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MODELING THE OPERATION PROCESS
OF A SHIP DUAL-FUEL GAS-DIESEL GENERATOR UNIT

The article addresses the urgent task of modeling the operation of ship dual-fuel gas-diesel generator units (GDGU), in particular Wärtsilä 50DF engines widely used on LNG carriers and LPG carriers. The rapid development of liquefied gas transportation has led to the replacement of steam turbine installations with more economical electric propulsion systems based on dual-fuel engines capable of operating both on diesel fuel and on boil-off gas (BOG) from cargo tanks. The authors emphasize the need for reliable stabilization of pressure in cargo tanks, safe utilization of excess vapor, and minimization of fuel costs through maximum replacement of diesel fuel with natural gas.

A mathematical dynamic model of the GDGU is proposed that takes into account the influence of the turbocharger (represented as an aperiodic link with positive feedback), nonlinear properties of the object, and real parameters of the gas-air mixture supply system. The model is presented in the form of a structural diagram and implemented in Simulink, which made it possible to adequately reproduce transient processes when the load is suddenly applied/dropped. Particular attention is paid to the correct selection of PID-controller settings, since the amplification factor of the object changes significantly depending on the load level. It is shown that tuning the regulator at minimum load provides the greatest margin of stability when moving to nominal and maximum modes.

The features of the electronic speed control and fuel mode switching system are considered: instantaneous (within 1 s) transfer from gas to diesel mode at any load, longer (up to 2 min) controlled transfer from diesel to gas with mandatory leak testing and combustion verification, automatic blocking of gas mode in case of faults or blackout start. The advantages of isochronous load sharing in multi-generator ship power plants and the possibility of forced transfer to backup diesel mode are noted.

The developed model and recommendations for regulator optimization ensure high stability of voltage and frequency in the ship electric power system under sharp load fluctuations, increase the safety of liquefied gas transportation and contribute to the reduction of operating costs due to efficient use of boil-off gas as the main fuel.

Key words: *Gas-diesel generator unit, Dual-fuel engine, Ship Electrical Power System, Modeling.*

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МОДЕЛЮВАННЯ ПРОЦЕСУ РОБОТИ ДВОПАЛИВНОГО
СУДНОВОГО ГАЗОДИЗЕЛЬНОГО ГЕНЕРАТОРНОГО АГРЕГАТУ

У статті розглядається актуальне завдання моделювання процесу роботи суднових двопаливних газодизельних генераторних установок (ГДГУ), зокрема двигунів Wärtsilä 50DF, що широко застосовуються на газовозах СПГ. Швидкий розвиток перевезень зрідженого газу призвів до заміни паротурбінних установок економічнішими системами електроруху на базі двопаливних двигунів, здатних працювати як на дизельному паливі, так і на випарному газі (BOG) із вантажних танків. Автори наголошують на необхідності надійної стабілізації тиску у вантажних танках, безпечної утилізації надлишкових парів та мінімізації витрат палива шляхом максимального заміщення дизеля природним газом.

Запропоновано математичну динамічну модель ГДГУ, яка враховує вплив турбокомпресора (представлений як аперіодична ланка з позитивним зворотним зв'язком), нелінійні властивості об'єкта та реальні параметри системи подачі газоповітряної суміші. Модель подана у вигляді структурної схеми та реалізована в Simulink, що дало змогу адекватно відтворити перехідні процеси за раптового накидання/скидання навантаження. Особливу увагу приділено правильному вибору налаштувань ПІД-регулятора, оскільки коефіцієнт підсилення об'єкта суттєво змінюється залежно від рівня навантаження. Показано, що налаштування регулятора на мінімальному навантаженні забезпечує найбільший запас стійкості за переходу до номінального та максимального режимів.

Розглянуто особливості системи електронного регулювання частоти обертання та перемикання паливних режимів: миттєвий (до 1 с) перехід із газового на дизельний режим за будь-якого навантаження, триваліший (до 2 хв) керований перехід із дизельного на газовий з обов'язковою перевіркою герметичності та контролем згоряння, автоматичне блокування газового режиму за несправностей або старту в режимі blackout. Відзначено переваги ізохронного розподілу навантаження в багатогенераторних суднових енергосистемах та можливість примусового переходу на резервний дизельний режим.

