The experimental studies of operating modes of a diesel-generator set at variable speed

S G Obukhov, I A Plotnikov, M A Surkov and L P Sumarokova

Tomsk Polytechnic University, 30, Lenina ave., Tomsk, 634050, Russia

E-mail: masur@tpu.ru

Abstract. A diesel generator set working at variable speed to save fuel is studied. The results of experimental studies of the operating modes of an autonomous diesel generator set are presented. Areas for regulating operating modes are determined. It is demonstrated that the transfer of the diesel generator set to variable speed of the diesel engine makes it possible to improve the energy efficiency of the autonomous generator source, as well as the environmental and ergonomic performance of the equipment as compared with general industrial analogues.

1. Introduction

All industrial diesel generator sets (DGSs) work at a constant speed with a wide range of changes in electric load. This approach has been tested by years of practice and allows for use of sufficiently simple and reliable control systems. However, this strategy for controlling DGSs has a series of serious drawbacks: specific fuel consumption increases significantly in fractional load operating modes, the operating life of the diesel engines is lowered, and emissions of harmful substances increase. One of the more promising technical solutions to increasing the efficiency of autonomous power supply systems is changing the DGS operating mode from constant speed to variable speed, optimized according to the size of the electric load [1, 2].

When the DGS is switched to variable speed, the parameters of the output voltage, created by the generator, change [3, 4]. In order to guarantee supplied output voltage parameters, it is necessary to introduce power converters (controlling rectifiers and inverters) into the system, which, on the one hand, makes the system more complex and costly, but, on the other, creates a set of benefits: specific fuel consumption decreases significantly, the quality of generated electric power increases, the generator is discharged of idle currents, etc.

The goals of the research presented in this paper were to experimentally prove the efficiency of changing the DGS operating mode from constant to variable speed and to determine areas for regulating the unit's operating modes.

2. Diesel generator sets operating at variable speed

As stated above, the energy efficiency of a DGS can be increased significantly by changing the operating mode of the diesel engine from constant to variable speed and by using specialized regulators for controlling the plant [5-8]. A structural diagram of such a diesel generator set (DGS) is shown in Figure1.

As can be seen from Figure 1, the system must have several control loops in order for the variable speed DGS to operate. By acting on the actuating device of the high-pressure pump, the speed regulator sets the optimal shaft speed for the diesel engine based on the criteria for minimal fuel use and stable operation of the diesel engine. The synchronous generator field current regulator sets the current value based on criteria for loss minimization in electrical machinery. The power converter controller provides the necessary algorithms for switching semiconductor rectifiers to create parameters for the electricity provided to consumers in accordance with established standards.

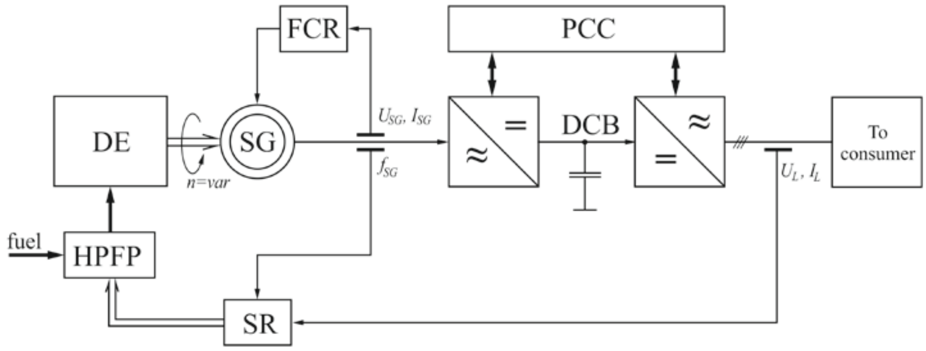

Figure 1. The variable speed DGS structural diagram: DE – diesel engine; PCC – power converter controller; SR – speed regulator; FCR – field current regulator; SG – synchronous generator; HPFP – high-pressure fuel pump; DCB – direct current bus.

While working at variable speed, the DGS is thus a rather complex, multichannel, non-linear, mobile automatic control system. The direct experiment, a common way to research them, makes it possible to obtain reliable results.

3. Laboratory bench

A laboratory bench was developed and manufactured in order to conduct experimental research on variable speed DGSs. A key development requirement was providing high level of automation for the control flow of bench components, and for control and recording of measured variables [9].

Development of the structural and functional design of the laboratory bench was conducted in view of the following technical requirements: the possibility of modeling static and dynamic DGS modes of operation for all main parameters of the operating mode; use of the modular construction principle, which allows for simple attachment/detachment of separate components from the power plant; satisfying all mandatory fire, environmental, and electrical safety regulations; convenience in use and maintenance; the possibility of further modernization of the bench.

