

## MODELLING OF THE GENERATOR DIAGNOSIS SYSTEM BASED ON A SPARK IGNITION ENGINE

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This study proposes a new approach to the diagnosis of autonomous power-generating equipment operating on the basis of a spark-ignition engine, using computer simulation of the technical diagnosis system. The main idea of this method is the ability to mathematically determine the diagnostic parameters of the system, which allows analytically assessing the degree of wear of the cylinder-piston group. Determining the currents of the electric starter allows setting the functional parameter – the real degree of compression. This definition of the degree of compression allows setting the energy indicators of the generator. Using this method it is possible to establish the dependence of specific energy indicators on the technical condition of the generating plant. The conducted research resulted in the development of a multi-level hierarchical multi-component model of the system of technical diagnostics of a generator based on a spark-ignition engine. This model allows one to predict the diagnostic parameters of the research object and choose the necessary diagnostic tools. Calculation data obtained using the developed mathematical model of an electric generator with a single-cylinder engine and spark ignition based on real parameters testify to the high adequacy of the proposed mathematical model.

**Keywords:** *Electric generator, energy efficiency, internal combustion engine, fuel consumption.*

## 1. INTRODUCTION

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Ukraine has considerable experience in the practical use of renewable energy sources. According to the estimated data of the long-term programme “Energy Conservation and Improvement of Energy Efficiency of Ukraine until 2050”, the maximum use of renewable energy sources (RES) in Ukraine opens up real opportunities for increasing generation capacities based on them. Often, the use of RES technologies for autonomous power supply systems requires the availability of a reliable backup source of electricity. Electric generators based on internal combustion engines occupy the first place among reliable and profitable backup sources of electricity [1]–[3]. Electric generators based on internal combustion engines are also widely used independently to provide electricity in emergency situations and for humanitarian power supply.

Ensuring the efficient use of energy resources has always been of great interest to decision-makers at the national, European and international levels. The European Union (EU) and all its members signed and ratified the Paris Agreement, committing to reduce greenhouse gas emissions by 55 % by 2030 compared to 1990 levels. Achieving such a goal is possible only if reliable energy-generating equipment based on internal combustion engines with high energy efficiency and low emission levels is used. Maintenance of this equipment in good condition is possible thanks to the application of diagnostic methods aimed at monitoring indicators of its condition, which affect energy efficiency as a whole. Cylinder compression, or real compression, is one of the key indicators affecting the energy efficiency of power generating equipment. This indicator is determined

by the ratio of the volume of the combustion chamber to the volume of the fuel-air mixture after closing the exhaust valve. Increased compression levels play a crucial role in enhancing the efficiency of fuel-air combustion. This, in turn, boosts productivity and lowers fuel consumption, thereby aiding in the pursuit of greater energy efficiency [4]–[8].

Obtaining experimental data and analysing diagnostic signs is the basis of the diagnostic process. These signs determine the state of the object under study depending on their informativeness. There are several diagnostic methods for the diagnosis of internal combustion engines, which is often carried out by comparing the obtained experimental data with normative ones. Compression measurement using compressors and barographs is a progressive method for diagnosing the tightness of the cylinder-piston group of an internal combustion engine. Among the disadvantages of this method, we can note the great laboriousness associated with disassembling the engine to measure compression, as well as the possible unreliability of the data obtained, which can arise for various reasons, such as the condition of the engine, the quality of the equipment and the correctness of its application.

The internal combustion engine diagnostic system, which uses the starter current level as a diagnostic parameter, will avoid the disadvantages associated with high labour intensity and unreliability of data that may occur when measuring compression. This method allows one to carry out diagnostics without the need to disassemble the engine, which simplifies the process and reduces its time and effort [6], [8]. Thus, diagnostic systems that are based

on the analysis of the change in the cranking moment of the spark-ignition engine without fuel supply in the compressor mode use the measurement of the starter current and voltage level as a diagnostic parameter. This method allows detecting anomalies in the operation of the engine, such as wear of the cylinder-piston group or problems with the lubrication system, without the need for extensive labour and disassembly of the engine. The motor testers, such as KAD30003, M32, MT3500 and similar, are examples of diagnostic complexes that use a diagnostic method based on the analysis of the change in the torque of the crankshaft of a spark ignition engine. They allow for comprehensive diagnostics of various engine systems and units, including checking the cylinder-piston group, starting system, ignition system, and others. The use of this method of diagnosis really allows increasing the reliability and accuracy of the results, while reducing labour costs.

