% P_{rt} and at ΔP = 30% P_{rt}) at the moment of connection of the power load P_L (at relative units compared to the output power of the gas-diesel generator).

TABLE II: OPTIMAL VALUES OF THE CONTROLLER COEFFICIENTS IN IDLE MODE

P_L	K_d	K_i	K_p
0.1	1.4322	1.0624	1.4796
0.2	1.4322	1.0622	1.4681
0.3	1.448	1.0688	1.4744
0.4	1.448	1.069	1.468
0.5	1.4467	1.048	1.4537
0.55	1.4219	1.0655	1.4501
0.6	1.4041	1.0162	1.4366
0.65	1.3473	0.999	1.3677

TABLE III: OPTIMAL VALUES OF COEFFICIENTS AT ΔP = 15% P_{RT}

P_L	K_d	K_i	K_p
0.1	1.4203	1.067	1.4698
0.27	1.3946	1.0548	1.4699
0.4	1.3495	1.08	1.4753
0.5	1.3493	1.0787	1.4758

TABLE IV: OPTIMAL VALUES OF COEFFICIENTS AT ΔP = 30% P_{RT}

P_L	K_d	K_i	K_p
0.1	1.3825	1.0594	1.3584
0.2	1.4195	1.0769	1.4746
0.25	1.4229	1.0822	1.4719
0.3	1.3969	1.0724	1.5234
0.35	1.4199	1.0724	1.5181

To check the response of the PID controller, a Matlab model of a diesel unit with auto-adjustment of the optimized parameters of the PID controller based on the change in load power was built from the obtained dependences of the coefficients on the load power. The structure of the model is shown in Fig. 8.

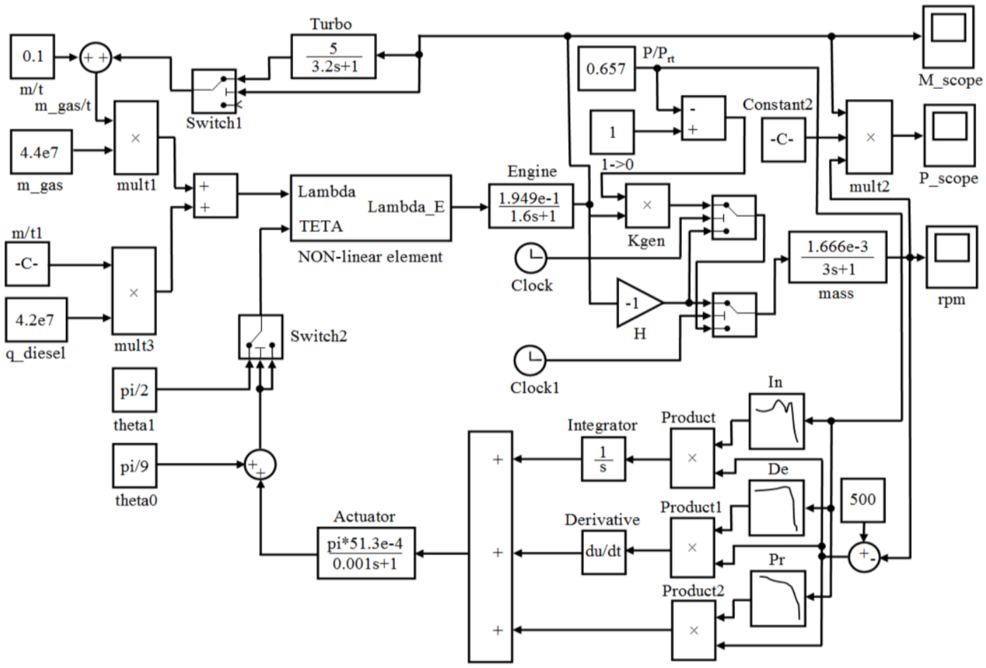
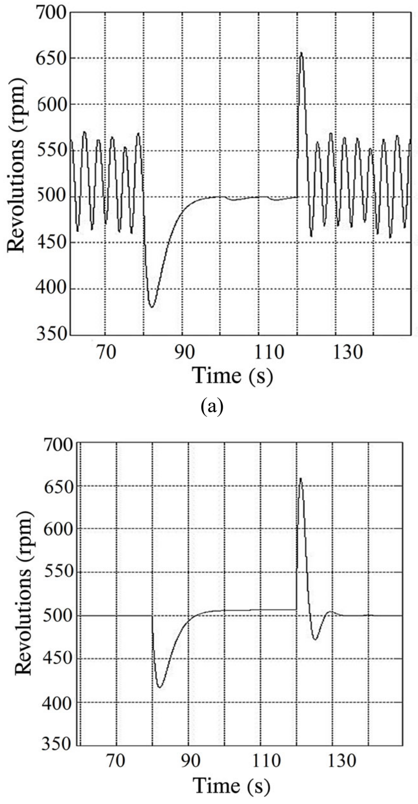


Fig. 8. Model of a gas engine with auto-adjustment of the controller.