4. Experimental studies

An experimental research program was developed that involved removing one of the primary characteristics of the DGS in standard mode (*n*=const) and at variable speed (*n*=var) and subsequently conducting a comparative analysis.

The following notation was used to characterize the position of the control rod adjusting screw: *h*_0 – the fuel pump control rod adjusting screw is in initial position (factory settings); *h*_4 – the fuel pump control rod has been displaced by 4 mm from its initial position in the direction of decreasing fuel delivery.

The DGS performance standards in standard operating mode were evaluated based on load characteristics. The experiments conducted have shown that, when the DGS load is measured within the range of idling to its nominal value, the frequency of output voltage is measured from 53.0 to 49.9 Hz. The all-regime shaft speed controller can regulate the fuel flow G_m, depending on the load size, in essentially linear fashion. However, the dependence of specific fuel consumption g on the load size is non-linear. In the entire range of electrical load changes, the DGS voltage standard regulating system stabilizes the size of output voltage within 230±5 V, and the field coil current changes from 0.85 to 2.45 A. The temperature of the engine cylinder block does not exceed 95^0C, the operating mode of the diesel engine is stable, and the vibrations do not exceed acceptable limits.

Mechanical loss in the diesel engine was determined by the dry motoring procedure and was equal, in the nominal mode, to P_{m}=5.47 kW, mechanical efficiency η_{m}=68%. The diesel engine temperature balance in the nominal load mode is shown in Figure 2. The net efficiency of energy conversion in the diesel engine at nominal load was equal to η_{e}=30.6%.

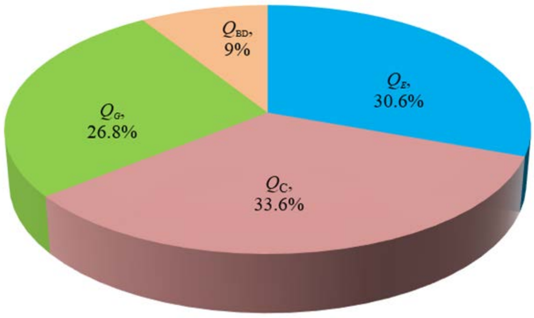

Figure 2. The temperature balance of the KM2V80 diesel engine in the nominal operating mode: Q_E – the amount of heat equivalent to effective operation; Q_G – the amount of heat lost with exhaust fumes; Q_c – the amount of heat removed by the cooling system; Q_{BD} – temperature balance discrepancy.

Figure 3 shows a series of regulatory characteristics of the KDE12EA3 DGS recorded at various positions of fuel feed control organ h. There is also a line of maximal outputs for partial speed modes 1, which determines the maximum accepted value of luminous flux declension coefficient K_{dop}, determined based on the experimental results. To ensure the most efficient diesel engine operational mode when in use, the resulting linear dependence must be displaced downward to the factory settings for the nominal capacity mode: h_0 – P_{n} = 9.5 kW (line 2).

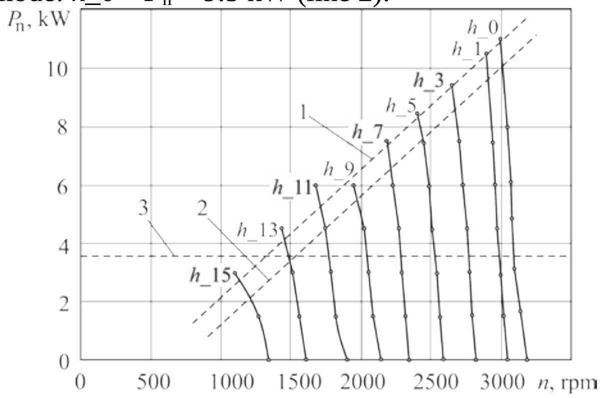

Figure 3. DGS KDE12EA3 regulatory characteristics.

In order to ensure stable operation of a diesel engine with small loads, its minimal operating shaft speed should be limited to 1600 rpm, which corresponds to a displacement of the fuel control rod by 12 mm from factory settings (line 3). Further lowering of the shaft speed is inadvisable, as the imbalance of fuel atomization and combustion increase significantly at low speeds, which leads to unstable engine operating modes.

