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DETERMINING THE EFFECT OF LOAD ON SYNCHRONOUS GENERATOR WITH SPARK-IGNITION ENGINE ENERGY EFFICIENCY

S. Zaichenko[1*], A. Dychko[1], U. Ercetin[2], V. Opryshko[1], A. Kleshchov[1]

[1] Institute of Energy Saving and Energy Management,
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
37 Peremohy Ave., Kyiv, 03056, UKRAINE
[2] Dumlupinar University
Merkez Kampüsü Tavsanlı Yolu10 km, Kutahya, 43040, TURKEY
*email: zstefv@gmail.com

The paper presents a new approach to energy indicator determination, such as specific fuel consumption and energy efficiency of the power plant. The essence of the new method is to determine the instantaneous power of the installation with subsequent data processing. The use of this method allows establishing the dependence of specific energy indicators on the generating unit load levels. The established distribution allows defining optimum parameters of experimental setup and consumption at various loading levels. The highest specific energy consumption of fuel is observed (1189–1297 g / (kW·h) and 962–1147 g / / kW·h)) at the lowest and the highest load for different fuels. Experimental data show that fuel without ethanol impurities can generate more electricity, which should be used at higher demand.

Keywords: *Braking specific fuel consumption, energy efficiency, power plants, spark ignition engine.*

1. INTRODUCTION

World's energy strategy supports the course of rational "minimization" of energy, in particular, in Ukraine a significant increase in the share of renewable energy sources and off-balance energy resources to 57.73 million toe at the level of 2030 compared to 15.51 million toe used in 2005 (an increase of 3.72 times). It was forecast that electricity production by power plants using renewable energy sources for Ukraine (excluding elec-

tricity production at small hydropower plants and biofuels in the baseline scenario) would grow to 50 million kWh in 2010; 800 – in 2015; 1500 – in 2020; 2000 million kWh – in 2030. At the same time, electricity production by industrial and municipal power units will increase to 9.85 billion kWh in 2010; 10.8 – in 2015; 11.4 – in 2020; 13.5 billion kWh in 2030 [1], [2]. Analysis of the dynamics and structure of Ukraine's electricity production over the past two years (2019–2020) shows a steady increase in the share of autonomous power generation in total electricity production from 1 to 2 %, respectively 2372 million kWh and 5 357 million kWh.

This feature is explained by the development of autonomous power supply systems, which not only complement stationary power plants, but in many cases provide solutions to important technical problems of power supply in hard-to-reach areas. Autonomous energy allows consumer not to depend on the centralized energy supply and to use the technology, optimal for these conditions as SmartGrid source of energy production [3]. In different modes of the power supply system, electric generators usually operate with a load less than the nominal. This is due to the need for a reserve to provide electricity to different numbers of energy consumers.

Analysis of autonomous energy sources market, which becomes the most widespread, shows a fairly narrow range of used generators [4]. The most common variant of an autonomous energy source (more than 50 % of all units) is gasoline generators with spark ignition with a synchronous electric generator of 2.5–3.5 kW.

The actual efficiency of the generator unit in case of underload depends on the efficiency of the engine and the efficiency of the synchronous generator at different loads. There are a number of methods for setting these parameters for both internal combustion engines (ISO 15550: 2016) and for synchronous generators (DSTU IEC 60034-2-1: 2019). However, the application of these methods for autonomous generators is complicated by individual components, the internal combustion engine and the generator, which in some cases are impossible to define due to its design. That is why the consideration of the system states, as a whole, needed to facilitate the process of setting the parameters of engine-generator system.

To use this approach, it is necessary to modernize existing research methods of autonomous electrical installations at different load levels, which are generally aimed at determining the quality of power supply in nominal operating modes or close to nominal (overload).

2. REVIEW OF SCIENTIFIC SOURCES

A number of works, which can be divided into two main groups, are devoted to the analysis of energy efficiency parameters of installations based on internal combustion engines. The first group considers the process of determining the energy parameters by studying mainly the characteristics of the internal combustion engine. In this case, as a characteristic of energy efficiency using the ratio of fuel consumption rate to engine power is brake-specific fuel consumption. This approach is based on the fact that the main losses of installations fall on the internal combustion engine [5]. The second group of studies is devoted to power plant as a whole, in some cases considering the energy performance of system components. Energy efficiency in this case is assessed by the ratio of generated power and fuel consumption. A character-

istic common feature for these studies is the determination of energy efficiency indicators of installations with load variation. Also for both research groups for internal combustion engine load is connected to the electromechanical loader – an electric brake or the generator.