The algorithm of the controller auto-tuning was implemented in the software for a microcontroller. Setting the value P=0 means that the PID controller coefficients are configured for idle mode. The initial value of the proportionality coefficient and the time for increasing the value of this coefficient are selected. Before setting the proportional band, the integral and differential components are turned off, or the integration constant is set to the maximum possible value, and the derivative constant to the minimum possible value. Coefficients K_i, K_d are set equal to zero. Then the proportionality coefficient K_p is increased until the system loses stability. This mode is monitored by calculating the derivative of the controlled parameter. If the object is stable, then the derivative of the controlled parameter is 0 (or close to 0). When output oscillations appear, the derivative will differ from 0. The boundary value of K_p is designated as K_u, the period of auto-oscillation as P_u. When this mode occurs, it is necessary to measure the oscillation period. The algorithm is based on the Ziegler-Nichols method for tuning PID controllers. The following values of the controller coefficients are set:

$$K_p = \frac{3K_u}{5};\ K_i = \frac{6K_u}{5P_u};\ K_d = \frac{3K_uP_u}{40}.$$

After this, a signal is generated to connect 20% of the load of the generator maximum power. A new adjustment of the coefficients for the given load is performed. After the controller settings have been made for 6 points (0%, 20%, 40%, 60%, 80%, 100%), the algorithm ends its work. The obtained coefficients are used during the operation of the GDGU and are adjusted depending on the load connected to the generator. When optimizing the controller settings using the proposed approach, the real properties of not only the control object, but also all other parts of the closed-loop system are taken into account.



(a)

(b)

Fig. 9. The process of dip and burst of revolutions of a diesel engine: (a) non-optimal parameters of the controller and (b) with optimized controller parameters.

A type of auto-tuning is the open control of the controller parameters, when previously found controller parameters for various operating conditions of the system are entered into a table, from which they are taken when the conditions for which adaptation is initiated occur. For this case, the dependences of the PID controller coefficients K_p, K_i and K_d on the load power are implemented in Matlab/Simulink through nonlinear elements Pr, In, De (Look-Up Table block), the outputs of which the corresponding values of K_p, K_i and K_d are given automatically when the load power changes.

C. Evaluation of the Efficiency of Stabilization of Gas-Diesel Unit Parameters

In Fig. 9(a), the transient process of dips and rises of revolutions of a gas engine without auto-adjustment is shown. In Fig. 9(b), the transient process of dips and rises of revolutions of a gas engine with optimized parameters K_p, K_i and K_d is shown. In both cases the load is equal to $0.357P_{\text{rt}}$.

In the case of sharp fluctuations of the controlled value, the quality of the transient process in the system with a PID controller may turn out to be unsatisfactory, since the initial assumption about the linearity of the object is not fulfilled. That is why there is a need to use additional devices that adjust the operation of the PID controller, which has been done in this work.

Since in the real system the controller was adjusted to only one point of the operating range, there is every reason to believe that the proposed control algorithm will significantly increase the stability of gas-diesel revolutions in the entire range of load capacities.

With the optimal setting of the PID controller for the entire power range, it is possible to reduce the range of gas-diesel revolutions by 15–20 times theoretically. Optimizing the parameters of the controller of a diesel-generator unit during its single operation made it possible to actually increase the stability of the revolutions of the diesel unit, which in turn makes it possible to ensure their parallel operation under the condition of effective control of the active power of each of the generators.

The further development in this direction is in the study of the possibility of using a fuzzy logic based controller to solve a similar problem. At the same time, to identify the parameters of a gas-diesel engine as a nonlinear control object and construct the membership functions of the controller, the fuzzy clustering method is used. It is also necessary to build a simplified but adequate model of a synchronous generator and combine it with a gas-diesel model to study the dynamic operating modes of a gas-diesel generator and solve optimization problems to improve the quality of control.

III. CONCLUSION

The research analyzed gas-diesel engine revolution fluctuations, estimating potential power fluctuations between units on total load. This highlights the necessity for adaptive control systems with nonlinear controller coefficients. Analyzing the gas-diesel generator's design features revealed causes for revolutions fluctuations, leading to enhancements in the dynamic model. This considers the turbocharger's influence, nonlinear properties, and actual parameters of the fuel supply system. The proposed model addressed low-frequency engine revolution fluctuations in static and dynamic. The necessity of using a differential component in the gas-diesel revolution controller has been substantiated, and the analytical dependence between the parameters of the controller and the diesel engine has been established, which allows to determine the acceptable degree of the revolution system. An adaptive structure of the GDGU control system has been developed, which provides automatic search and implementation of optimal coefficients of the PID controller during operation based on dynamic processes caused by load switching. By using the Matlab simulation environment, the optimization of the controller parameters has been performed and nonlinear dependence of the controller coefficients on the load have been found, which ensured an effective increase in the quality of GDGU control, and as a result, frequency stability in the AEPS network. The developed hardware and software for controlling the parameters of the PID controller depending on the load of the GDGU made it possible to optimize the dynamic modes of its operation in the wide range of loads and reduce the dispersion of gas-diesel engine shaft revolutions by 15–20%.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Mahmoud M. S. Al-suod conducted an analytical review of the literature; developed the structure of an auto-tuning gas-diesel engine control system; developed a Matlab model of the control system and obtained the optimal values of the PID controller coefficients, quantified the degree of reduction in gas-diesel revolution fluctuations. O. Ushkarenko developed a bench and carried out an experimental study of self-oscillatory processes of a gas-diesel shaft, determined the possible range of uneven distribution of active power between generators due to frequency oscillations; developed a simplified dynamic model of a gas-diesel engine taking into account its design features, justified the need to use an adaptive PID controller to improve control quality. All authors had approved the final version.

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