Розроблена модель та рекомендації щодо оптимізації параметрів регуляторів забезпечують високу стабільність напруги та частоти в судновій електроенергетичній системі за різких коливань навантаження, підвищують безпеку перевезення зрідженого газу та сприяють зниженню експлуатаційних витрат за рахунок ефективного використання випарного газу як основного палива.

Ключові слова: *газодизельні генераторні агрегати, двопаливний двигун, суднова електроенергетична система, моделювання.*

Problem statement

The rapid growth in the consumption of combustible gases and the expansion of their international trade contributed to the invention of a new special type of vessels in the 1950s – gas carriers. Specialized vessels for the transportation of liquefied natural gas (methane, ethane, etc.) and vessels for the delivery of liquefied petroleum gas (propane, butane, etc.) were created.

The first generation of methane tankers was equipped with steam turbine units (STU). By this, the idea of using cargo as fuel, which is used in our time, was realized. For forty years, STUs have confirmed their advantages, consisting of reliability, reliability, and ease of maintenance. Further improvements in membrane tanks in the late 1990s resulted in significant reductions in cargo evaporation. This led to the demand for economical gas-diesel propulsion complexes of the Wartsila type, which operate on two types of fuel, gas and diesel. Gas-diesel generating units (GDGU) produce electricity to ensure the electric movement of gas carriers. The Wartsila 50DF gas-diesel unit is most often used on gas carriers – it is a four-stroke, non-reversible, diesel engine with turbocharging and an intercooler, with direct injection of liquid fuel and indirect injection of gas fuel [1]. The engine can be operated in gas or diesel mode.

For the safe transportation of liquefied gases, it is necessary to stabilize the gas pressure in cargo tanks. The system must react stably to possible effects of pressure changes in the cargo tank, supply of cargo vapors to low-pressure consumers (diesel generators, gas re-liquefaction units, steam incinerators). Considering the lack of experience in the operation of the mentioned propulsive complex in the world fleet, the theoretical analysis of the safety and efficiency of gas supply systems is an urgent problem.

One of the most important problems arising during the transportation of liquefied gas by sea is, on the one hand, ensuring the safety of transportation, survivability and unsinkability of the vessel, which makes it necessary to dispose of the vapor fraction of liquefied gas. On the other hand, the problem of reducing fuel consumption and its more efficient use is also relevant. Both problems can be solved thanks to the introduction of gas-diesel generator units (GDGU), which are able to work on both liquid and gaseous fuel. The fuel system of such vehicles requires more advanced control systems that implement more complex control algorithms.

When developing engines for LNG carriers, liquefied gas is already on board, and it is necessary to use boiled-off gas (BOG) as fuel. Then the gas supply system must provide gas from the cargo tank to the main engine and generators operating on two types of fuel. The gas supply system should also provide for the supply of gas to the gas combustion unit (GCU) in case of high gas pressure in the tanks, approaching the permissible limit value.

A dual-fuel gas-diesel engine is a conventional diesel engine with additional devices for working with gas fuel.

In the dual-fuel gas-diesel mode, two fuels – the main diesel fuel (but in a significantly smaller amount) and the additional one, substitute gas, are supplied to the engine. At the same time, the main diesel fuel plays the role of a "fire-starting" dose for igniting the integral gas-air fuel mixture.

Analysis of recent research and publications

The degree of replacement of diesel fuel by gas is the most important indicator of engine operation in gas-diesel mode. The value of the degree of substitution can vary widely from 40% to 85% for methane and from 15% to 50% for liquefied hydrocarbon gas [2].

The fact is that starting the engine and its operation in the mode of small loads (up to 20% of the maximum) is carried out almost on pure diesel fuel, because in this mode it is very difficult to choose stable gas supply parameters.

Further, as the load increases (approximately to 70–80%), comes the most favorable section for the gas-diesel mode, the degree of substitution of gas for diesel fuel in this section is maximum and can reach 85%. However, in order to maintain the design thermal regime of the engine, it is necessary to set aside some diesel fuel consumption for cooling the fuel injectors.