Among total scope of research of the first group in terms of detailing the description, setting tasks and conducting research, it is possible to note the works devoted to use of alternative fuels with mineral fuel mixtures. These studies mainly experimentally investigate the influence of various factors (the ratio of biofuels and mineral fuels, gas and liquid fuels, speed, angle of advance of the spray or ignition) on energy performance. The main goal of these studies is to confirm the possible reliable and safe use of alternative fuels for the environment. A number of studies note the independence of costs on the power plant level [6].

In [7], the authors aimed at operation optimization of the power plant using a mixture of fuels (hydrogen and gasoline) as the main factors for the concentration of fuels and the speed of the generator internal combustion engine shaft. A characteristic of the established pattern is the optimal efficiency value change at different concentrations of the mixture and the load, which allows optimising the generation process by using different mixtures. To determine the conditions that correspond to the optimal value, most experiments were conducted at the minimum installation power values of 2.5 kW (<50 %) and did not cover the entire possible range.

In [8], the authors aimed at studying the efficiency of a spark ignition engine by converting the thermal energy of exhaust gases into electricity using a thermoelectric generator, thus investigating the issue of the power plant energy efficiency increase [8]. When power increases from 25 to 75 kW, there is no significant change in specific fuel consumption (within 3 %), which differs significantly from the known data.

The general characteristics of the presented studies include the rarity of the described fuel mixtures and methods of electricity generation usage. Little attention is paid to the conditions of the experiment, the influence of engine parameters, rheological parameters of the fuel, namely the density of the fuel. Also, the studied models of autonomous generators and motors have a narrow use for power supply as backup sources.

Given above, it is possible to conclude that it is necessary to study the energy performance of a common generator type, namely a synchronous generator with a spark ignition engine. Also, special attention should be paid to the type and conditions of fuel use, which are maximally represented at the market.

The aim of the study is to determine the energy performance of autonomous electric generators based on spark ignition engines using the most common fuels.

3. DESCRIPTION OF RESEARCH METHODS

Energy indicators that are necessary for modeling power supply system dynamics and technical and economic assessment of setup options for new power systems belong to:

- fuel consumption for electricity generation at different load levels, g / kWh;
- efficiency at different load levels.

Two types of the most common used fuels for the conducted experiments:

- gasoline automobile A-95 - Euro5;
- gasoline automobile A-95 - Euro5 - E7.

The experiments were performed indoors at a temperature of (298 ± 3) K [(25 ± 3) ° C] and relative humidity (95 ± 3) %. The value of atmospheric pressure was in the range of 755–165 mm Hg. Art. (100 658–101 991 Pa). Under these conditions, one of the main rheological parameters of the fuel, density, was determined. Thus, for A-95 - Euro5 it was 735 kg / m3, and for A-95 - Euro5 - E7 – 757 kg / m3.

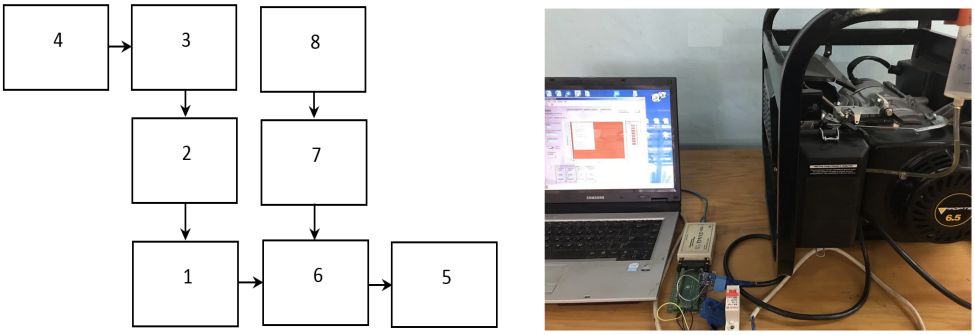
Among the wide range of autonomous generators, the authors paid attention to generating units based on a single-cylinder gasoline four-stroke internal combustion engine with an engine displacement of 200 cm^3. Technical characteristics are given in Table 1. Most generators use as an alternator a synchronous generator with automatic voltage regulator (AVR), which contains the rotor and stator windings. The rotor speed of the generator is maintained by a centrifugal frequency regulator connected to the carburetor.