## 2. LITERATURE REVIEW

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The studies of energy efficiency parameters of systems using a starter motor are divided into two main groups. The first group of studies concentrates on starting engines without switching the system into a special mode and describing functional diagnostic systems. The second group includes tests of the system in special modes, such as compression or with partial depressurization, and a description of diagnostic test systems.

Among the studies of the first group, which are distinguished by the high quality of the detailed description and formulation of the problem, it is possible to single out the starter alternator system in a hybrid electric vehicle [9]–[11]. The mentioned articles present an analytical model that is

However, for the successful application of this method, it is necessary to have previously known values of diagnostic parameters, which can become a problem in the case of new diagnostic objects or unknown anomalies. Such limitations require careful planning and preparation before applying the method.

To predict the parameters of the system of technical diagnostics of the generator based on the engine with spark ignition using the compressor method, it is necessary to develop a process model that allows selecting system components. This model may include such components as mathematical equations, data analysis algorithms, statistical methods and other tools for predicting the state of the object and identifying possible malfunctions. An important part of developing such a model is choosing the right diagnostic parameters and their optimal combination to achieve the best forecasting results.

useful for analysing the torque of an internal combustion engine. This model also describes a control system that uses torque transfer with direct engine speed feedback to reduce engine torque ripple. The article proposes to use the dependencies describing the isothermal process to illustrate the process of air compression in cylinders. The application of these dependencies is possible provided that the real process of air compression by the engine starter in the compressor mode is considered.

In the studies devoted to the description of the functional diagnostic system, the crankcase gas pressure is used as a diagnostic parameter of the engine condition [12]–[14]. The articles do not contain proposals for mathematical modelling of the

diagnostic process. Application of the proposed method is possible only if experimental data are available for each specific object.

Research into the process of diagnosing the cylinder-piston group in the compressor mode is concentrated on the electrical parameters of starting the starter motor [15]–[18] or the pressure generated as a result of air compression [19]–[21] used as diagnostic indicators. The proposed models of the battery, electric starter and resistance of the engine with spark ignition can be useful for modelling the system of technical diagnostics of the generator.

When analysing the currents and pressures that occur during engine rotation, the supports originating from compression forces are taken into account, using the geometric parameters of the cylinder-piston group and the crank-connecting mechanism. Nevertheless, it is important to acknowledge that the overall resistance to rotation is not solely dictated by compression forces; rather, it is influenced by various other factors. These include the resistance stemming from lubricant blending, friction within rotating or slowly moving components, hindrance from auxiliary

components within the power system, and inertial forces.

Setting the components of these components is a very difficult task due to the significant influence of the rheological and tribological properties of the system on the mechanics of the contact interaction of the elements [22]. Considering all the specified components, it is practically impossible to obtain a solution to the acquired systems of equations. Also, preliminary experimental studies confirm the significant influence of the flywheel, which temporarily evens out the curve of the current change.

Due to the complexity of the analytical solutions in many studies, numerical methods have been employed, utilising the Simulink/Matlab interactive simulation and analysis tool [23].

Considering the above, it is possible to conclude about the need to improve the theory, methods and means of existing methods of diagnostics of power equipment based on engines with spark ignition.

The aim of this research is to develop a mathematical model of a system of technical diagnostics of a generator based on a spark-ignition engine, where the starter current is used as a diagnostic indicator.

### 3. DESCRIPTION OF RESEARCH METHODS

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Diagnostic indicators are used to determine the state of the spark-ignition engine as part of the power plant, particularly the current strength of the starter, which rotates the engine in compressor and depressurized modes. Diagnostics of the electric generator engine is carried out without fuel supply and with the load on the electric generator turned off.

Among the diverse spectrum of autonomous generators, the authors paid spe-

cial attention to generating units that use a single-cylinder gasoline engine with a volume of 150 to 250 sm<sup>3</sup>. Table 1 shows the technical characteristics of these energy-generating systems. Most generators use a synchronous generator with an AVR, which includes both rotor and stator windings. The rotation of the generator rotor is provided by a centrifugal frequency regulator connected to the carburettor.