The results of the experiments determine the displacement range of the KDE12EA3 DGS fuel pump control rod necessary for implementing the power station control mode in accordance with minimum fuel use criteria, which is equal to 12 mm from h_0 in nominal capacity mode to h_12 in small load mode, with an operating range of shaft speeds from 3000 to 1600 rpm (Figure 3). As a result, a functional relationship was obtained that connects the position of the fuel pump control rod with the capacity of the DGS electrical load at which specific fuel consumption will be at a minimum, Figure 4.

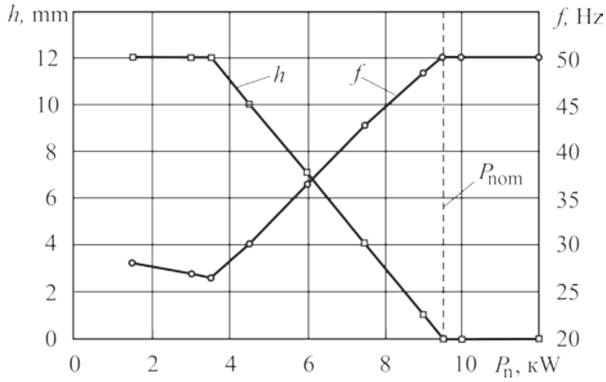

Figure 4. The functional relationship of the fuel pump control rod position with the KDE12EA3 DGS electrical load that guarantees minimum fuel use.

Figure 4 also shows the dependence of the frequency of output voltage *f* on the size of the DGS electric load which operating modes have been optimized for specific fuel consumption. The relationship is also linear, which makes it possible to use current shaft speed values as the feedback signal in an automated regulating system of the fuel feed control organ in inverter DGSs.

The empirical relation between the specific fuel consumption of the researched DGS operating in standard mode (n=const) and optimized for consumption (n=var) is presented in Figure 5. We can see from it that changing the DGS to variable speed saves fuel across the entire spectrum of operating modes, and the maximum savings are in small load modes.

Reducing specific fuel consumption in a variable speed DGS can be done by reducing mechanical loss in the diesel engine, increasing generator efficiency η_g and using efficient diesel fuel η_e.

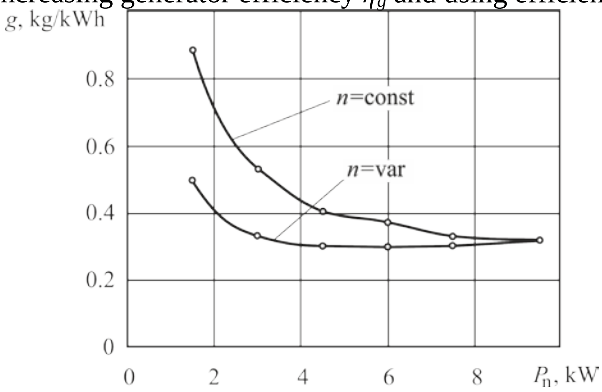

Figure 5. Dependence of specific fuel consumption on the size of electrical loads in variable and constant speed DGSs.

Figure 6 shows comparative DGS energy characteristics generated based on the results of the experiments conducted. The net efficiency of diesel fuel η_e in a variable speed DGS can be increased by using higher-quality air-fuel mixture in fractional load modes. The quality of the mixture is largely determined by excess air coefficient α which value in modern diesel engines varies between 1.2 and 1.8 (depending on the type of combustion chamber and pressurization). As a rule, manufacturers ensure optimal values for α in fractional modes, which are at about 80% of the engine's nominal capacity. A diesel engine without a pressurization system is used in most DGSs with a capacity of up to 60 kW.

Correspondingly, in DGSs with constant speed, the airflow rate remains practically unchanged for all fractional load modes, and the diesel engine is stabilized only by changing the fuel delivery, to which the size of α is inversely proportional. In a variable speed DGS, when the load size is reduced, the shaft speed decreases along with a change in fuel delivery, and, correspondingly, the airflow rate, which leads to slightly lower α values on fractional modes. A divided combustion chamber with a swirl chamber is used in the diesel engine being studied, and the best mixture conditions are created at values of $\alpha \approx 1.4$. During operation of a variable speed DGS, the α for most fractional load modes will be closer to optimal compared with general industrial units.

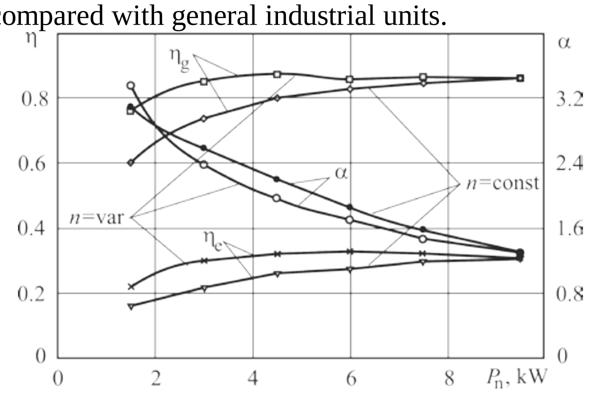

Figure 6. Comparative energy characteristics in constant and variable speed DGSs.