The research notes the growth of a part of production by powerful autonomous stations and by small stations of public utilities. The chosen generator has the most common design among existing generators, as it is pointed, due to its simplicity of design and cost. The generator design is a copy of the Honda generator. Considered above, the collection of data is important for determining the quality indicators of power supply for various objects.

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

Parameter	**Unit**	**Value**
Engine type	-	4-stroke gasoline engine with air cooling OHV
Number of cylinders	pcs	1
Engine model	-	H-168
Engine displacement	cm^3	196
Internal combustion engine power	W	4780
Maximum power of the electric generator	W	2800
Fuel tank volume	m^3	0.015
Oil sump volume	m^3	0.0006
Generator weight	kg	53.6

Figure 1 demonstrates a schematic representation of the experimental setup, as well as measuring devices on it. The basis of the experimental setup is an autonomous electric synchronous generator – 1 with a spark ignition engine – 2. The carburetor of the engine – 3 is disconnected from the tank (not shown) and connected to the vessel with the divisions marked on it – 4. Synchronous generator – 1 is connected to the loader in the form of a liquid rheostat – 5. Power measurement is performed by registering the voltage on the generator panel and Hall's current sensor – 6. Analog signal from the current sensor YHDC HK 16 and voltage sensor based on inductive module with voltage transformer series ZMPT101B is converted by 14-bit data acquisition microsystem DAQ12 – 7 with fixing on the computer – 8.



a *b*

Fig. 1. Scheme of the experimental setup for determining the energy parameters of a synchronous electric generator with a spark ignition engine.

The process of electricity generation by a synchronous generator with a direct kinematic connection to the motor depends on a number of factors that significantly affect the quality. Among the main factors that significantly affect the voltage and current should be noted the type of load and stability of the engine crankshaft. In our case, the active load is used as a load, which minimizes the possible voltage phase shift. At the same time, it is possible to note at loading of the generator essential curvature of a sinusoid with emergence of harmonics of various order with asymmetry and deviation of frequency from the nominal value (to 7 %) (Fig. 2). Increasing the load from 500 W to 1500 W leads to 30 % sinusoidal distortion.

To determine the energy consumption, the RMS voltage can be used, which is the result of periodic function integration:

$$\Delta P = \frac{\int_0^T (U(t))^2\, dt}{R} = \frac{\int_0^T \left(U_m \sin(2\pi \frac{t}{T})\right)^2 dt}{R} = \frac{TU_m^2}{2R} = \frac{TU_{rms}^2}{R}, \quad (1)$$

where

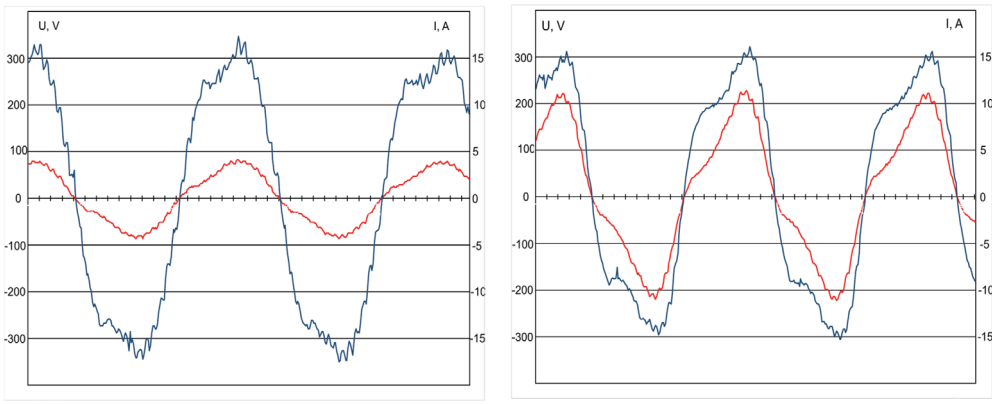
T is the period of voltage fluctuations; $U(t)$ is the voltage change function.

Due to these distortions, the real diagram with increasing load in a certain approximation for some areas can be described as straight. In this case, energy consumption for the period is as follows:

$$\Delta P = \frac{\int_0^T (U(t))^2\, dt}{R} = 4\frac{\int_0^T \left(\frac{U_m}{T/4} t\right)^2 dt}{R} = \frac{TU_m^2}{3R}. \quad (2)$$

Comparison of the obtained values shows that the calculation error can be 30 % of the generator nominal power.