**Table 1.** Technical Characteristics of a Synchronous Electric Generator with a Spark Ignition Engine

| Parameter                   | Unit            | Value                                         |
|-----------------------------|-----------------|-----------------------------------------------|
| Engine type                 | -               | 4-stroke gasoline engine with air cooling OHV |
| Number of cylinders         | -               | 1                                             |
| Engine model                | -               | 168F, 170F, HONDA GX160, GX200                |
| Engine capacity             | cm <sup>3</sup> | 150-250                                       |
| Rated engine power          | W               | 3.3-4800                                      |
| Maximum power               | W               | 2800                                          |
| The volume of the fuel tank | m <sup>3</sup>  | 0.015                                         |
| The volume of the oil sump  | m <sup>3</sup>  | ~0.0006                                       |
| Weight                      | kg              | 53.6                                          |

This type of equipment uses a permanent magnet DC collector motor that has a high torque. The electric starter is equipped with a special relay that switches the power supply to the electric motor and controls a special clutch assembly with the engine fly-wheel with spark ignition.

The generator diagnostics process includes the following main components: generator (1), internal combustion engine (2), gearbox (3), starter (4), direct current sources (battery) (5), Hall effect sensor (6), sensor power source (7), analogue-digital converter (8) and computer (9) (see Fig. 1). The process of obtaining diagnostic data involves fixing the position of the crank-shaft of the internal combustion engine (2) and the stator current (4) by the computer (9). This diagnostic system allows detect-

ing the relationship between the stator current and the state of the thermal unit of the power plant. During the development of this diagnostic test system, the main aspect is the determination of the equipment parameters that will ensure the necessary accuracy and reliability of the process. The effectiveness of diagnostics depends on the energy characteristics, which determine the choice of sensors according to a certain level of direct current, the power of the current source and the polling frequency of the analogue-to-digital converter channels. The use of interactive tools for building multi-level hierarchical multi-component models of the system of technical diagnostics of a generator based on a spark-ignition engine will allow predicting the physical parameters of processes.

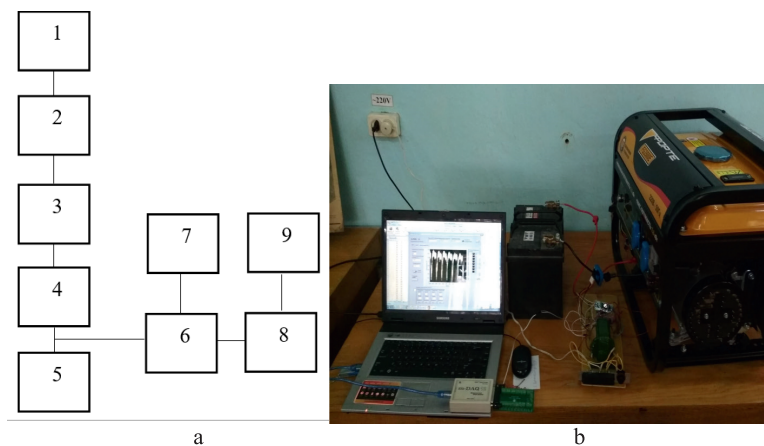


Fig. 1. Scheme (a) and appearance (b) of the system for diagnosing generators by starter current.

Figure 2 shows the scheme of the mathematical model of the system of technical diagnostics of the generator based on the engine with spark ignition. In the electro-mechanical scheme of this diagnostic system, the main components are the elements

of the crank mechanism, such as piston (1), connecting rod (2) and crankshaft (3), as well as the generator rotor (4) and flywheel (5). There are also starter armature (6) and armature windings (7).

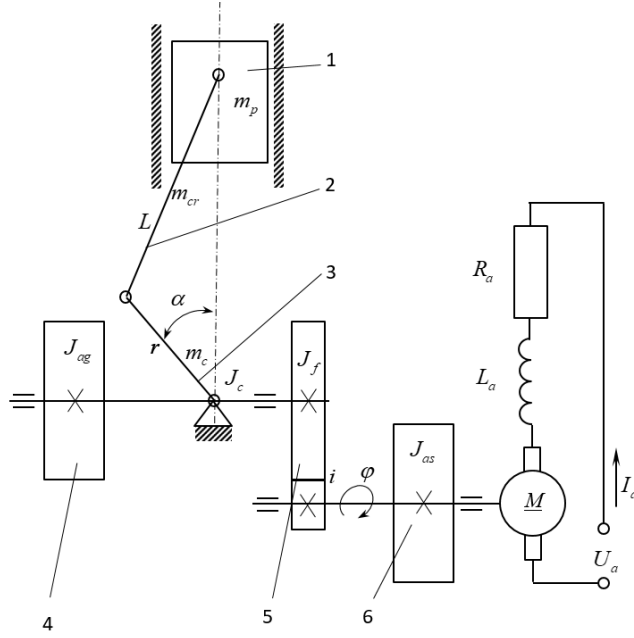


Fig. 2. Scheme of the electromechanical system of diagnostics of a generator operating based on an engine with spark ignition.