When the engine reaches full power and maximum revolutions, the time of the duty cycle decreases and the gas simply does not have time to burn and the gas-diesel control system has to reduce its supply. For practical calculations, you can use the guaranteed degree of substitution of 50–60% for engines for methane and 20-50% for propane.

Due to the higher coefficient of performance, methane consumption is approximately 1.1–1.4 m^3 per 1 liter of the replaced diesel fuel (in a 100% gas engine 1.3–1.8 m^3 = 1 liter of the diesel fuel).

Aim of the Study

The article aims to develop and analyze a mathematical model of a ship dual-fuel gas-diesel generator unit, incorporating the effects of the turbocharger, nonlinear properties, and real parameters of the fuel supply system, to optimize the regulator parameters for enhancing voltage and frequency stability in the ship's electrical power system (SEPS) under sharply varying loads.

Presentation of the Main Research Material

A successful solution to the complex automation problems of the ship electrical power system (SEPS) is connected with the need to take into account the influence of a large number of diversely acting factors that meet the requirements of increasing reliability and improving technical and economic indicators. A modern approach to the design and implementation of automated control systems is the use of a three-level hierarchical architecture. This will allow, in addition to the direct control of the electric power system, to accumulate statistical data on the modes of operation of consumers and electricity generators, which can be used to formalize the behavior of consumers in order to highlight the characteristic modes of operation of the power plant, reconfiguration of the SEPS in order to increase the optimality of the use of generating units, evaluation of the SEPS operation after the application of measures regarding increasing its energy efficiency. In order to ensure the electromagnetic compatibility of electrical networks of power supply systems and electricity consumers, it is also necessary to control the quality of electricity in SEPS [3].

The experience of testing and operation of electric power systems shows that during the parallel operation of generator units (GUs) in individual modes, instability is manifested in the form of undamped rotor oscillations.

In order to build highly efficient active power distribution systems in the presence of constant disturbing influences (random load connections/disconnections), as well as due to inherent fluctuations in the frequency of rotation of the shafts of the drive motors, it is necessary to determine the type and parameters of the dynamic model of the GDGU with sufficient accuracy for practice [4]. The general dynamic model of the GDGU contains both mechanical and electrical parameters. However, since electrical processes in the generator in the absence of excitation control occur many times faster than mechanical ones, their general influence on the dynamics of the system can be ignored.

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

In accordance with the description of the work of the GDGU, Fig. 1 shows a structural diagram that reflects the characteristic of the work of the GDGU both in statics and in dynamics.
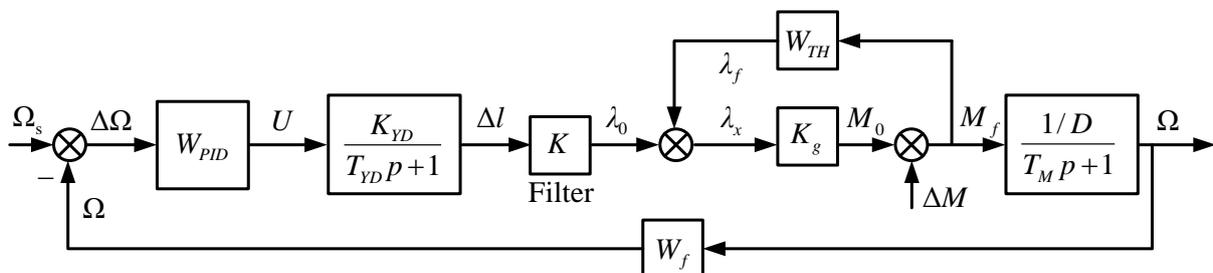

Fig. 1. Structural diagram, which reflects the characteristic of the work of the GDGU

The PID controller is conventionally represented by a transfer function W_{PID}. It forms the frequency response of a single-loop closed system. 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. Actually, GDGU is presented in the form of two links. The amplifying link K_g, which reflects the transformation of the gas-air mixture flow into the moment on the shaft M, and the inertial link of the first order, which establishes the relationship between the revolutions on the shaft and the value of the moment.