From the above, it is obvious that determining the amount of electrical energy, the use of the ratios of maximum values and root mean square values of voltage and current leads to significant errors in the calculation. More accurate values in determining the amount of electrical energy can be achieved by taking into account the instantaneous change in power.



a *b*

Fig. 2. Voltage change diagrams (———) and current (———) at different load for (gasoline automobile A-95 - Euro5):
a – generator load 500W;
b – generator load 1500W.

In the general case, the energy balance of the diagnostic system is as follows:

$$\Delta Q - (\Delta A + \Delta P) = 0, \tag{3}$$

where

Q – fuel combustion energy;
ΔP – useful work in the form of electricity;
ΔA – total thermal, mechanical and electrical energy losses.

Combustion energy is determined by volumetric measurement of fuel for a certain time of generator operation Δt:

$$\Delta Q = q \rho \Delta V, \tag{4}$$

where
q – specific heat of combustion;
ρ – fuel density;
ΔV – amount of fuel consumed by the generator during operation Δt.

During the operation of the generator based on the internal combustion engine, the voltage and current values change significantly over time due to fluctuations in the speed of the crankshaft, which needs to be clarified when determining the power while operation. Useful work in the form of electricity depends on the level of current and voltage:

$$\Delta P = \int_0^{\Delta t} P'(t)dt = \int_0^{\Delta t} I(t)U(t)dt\,. \tag{5}$$

Specific fuel consumption for electricity generation:

$$BSFC = \frac{m}{\Delta P} = \frac{\rho \Delta V}{\Delta P} = \frac{\rho \Delta V}{\int_0^{\Delta t} I(t)U(t)dt}\,. \tag{6}$$

The presented dependence of the definition allows determining with high accuracy the energy performance of a synchronous generator with a spark ignition engine by taking into account fluctuations in current and voltage levels.

Efficiency at different load levels:

$$\eta = \frac{\Delta P}{\Delta Q} = \frac{\int_0^{\Delta t} I(t)U(t)dt}{q \rho \Delta V}\,. \tag{7}$$

When conducting experimental studies, the main variable factors were the ratio of active load to the nominal value of the electric generator N/N_0 and fuel type. Each experiment was performed three times at

each power level. To determine the fuel consumption for each experiment, the same amount of fuel 2 · 10–5m^3 was used with time fixation.

Tables 1 and 2 show the results of the experiment and calculate the energy efficiency according to the established data of voltage and current changes (Fig. 2). When determining the useful work in the form of electricity, ΔP is determined by the trapezoidal method with the previous product of voltage and current data:

$$\Delta P = \sum_{k=1}^{N_m} \frac{U_{k-1} I_{k-1} + U_k I_k}{2} \frac{1}{f}, \quad (8)$$

where

U_{k-1}, I_{k-1}, U_k, I_k – adjacent values of voltage and current;

f – ADC channel polling frequency (1000Hz);

N_m – number of measurements:

$$N_m = \Delta t \cdot f. \quad (9)$$

During the one-factor experiment, the measurement study is carried out at six power points, the power range is divided into five intervals. The number of measurements at one level is 3. Thus, 18 tests are made for each fuel, which totaled 36 tests. As the experimental curve is of the second order, six points for approximation with the required accuracy are sufficient. Also, the number of points can be justified by some sections of the curve, two rectilinear and one curvilinear, respectively, two points on the rectilinear sections and three on the curvilinear.

Table 1. Energy Efficiency Parameters of the Generator for Gasoline A-95 - Euro5

No.	$\frac{N}{N_0}$	Δt, s	r, g / s	$BSFC$, g / J	$BSFC$, g / (kWh)	ΔP	η
1	0	97	0.15608	-	-	-	-
2	0.2	89	0.17011	0.00033	1189,21	44828	0.0688
3	0.4	70	0.21629	0.00021	756.00	70693	0.1082
4	0.6	62	0.24419	0.00015	569,03	93320	0.1437
5	0.8	44	0.34409	0.00016	601,36	88843	0.1360
6	1	21	0.68818	0.00026	962,18	55453	0.0850