The functioning of the electric starter can be described by a system of differential equations in the normal Cauchy form for a

DC motor with independent excitation from permanent magnets:

$$\begin{cases} U_a - R_a I_a - k_\omega \frac{d\varphi}{dt} = L_a \frac{dI_a}{dt}; \\ k_m I_a - b \frac{d\varphi}{dt} - M_0 / i_g = J_0 \frac{d^2\varphi}{dt^2}; \end{cases} \quad (1)$$

where  $U_a$  – DC power supply voltage;  $i_g$  – gear ratio of the electric starter reducer;  $R_a$  and  $L_a$  – active resistance and inductance of the armature winding;  $b$  – viscous friction resistance;  $k_\omega$  – constant electromotive force of the engine;  $k_m$  – engine torque constant;  $M_0$  – moment of resistance to rotation of the shaft;  $J_0$  – the given moment of inertia.

The moment of inertia, taking into account the flywheel transmission ratio, is formed from a constant moment and a vari-

able moment associated with a change in the inertia of the system:

$$J_0 = J_1 + J_2 = J_{as} + (J_f + J_{ag} + J_c + m_2 R^2) \left( \frac{1}{i_g} \right)^2 + (m_p + m_1) \left( \frac{r \left( \sin \left( \frac{\varphi}{i_g} \right) + \frac{R}{2L} \sin 2 \frac{\varphi}{i_g} \right)}{i_g} \right)^2, \quad (2)$$

where  $m_1$ ,  $m_2$  – the separated mass of the connecting rod, which connects the piston and the crankshaft.

The analysis of the dependence of the change in the components of the moment of inertia of the selected diagnostic system during one rotation of the crankshaft shows the harmonic nature of the changes during the rotation of the crankshaft and the change in the moment of inertia within 0.8 %. Taking into account the insignificant influence of the variable inertial component, this system moment of inertia can be calculated

with high accuracy by considering only its constant component.

In the balance of the moment of mechanical losses, the main parameter under consideration is the moment of resistance arising from the compressive forces in the cylinder. The moment of resistance is calculated using the dependence that connects the pressure and the kinematic characteristics of the system:

$$M_c \approx p_c F_c R \left( \sin(\varphi / i_g) + \frac{\lambda}{2} \sin(2\varphi / i_g) \right), \quad \varphi / i_g \in (0; \pi), \quad (3)$$

where  $F_c$  – piston area;  $\lambda = R / L$  – crank radius ratio  $R$  to the length of the connecting rod  $L$ ;  $p_c$  – current pressure in the cylinder;  $R$  – crank radius.

With a certain approximation, it can be assumed that the increase in current pres-

sure in the cylinder occurs according to the following dependence:

$$M_c \approx \frac{p_{\max}}{\pi} \varphi / i_g F_c R \left( \sin(\varphi / i_g) + \frac{\lambda}{2} \sin(2\varphi / i_g) \right), \quad \varphi / i_g \in (0; \pi). \quad (4)$$

The resistances that arise from the forces of mechanical friction in the cylinder-piston group and from the hydraulic resistance during the passage of air are also significant. Mechanical losses include a number of aspects, such as overcoming the friction of pistons in cylinders, friction in bearings, losses associated with the operation of the pump (to carry out intake and exhaust processes), energy losses on the drive of auxiliary mechanisms (such as the

distribution mechanism, oil, water and fuel pumps, as well as ventilation losses, etc.). During engine diagnostics at low speeds ( $< 20$  rad/s), hydraulic expenses are negligible. At this operational mode, approximately 90 % of mechanical losses stem from piston friction within the cylinders. The means of theoretical courses and special literature on the mechanics of contact interaction allow calculating the friction moment of piston rings using the following expression:

$$M_r \approx p_r i_r \pi D h \mu R \left( \sin(\varphi / i_g) + \frac{\lambda}{2} \sin(2\varphi / i_g) \right), \quad (5)$$

where  $p_r$  – radial pressure from the elastic forces of the piston ring;  $h$  – the height of the piston ring;  $i_r$  – the number of piston rings;  $D$  – cylinder diameter;  $\mu$  – a coefficient of friction of the piston rings on the cylinder wall.