A special feature of this dynamic model is taking into account 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 amplification factor, which covers the actual first link of the diesel engine with positive feedback. The power output 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.

When the load is applied, the momentarily achieved output moment is $M_f = M_0 - \Delta M$, which is supplied to the last link, as a result of which, according to the time constant (T_{E}/D), the engine revolutions decrease. A decrease in torque will lead to a decrease in signals, which leads to an additional decrease in torque M_f. This strengthens the transition process. Therefore, the revolutions continue to decrease until, with the help of the main feedback, the appropriate opening of the valve and an increase in the amount of gas-air mixture is provided.

When the load is dropped, the reverse process takes place – the process of increase $M_f = M_0 + \Delta M$. The engine speed starts to increase. At the same time, an increase of M_f leads to a growing λ_f and, accordingly, $\lambda_x = \lambda_0 + \lambda_f$. This corresponds to an additional growth M_f and, accordingly, engine revolutions Ω.

Let us consider the optimization of the regulator parameters for the gas-diesel generator unit. Figure 2 shows the dynamic model of the GDGU with the set parameters close to the physical ones for the considered machines. It can be seen from the figure that the GDGU itself is represented by three serially connected links with a rather large amplification factor. The link with positive feedback takes into account the influence of the turbocharger [5].
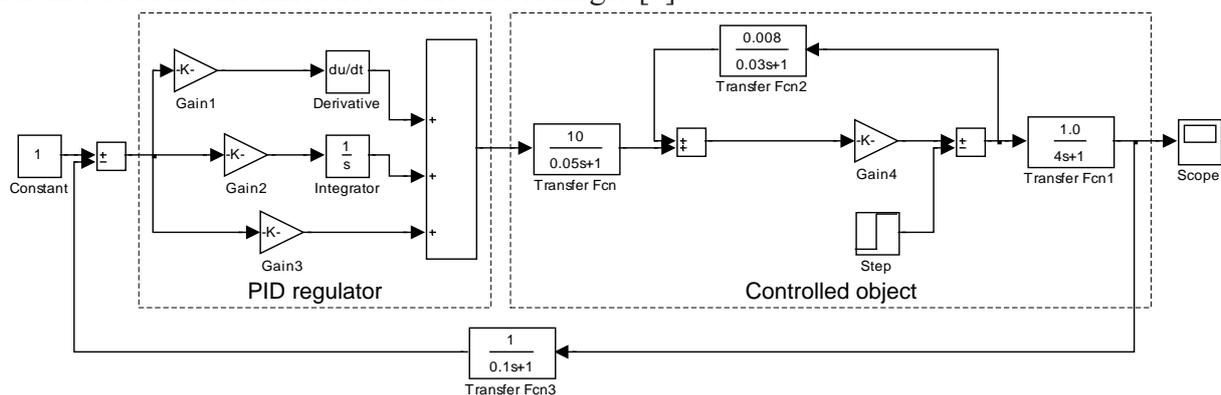

Fig. 2. Dynamic model of GDGU

The parameters of the dynamic model of the GDGU are determined using methods of identification and further tuning for the adequacy of the transition processes of dropping/connecting the load, as well as for control.

In relation to the PID regulator, the GDGU is the object of regulation. The dynamic properties of the object of regulation in terms of controlling and disturbing influences are characterized by

the curve of the transition process, and reflect the oscillatory nature of the processes with their own frequency and coefficient of oscillation.

It is obvious that 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 damping of the system that excludes the appearance of oscillatory processes in the output parameter.

From the analysis of logarithmic amplitude-frequency characteristics (LAFC) it follows that the regulator should be tuned not at the nominal power of the generator, but at the minimum power [4]. In this case, an increase in the load due to a decrease in the amplification factor will lead to an increase in the stability margin.