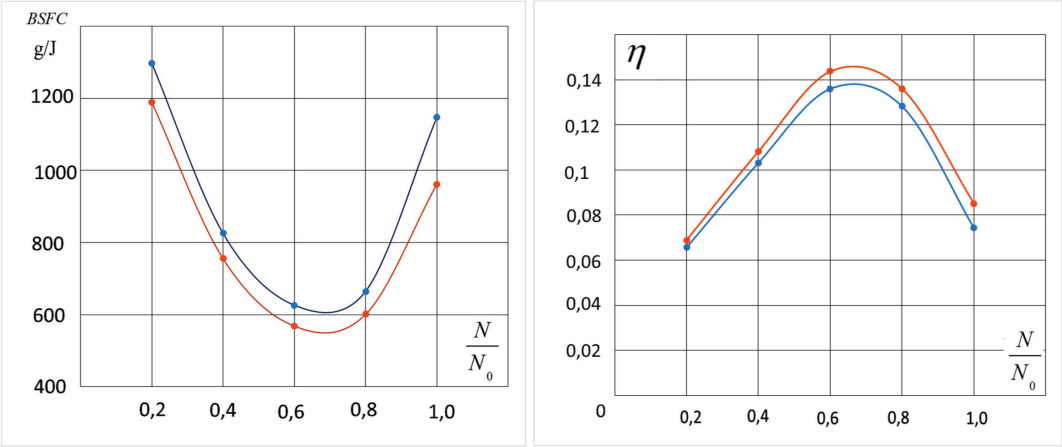
Table 2. Energy Efficiency Parameters of the Generator for Gasoline A-95 - Euro5 - E7

No.	$\frac{N}{N_0}$	Δt, s	r, g / s	$BSFC$, g / J	$BSFC$, g / (kWh)	ΔP	η
1	0	92	0.16457	-	-	-	-
2	0.2	84	0.18024	0.00036	1297,71	42011	0.0656
3	0.4	66	0.22939	0.00022	825,81	66509	0.1032
4	0.6	58	0.26103	0.00017	626,48	87265	0.1360
5	0.8	41	0.36927	0.00018	664,68	82779	0.1282
6	1	19	0.79684	0.00031	1147,45	47803	0.0742

From the analysis of the data given in Tables 1 and 2, it is necessary to determine the reduction of operating time of the generator Δt and, accordingly, an increase in fuel consumption r on average by 4.3 %, due to the lower calorific value of alcohol-containing gasolines.

The analysis of the data from Tables 1

and 2 is presented at the graphs of changes in specific fuel consumption and efficiency (Fig. 3). Significant specific energy consumption (1189–1297 g / (kW·h) and 962–1147 g / (kW·h)) is observed at low (0.2) and maximum load of the generator. Moreover, approaching the load to the minimum value leads to much higher unit costs than overloading the generator. The optimal load level for electric generators of this design, at which the lowest level of specific fuel consumption is expected, is 0.7 for different types and 560 and 605 g / (kW·h), respectively.



a b

Fig. 3. Diagrams of changes in specific fuel consumption (a) and efficiency (b) when using different types of fuels:
———- gasoline automobile A-95 - Euro5;
——— - gasoline automobile A-95 - Euro5 - E7.

The reason for these effects is a number of negative phenomena that accompany the process of electricity generation when the load deviates from the optimum. The main reasons include, in the case of increased power, deterioration of the gas filling of the cylinder, reduction of turbulence with the charge part release from the cylinder into the inlet system with increasing fuel supply. Also, costs increase in the mode close to idle to the total energy consumption ΔA, when the costs of generating reactive power, which is required for generation at different load levels, is added.

An excessive use of fuel at low load is typical of most generators due to the need to maintain the frequency of the internal combustion engine, which is accompanied by the cost of friction, including aerodynamic. High specific fuel consumption at the maximum load of the generator is related to deterioration of filling of cylinders and incomplete combustion of fuel. Taking into account these features, data acquisition will be characteristic for all spark ignition generators.

The established distributions of specific values of fuel consumption and the value of the energy efficiency factor for different load levels using different fuels according to the new measurement method are necessary for modeling and planning of energy system consumption using generating units of this type.

4. CONCLUSIONS

The present study has proposed a new method of determining the values of fuel consumption and the value of power plant energy efficiency with two fuels (ethyl gasoline), which allows monitoring the maximum efficiency. Thus, for this equipment it is 0.147 and 0.138 at the load of 0.7 from nominal for different types of fuels. Specific costs for optimal load are 560 and 605 g / (kWh), respectively.

Under certain conditions the use of this technique, which is based on the determination of instantaneous power values, allows avoiding significant errors (30 %) in determining the energy parameters.

In addition, the experimental evaluation of the generating unit operation has confirmed that the fuel without ethanol impurities allows generating more electricity, which should be used when there is a great need.

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