The total resistance arises from the forces of mechanical friction in the cylinder-piston group and from the compression forces in the cylinder:

$$M_r \approx \left| R \left( p_r i_r \pi D h \mu + \frac{p_c}{\pi i_g} \varphi F_c \right) \left( \sin(\varphi / i_g) + \frac{\lambda}{2} \sin(2\varphi / i_g) \right) \right|. \quad (6)$$

It should be noted that the total resistance to the rotation of the generator by the starter (6) has a constant value, regardless of the position of the crankshaft. It is also

necessary to specify that the compression component of the total resistance acts on the part  $(0; \pi)$  the entire cycle  $(\pi; 4\pi)$  :

$$\begin{aligned} M_c &= R, \text{ with } \varphi / i_g \in (0; \pi); \\ M_c &= 0, \text{ with } \varphi / i_g \in (\pi; 4\pi). \end{aligned} \quad (7)$$

The following expression was used in the modelling process:

$$f(\varphi) = \frac{\varphi}{i_g} \cdot \theta \left( 0,25 - \left( \frac{\varphi}{i_g \cdot 4\pi} - \left[ \frac{\varphi}{i_g \cdot 4\pi} \right] \right) \right). \quad (8)$$

Figure 3 shows a block diagram in an interactive programming environment for displaying the resistance that arises from the mechanical friction forces of the cylinder-piston group and from the compression forces in the cylinder (6).

In the block diagram using frames, the components reflecting the compression forces in the cylinder (3) and the friction forces of the piston rings (5) are marked. The function that determines the position of the crankshaft depending on the angle of rotation of the stator armature is shown by block (8). The main

parameters describing the mechanical system include: maximum pressure  $p_{\max} = 0.9 \text{ MPa}$  ; diameter of the cylinder  $D = 0.07 \text{ m}$  ; crank radius  $R = 0.0275 \text{ m}$  ; connecting rod length  $L = 0.06 \text{ m}$  ; thickness of piston rings  $i_r = 0.025 \text{ m}$  ; the number of piston rings  $i_r = 3$  ; radial pressure from the elastic forces of the piston ring  $p_r = 0.3 \text{ MPa}$  ; coefficient of friction of the piston rings on the cylinder wall  $\mu = 0.4$  .

The total moment of resistance arising from the forces of mechanical friction (Fig. 2) makes it possible to create a block

diagram based on the system of equations (1), which describes the functioning of the generator electric starter. The block diagram that describes the operation of the electric generator starter includes three main blocks: (I) – the block of integration of the first equation to determine the current of the armature windings; (II) – the block of integration of the second equation for determining the angle and speed of rotation of the armature; (III) – the load unit from a spark-ignition engine. Parts reflecting inertial forces and resistance from mechanical friction and air compression are added

using a negative sign (Fig. 4). The parameters of the circuit block in the interactive environment for determining the parameters of the diagnostic system became: DC power supply voltage  $U_a = 12V$ ; became the electromotive force of the engine  $k_\omega = 0.35 Nm / A$ ; viscous friction resistance  $b = 0.012 Nms / rad$ ; became the torque of the engine  $k_m = 0.35 Vs / rad$ ; gear ratio of the electric starter gearbox  $i_g = 15$ ; active resistance  $R_a = 0.1 \Omega$  and the inductance of the armature winding  $L_a = 0.0001 H$ ; given moment of inertia  $J_0 = 0.00093 kg \cdot m^2$ .