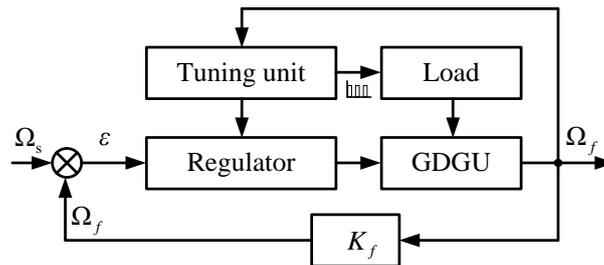Figure 3 shows the structural diagram of the control system, which includes a self-tuning regulator [2].

Fig. 3. Structure of the GDGU control system with auto-tuning of the regulator

Figure 3 illustrates: Ω_s – set speed, Ω_f – actual speed, ε – error signal. The basis of the system is a digital PID controller.

The regulator tuning works as follows. The operator sets the requirements for the system. The regulator tuning unit generates forms a 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 precise tuning of the regulator (reducing the impact of measurement error), connection and disconnection of the load is performed for each point a specified number of times. Identification of the control object is performed according to the experimental transient characteristic.

Control signals such as start, stop, fuel select and emergency are connected via hard-switched lines to ensure safe operation even if the external data bus fails while the engine is running.

The electronic speed control system is integrated into the engine automation system. Load distribution can be based on standard static characteristics, or can be carried out independently by speed control nodes without statics. The last method of regulation usually refers to the isochronous type of load distribution. With isochronous load sharing, there is no need for load balancing, frequency tuning or generator load/unload control by the external control system.

In a static control system, each frequency control node increases its internal reference frequency if the node has detected an increase in the load on the generator. Reducing the frequency in the power grid with a large load in the system leads to the fact that all generators proportionally distribute the total increased load among themselves. Engines with the same statics and reference frequency distribute the load equally among themselves. Loading and unloading of the generator is carried out by adjusting the reference frequency of each speed control node. The amount of stat is standard 4%, that is, the difference in frequency between zero and maximum loads is 4%.

In the isochronous mode, the reference signal of the rotation frequency remains unchanged, regardless of the load level. Both modes, isochronous distribution and static, are standard in speed control systems, that is, it is possible to select either. If the vessel has several distribution sections with circuit breakers between sections, the state value of each circuit breaker is required to control the load distribution in isochronous mode.

Additionally, the control and safety system or the power failure detection system can force the engine to operate in reserved mode (diesel fuel supply only).

It is possible to switch the running engine from gas mode to diesel mode. When working up to a certain load limit, the engine can be switched from working on diesel fuel to working on gas normally. In certain situations of activation of the alarm system, the engine is automatically switched from gas operation mode to diesel operation mode (disconnection of gas supply). A request to run on diesel always blocks a request to run on gas.

The control and safety system forcibly transfers the engine to reserved mode (regardless of the operator's choice of mode) in two cases:

– a malfunction was detected in the ignition fuel system (disconnecting ignition fuel);

– the engine starts when the signal of the absence of power supply is active (signal from an external system).

Control of the switching between gas and diesel fuel modes:

1. The switching from gas operation mode to diesel fuel operation mode is performed at any load within 1 second. The transition can be performed in three ways: manually, by the engine control system or by the gas safety system (gas mode blocking).

2. The switching from diesel fuel mode to the gas operation mode is carried out when the engine load is below 80%, if there are no signals of the gas mode blocking, in case of ignition fuel blocking and the engine was not started in the power supply absence mode (in which the combustion check is excluded).

It is not recommended to switch to gas operation mode at low loads. Switching to gas usually takes about 2 minutes to minimize the possibility of damage to the gas supply system.

The engine can run in the mode of no power supply, if it was started on an active power supply cutoff input signal or if there was a cutoff of the ignition fuel supply.

The switching to gas operation mode can be made only after checking the fuel combustion, which is possible only when the engine is restarted.

Checking gas leakage in gas control unit is performed automatically before each transition to gas fuel.

Conclusions

The structure and features of the technical use of the equipment of the control system of Wartsila dual fuel units are considered. A mathematical model of a gas-diesel generator unit is considered, which takes into account the influence of the turbocharger, nonlinear properties and real parameters of the fuel supply system. The optimization of the parameters of the regulators, which ensure an effective increase in the stability of the voltage and frequency in the SEPS grid at sharply changing loads, has been carried out.

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