Development of a mathematical model of diesel-generator units with a valve-inductor generator

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Abstract. The paper presents a comprehensive mathematical model of a diesel-generator units with a valve-inductor generator. The calculated data obtained using this model allows optimizing the operation of fuel injectors and adjust the injection characteristics. The electromagnetic part of the model allows taking into account the power losses and efficiency of the generator, calculating the phase windings and their connection schemes, methods for setting the voltage or current of any shape that feeds the windings of the valve-inductor generator, as well as the characteristics of the rotor, stator, and winding materials to obtain the most effective operation parameters of the engine in various operating modes as part of the generator unit.

1. Introduction

A significant part of the Krasnoyarsk Territory is characterized by remote energy-isolated areas, where diesel-generators units are used for power supply, which consume diesel fuel, whose annual costs associated with fuel purchase cost the regional budget almost 3.5 billion rubles. To increase energy efficiency, when reconstructing existing and designing new diesel power plants (DPP), it should be recommended to use diesel-generators units (DGU) with a variable operating speed in the load function, as well as energy-efficient valve-inductor generators (VIG) that will save diesel fuel and extend the service life of diesel-driven engines.

The DGU with frequency vector converter (FVC), built based on contemporary converter technology and microprocessor control systems, will ensure fuel economy, extend the service life of the internal combustion engine (ICE), and reduce the harmful impact on the environment. The technical solutions being developed for the DGU FVS can be used both in the development of new power plants of autonomous facilities and in the modernization of currently operated DPP. The most detailed overview of the possible structures of DGU FVS systems, which include generators of well-known designs, is given in [1], where, in particular, installations with asynchronous generators, a doubly-fed electric machine, and synchronous generators (SG) with electromagnetic excitation are considered.

To study the processes occurring in these DGU, it is proposed to develop a mathematical model that includes the calculation of heat and mass transfer processes in the combustion chamber, as well as
electromagnetic processes occurring in an inductor electric generator. This model will allow choosing the optimal operating modes of the DGU FVC through mathematical simulation.

2. Mathematical model
For simulations of processes occurring in the combustion chamber of a diesel generator engine with variable rotation speed, a mathematical model of combustion processes in the combustion chamber was developed, taking into account the characteristics of injection, ignition, and combustion of the fuel mixture. The developed mathematical model and its testing results are presented in a series of papers [2–3]. In this model, the nonstationary k-e RANS model for normalized groups (RNG) with additional terms that take into account the interaction of turbulent vortices and spray droplets was used to simulate turbulence [4]. The Rayleigh-Taylor model was used to simulate the further disintegration and fragmentation of fuel droplets [5]. A multicomponent model was used to simulate the evaporation of diesel fuel droplets [6]. To simulate the effect of turbulence on the fuel combustion kinetics, a generalized turbulence/chemistry interaction model was used described in the work of Kong et al. [7], which is widely used when simulating diesel engines. This model assumes that the rate of the chemical reaction is partially limited by the rate of turbulent mixing. To simulate the soot formation in the combustion chamber of a diesel engine, a two-stage model was employed [8-9].

For the mathematical description of processes in electric machines, various approaches are widely used, associated with each other by the fact that they are all, in one way or another, based on Maxwell's equations. These are direct simulations of energy transformation processes using Maxwell's equations, simulations using differential equations obtained based on a generalized electromechanical converter, as well as simulations based on differential equations composed for instantaneous values of physical quantities.

The RMxprt subroutine included in the Ansys Electronics software package was used to construct the geometry of the computational domain and set the input parameters. This package allows calculating the main characteristics of electric machines. To calculate and analyze the behavior of the electromagnetic field during the operation of the switched reluctance generator, a mathematical model of the generator was also created in the Maxwell ANSYS software package.

The calculation algorithm is based on the Finite Element Method (FEM) and allows calculating with high accuracy static, harmonic electromagnetic, and electric fields, as well as transient processes in field electromagnetic problems. To build the electrical circuit of the machine, the Maxwell Circuit Editor program was used, which allows using complicated functions when setting the voltage or current of any shape that feeds the SRG windings.

3. Problem formulation and simulation results
The study was conducted for a diesel generator widely used in diesel generator units within a wide range of crankshaft rotation speed. An inline six-cylinder diesel engine was considered. The working volume of all cylinders was 6.65 liters. The cylinder diameter was 105 mm, the piston stroke was 128 mm, the piston-rod length was 320 mm. The compression ratio was 17.5. The crankshaft rotation speed at a rated power was 2300 rpm. A closed-type fuel injector with multi-jet spray was used consisting of 7 jet injectors 0.182 mm in diameter. The maximum injection pressure provided by the fuel system was 180 MPa. The ambient temperature in calculations was 293 K. The temperature of the fresh charge, taking into account the cooling of the air in the coolers, was assumed to be 399 K. The average wall temperature was 450 K. To simulate the processes occurring in the combustion chamber, a mathematical model of the combustion processes in the combustion chamber was developed, taking into account the characteristics of injection, ignition, and combustion of the fuel mixture. The spatial geometry of the computational domain representing the internal part of the combustion chamber of a diesel engine was constructed.