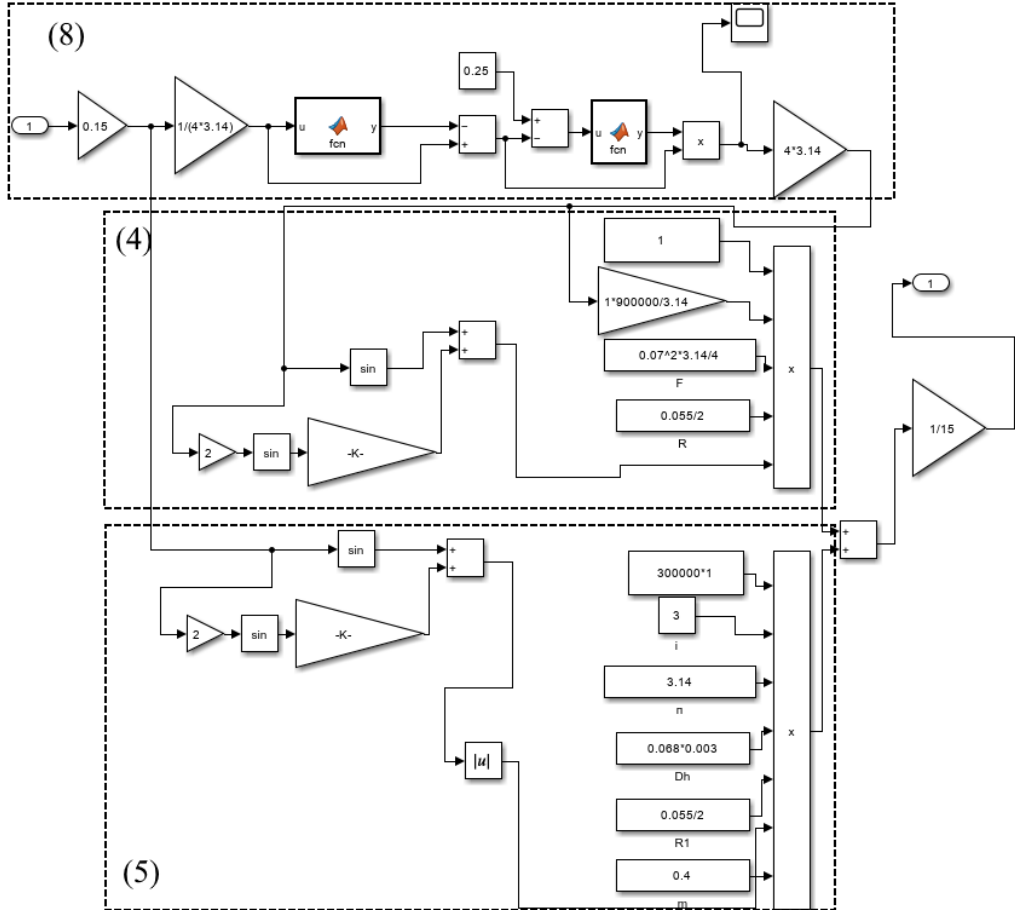


Fig. 3. Block diagram in an interactive environment for determining the resistance from the forces of mechanical friction and air compression.

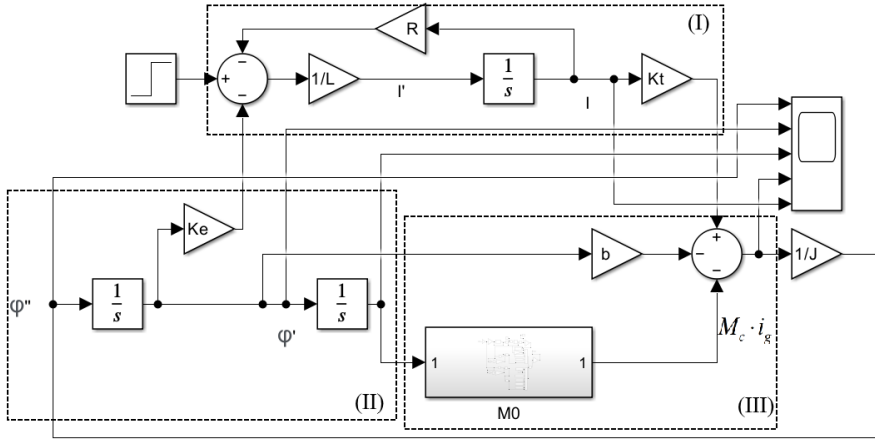


Fig. 4. Block diagram in an interactive environment for determining the parameters of the diagnostic system.