On the basis of the experiments, it can be concluded that changing the DGS operating mode to variable speed optimized for specific fuel consumption provides the following competitive advantages:

- lowers mechanical loss and increases efficiency of the diesel engine and generator for all fractional load modes except nominal mode;
- lowers specific fuel consumption for all fractional modes, saving up to 40% from the baseline scenario in low load modes.

Experiments were conducted on the basis of a specific model of a diesel generator set, yet the theory of similarity of internal combustion engines and electrical machinery, as well as analogous results obtained by other researchers [10-12] make it possible to extend the conclusions to other DGSs with the same capacity range up to 100 kW.

5. Conclusion

The main technical problem that arises when small-scale renewable power generation is used in practice is the necessity of coordinating production and energy use modes in an isolated energy system, with extreme temporal unreliability in primary energy carrier energy and random nature of the load of autonomous consumers. A guaranteed power source is necessary for such systems, and diesel generator sets are used as such in most practical scenarios.

Specific fuel consumption for the production of 1 kWh of electrical energy is a key indicator of DGS energy efficiency. In view of the fact that the largest portion of expenditures in prime cost of electrical energy produced by a DGS is taken up by fuel expenses, this factor is key.

As a result of the experiments, it has been empirically proven that changing a diesel generator set to variable speed optimized for the size of electric load lowers specific fuel consumption for the generation of electrical energy. The specific fuel consumption in a variable speed DGS is lowered by decreasing mechanical loss in the diesel engine, increasing the efficiency of the generator and efficiency of the diesel engine. For a typical load schedule of autonomous consumers, fuel economy amounts to 20-30%.

References

[1] Wang D, Nayar C and Wang C 2010 *2nd IEEE Int. Symp. on Power Electronics for Distributed Generation Systems* (USA: IEEE) p 1
[2] Chlodnicki Z, Koczara W and Al-Khayat N 2008 *J. Electr. Power Quality and Utilis.* **14** 13-24
[3] Iwanski G and Koczara W 2013 Variable Speed Power Generation *monograph: Power Electronics for Renewable and Distributed Energy Systems: A Sourcebook of Topologies, Control and Integration* (London:Springer Verlag) chapter 7 pp 309-378
[4] Lukutin B, Sarsikeyev Y, Surkov M and Lyapunov D 2014 *14th Int. Conf. on Environment and*

IOP Conf. Series: Materials Science and Engineering **177** (2017) 012143 doi:10.1088/1757-899X/177/1/012143

Electrical Engineering (Krakow: IEEE Computer Society) p 459
[5] Zhang Y, Li S, Lu G and Zhou Y 2012 *Int. Conf. on Systems and Informatics* (USA: IEEE) p 619
[6] Pichkalov I, Kyselova A, Kyselova O and Kyselov G 2013 *IEEE 33th Int. Scientific Conf. Electronics and Nanotechn.* (USA: IEEE) p 378
[7] Lukutin B, Shandarova E, Matukhin D, Makarova A and Fuks I 2016 *IOP Conf. Series: Mat. Sci. and Eng.* (Tomsk) vol 124 (Tomsk: Institute of Physics Publishing) p 4
[8] Lukutin B, Shandarova E, Makarova A, and Shvartsman I 2016 *IOP Conf. Series: Mat. Sci. and Eng.* (Yurga) vol 127 (Yurga: Institute of Physics Publishing) p 98
[9] Duraev N, Obukhov S and Plotnikov I 2014 Laboratory Stand for Research Mode Diesel-Generator Set for Variable Speed *Industrial ACS and controllers* (Moscow: Nauchtechlitizdat LTD) pp 33-40
[10] Leuchter J, Refucha V, Krupka Z and Bauer P 2007 *The 38th Annual IEEE Power Electronics Specialist Conf.* (USA: IEEE) p 2287
[11] Chlodnicki Z, Koczara W, Al-Khayatt and Brown N 2008 *13th Int. Power Electronics and Motion Control Conf.* (USA: IEEE) p 2150
[12] Beyerleyn E and Tyuteva P 2014 *15th Int. Conf. of Young Specialists on Micro/Nanotechnologies and Electron Devices* (USA: IEEE Computer Society) p 359