As an example, Fig. 1 shows the behavior of the temperature field in the combustion chamber during gas compression, fuel injection, ignition, and expansion of the combustion products at a
crankshaft rotation speed of 1800 rpm. As seen, the temperature field after the beginning of the fuel combustion process is quite heterogeneous.

Figure 1. Temperature field in the combustion chamber during compression and stroke of the piston.

The developed model is used to study the main characteristics of a diesel generator within a wide range of its operating modes. The crankshaft rotation speed in the calculations varied from 900 to 2300 rpm. The characteristics of fuel atomization, crushing, and ignition in the combustion chamber were analyzed, as well as the behavior features of the local and integral characteristics of the combustion chamber of the engine. At that, not only engine energy characteristics but also its ecological parameters were considered [2].

Further, a comprehensive mathematical model of electromagnetic processes occurring in an inductor electric generator was developed. This model was built based on the Ansys Electronics software package. Using this technique, models of several electric machines were developed. To test and verify the model, a reference geometry of an 8/6 teeth electric motor rotor/stator was constructed. The outer diameter of the stator was 125 mm, while the inner diameter was 63.7 mm, and the length was 90 mm. The outer and inner diameter of the rotor was 63 and 21 mm, respectively. Methodological calculations were carried out to study the effect of calculation grid refinement on the description accuracy of the main characteristics of the generator. The results of the numerical simulation of the test problem were compared with the known calculations by B. Ganji [10] that has shown a good qualitative agreement of the results obtained.

Next, a complete design model of the GWIT 2100 electric generator was created. This is an electric machine with 18 teeth on the stator and 6 on the rotor. The geometry of this machine is shown in Fig. 2a. The outer diameter of the stator is 620 mm, the inner diameter is 510 mm, and the length is 600 mm. The outer and inner diameter of the rotor is 509.2 mm and 350 mm, respectively. Thus, the air gap in the model was equal to 0.4 mm. The crankshaft rotation speed in the model varied from 900 to 2300 rpm. The calculation grid used in the numerical simulation is shown in Fig. 2b. A certain steel grade was used as the material for the rotor and stator. The temperature of the stator windings was 140 °C.
Numerical simulation of electromagnetic processes in the concerned valve-inductor generator was carried out. In the course of numerical simulation, the local fields of the electromagnetic characteristics of the generator, as well as the integral characteristics of its operation, were obtained. To link the output performance and power characteristics of an electric machine and a diesel engine, the calculation dependences of power and torque were used (Fig. 3).

As a result of the conducted calculations, the time behavior of magnetic induction fields in the rotor and stator of the electric machine, as well as the energy density fields in its elements were analyzed. As an example, Fig. 4 shows the distribution of the isolines of the magnetic induction module in the central section of the generator for different operation times of the electric machine. The dependences describing the change in the current in the electric
machine windings depending on the time, as well as average values of the current during the operation cycle of the generator, were obtained.

Figure 4. The distribution field of the magnetic induction module
a) 1.005 ms, b) 1.27 ms, c) 2.17 ms, d) 2.81 ms.

Conclusions
A comprehensive mathematical model has been developed, which includes a model describing heat and mass transfer processes in the combustion chamber, taking into account the injection characteristics of the diesel engine, and a model of electromagnetic processes of a switched reluctance generator. This comprehensive model allows solving the direct and inverse problem associated with the selection of the optimal torque of the generator, which depends on the engine operation. The calculated data, obtained using the developed model allows optimizing the operation of fuel injectors and adjusting the injection characteristics to obtain the most effective parameters in various modes of the engine operation as part of the generator unit. The model takes into account the actual geometry of the electric machine, rotation of its rotor, mechanical loads, loss coefficients in the charged steel packages and air gaps, power and efficiency losses, phase windings and their connection schemes, methods for setting the voltage or current of any shape feeding the windings of the switched reluctance generator, as well as characteristics of the materials of the rotor, stator, and windings. The simulation results have shown that within the control range from 1000 to 2300 rpm, output performance and power characteristics change very significantly. In this context, using generator units with variable rotation speed will be the most optimal, since this allows employing the diesel engine as efficiently as possible, adjusting it to the electrical load of the network.
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