The developed block diagram allows determining the main parameters of the diagnostic system: current  $I_a$ ,  $A$  and the angular speed of rotation of the electric starter  $\frac{d\varphi}{dt}, \text{rad}^{-1}$  from time  $t, s$ . In addition to these parameters, it is also possible to determine the total torque on the starter

armature, the angular acceleration of the starter, the rotation angle of the starter, and others. Figure 5 shows the graphs of changes in the angular speed of rotation of the electric starter  $\frac{d\varphi}{dt}, \text{rad}^{-1}$  from time  $t, s$  in pressurized (compressor) and depressurized states.

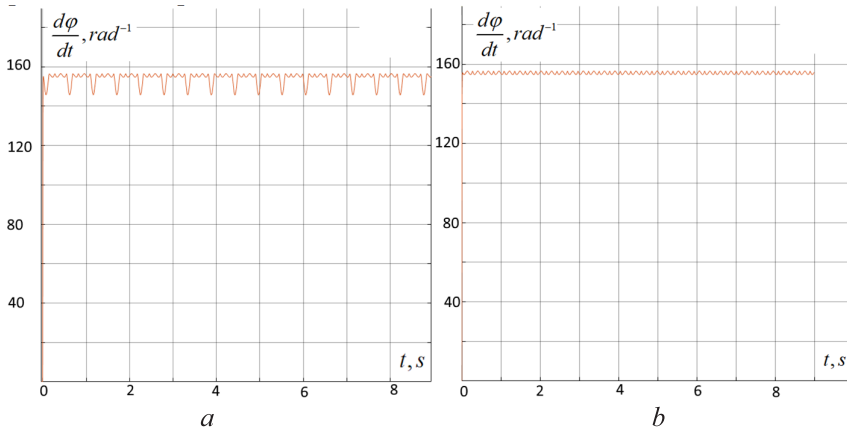


Fig. 5. Graphs of changes in the angular speed of rotation of the electric starter:  
a – sealed state; b – depressurized state.

It can be understood from the graphs that in the compressor mode there is a pulsation and a decrease in the average speed, which is caused by the influence of the compression forces in the cylinder and the kinematics of the crankshaft.

Analysis of graphs of changes in starter current  $I_a$  over time indicates a

substantial increase in pulsation, which is associated with the load from air compression forces (Fig. 6). The possibility of using the current strength of the electric starter to determine the state of the generator is confirmed by the significant influence of air compression forces.

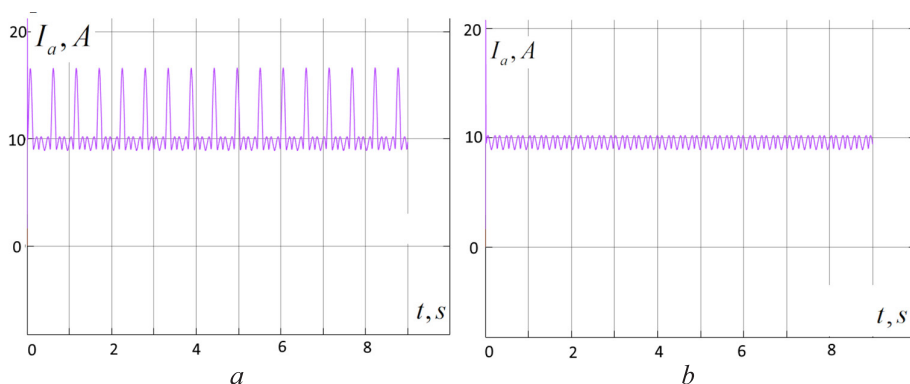


Fig. 6. Graphs of changes in electric starter current versus time:  
a – sealed state; b – depressurized state.

The generalized energy balance of the diagnostic system can be presented as follows:

$$\sum_{i=1}^n A_i = \sum_{i=1}^n Q_i, \quad (9)$$

where  $A_i$  – operation of an external energy source;

$Q_i$  – energy consumption for the implementation of a number of internal processes during engine rotation.

The power of the starter can be determined according to the technical documentation or depending on:

$$N_{st} = UI, \quad (10)$$

where  $U$  – battery voltage;

$I$  – the average current for one cycle of the engine is determined by the results of modelling (Fig. 5).

Energy costs for the implementation of internal processes during engine rotation consist of costs for friction of parts  $Q_{fr}$  and thermodynamic gas  $Q_{ad}$  processes:

$$\sum_{i=1}^n Q_i = Q_{fr} + Q_{ad}. \quad (11)$$

It is possible to ignore the energy consumption for the rotation of the generator

due to the fact that the starting frequency of the motor is only 5 % of the nominal frequency of rotation of the generator.

Friction costs of parts  $Q_{fr}$  are laid from a number of components that are related to the mixing of the piston, the rotation of the crankshaft, the operation of the oil pump, and the operation of the gas distribution mechanism. It is possible to determine friction costs of parts  $Q_{fr}$  when starting the engine without a screwed-in spark plug:

$$Q_{fr} = UI_1 \Delta t, \quad (12)$$

where  $I_1$  – the average starter current without a screwed-in spark plug (depressurized state) (Fig. 5).

The costs of the gas thermal processes in compressed air are caused by the emission of heat  $Q_{ad}$ . From the known dependence of the indicator efficiency coefficient of gas thermodynamic processes  $Q_{ad}$  is as follows:

$$Q_{ad} = \eta_i A_{ad}, \quad (13)$$

where  $\eta_i$  – indicator coefficient of useful action:

$$\eta_i = 1 - \frac{1}{\varepsilon^{n-1}}, \quad (14)$$

where  $n'$  – experimental coefficient  $1 < n < k$ ;  $\varepsilon$  – engine compression ratio.

Work with polytropic compression:

$$Q_{ad} = \frac{p_0 V_0}{n-1} \left[ \left( \frac{V_0}{V_1} \right)^{n-1} - 1 \right], \quad (15)$$

where  $p_0$  – initial pressure in the cylinder;  
 $V_0$  – the initial volume in the cylinder;  
 $V_1$  – final volume in the cylinder;  
 $n$  – polytropic index for air (1.2–1.365);

The relation  $V_0/V_1$  pertains to the engine's compression ratio  $\varepsilon$ .

After substituting dependence (10–15) in (9) and assuming equality of coefficients  $n' \approx k$  we obtain the energy balance equation of the diagnostic system:

$$\Delta t UI = \Delta t UI' + \frac{1}{\varepsilon^{n-1}} \frac{p_0 V_0}{\gamma - 1} \left[ \left( \frac{V_0}{V_1} \right)^{n-1} - 1 \right]. \quad (16)$$

Let us determine the degree of compression of the engine  $\varepsilon$ :

$$\varepsilon = \left( \frac{p_0 V_0}{\Delta t U (I(1-n) + I_1(n-1)) + p_0 V} \right)^{\frac{1}{n-1}}. \quad (17)$$

Solving Eq. (16) with respect to the degree of compression of the engine allows determining the energy efficiency of the electric generator. For analysis, we intro-

duce a substitution in the obtained solution (17) using the ratio of currents:

$$k_I = \frac{I_1}{I}. \quad (18)$$

The current ratio coefficient in the adopted diagnostic system is an informative criterion that establishes a connection between two states of the system (pressurized (compressor) and depressurized states).

After substituting (18), the solution (17) takes the form

$$\varepsilon = \left( \frac{p_0 V_0}{\Delta t UI ((1-n) + k(n-1)) + p_0 V} \right)^{\frac{1}{n-1}}. \quad (19)$$

As a result of using the value of the ratio of currents in the formula for the compression ratio, a value of 8.78 was obtained. The value of the passport compression ratio for this engine model is 9 units. Using Eq. (13) to determine the compression ratio, we can calculate the energy efficiency of the generator using the indicator coefficient of useful action. In this case, under the condition that the efficiency of the alternator is almost equal to 1, the energy efficiency of the generator is 0.22. The obtained value of energy efficiency corresponds to the results of previous studies conducted earlier [8].

## 4. CONCLUSION

A mathematical model has been developed in an interactive environment for diagnosing generators based on a spark-ignition engine. This model uses starter current as a diagnostic indicator. The mathematical model allows determining the main parameters of the diagnostic system, such as the current and angular speed of rotation of the electric starter as a function of time. In addition to the main parameters, the model also allows determining additional indicators

that can be useful for assessing the condition of the generator, such as the total torque on the starter armature, angular acceleration and angle of rotation of the starter. Determining the ratio of current strength values in different modes allows establishing the energy efficiency of the generator. For a specific example of a generator based on the HONDA GX160 engine, it has been found that its energy efficiency is 0.22. Therefore, the developed mathematical model in an

interactive environment is a powerful tool for diagnosing and evaluating the energy

efficiency of spark-ignition engine-based generators.

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