Improving energy performance power station of ship with integrated electric propulsion

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Abstract. The article presents the method of calculating the power plant fuel consumption on the basis of diesel-generating installation (DGI) with variable speed for ships with integrated electric propulsion. Application DGI with variable speed allows saving fuel and therefore reducing harmful emissions into the atmosphere. In the paper calculated the fuel efficiency of unified power station on the basis of a variable speed DGI power of 1000 kW.

1 Introduction

On water transport are increasingly using integrated electric propulsion. This propulsion motors (PM) can be supplied together with other consumers from a unified power station (UPS). Application UPS simplifies maintenance and improves the reliability of the energy system of autonomous object by reducing the total number of system elements. The primary engine UPS widely used internal combustion engines (ICE).

As a rule, UPS are based on diesel DGI of constant rotation speed rotation. The electric power station gain in performance is possible due to variable speed rotation of DGI application. Fuel saving in this case is performed by setting for each load power value the optimal ICE shaft rotation frequency corresponding to the minimal fuel-consumption rate [1, 2].

The UPS - DGI with variable speed rotation is a relatively new technical trend in small power. Research this systems carried out several foreign companies such as Fubag, Honda, Hyundai, Kypor, ABB, Wartsila etc. In Russia research carried out – JSC "R&D Center for power engineering" (Moscow), JSC "ZVEZDA" (St. Petersburg), JSC "Sigma" (Kovrov), VSUWT and NNSTU (N.Novgorod).

The use of UPS - DGI can reduce the absolute and relative Fuel consumption and ensure optimal thermal operation of DGI, improve service life and reduce the amount of harmful emissions into the atmosphere.

2 Fuel saving calculation of UPS with variable speed rotation

Determination the relative and absolute indexes of fuel consumption of UPS with a variable frequency of rotation DGI has been carried out as shown by UPS ship with electric propulsion [4]. The calculation takes into account the energy loss of each element of the power structure of the UPS (fig. 1) when the load power changing over the entire range. On fig. 1 energy diagram, where G - absolute fuel consumption rate, P_m – power of DGI, P_{SG} - power of SG, P_{FC} – power of frequency converter, P_T – power of transformer, ΔP_m, ΔP_{SG}, ΔP_{FC}, ΔP_T – power loss.

It should be noted that the change load power in UPS causes a change speed shaft of DGI [3]. When calculating UPS efficiency it is taken into account those electrical equipment elements, comprised in UPS with a variable frequency of rotation DGI (synchronous generator (SG), PM, transformer (T), frequency converter (FC)) operate at variable frequency and voltage range. The ICE fuel consumption rate is determined according to the multivariate ICE characteristic [1].
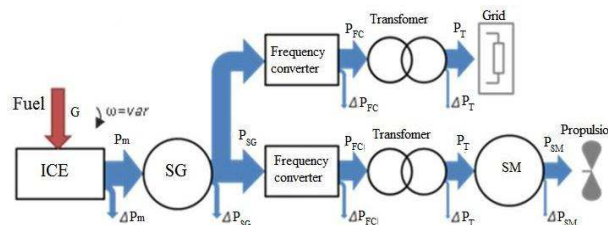

Figure 1. Energy diagram of power circuit UPS with variable speed DGI.

3 UPS elements efficiency calculation

To calculate the efficiency of the UPS are used depending on the efficiency of the voltage frequency for each power element of UPS.

3.1. Efficiency of synchronous machine

The synchronous machine efficiency (SM) is determined through the following equations

$$\eta_{SM} = 1 - {p_\Sigma}\big/{P_1},$$
$$p_\Sigma = p_i + p_b + p_c + p_{add} + p_{mech},$$
$$p_{add} = 0{,}005 P_1 \left(\frac{I_1}{I_{1n}} \right),$$
$$p_i = p_{1,0/50}(f/50)^\beta K (B_{s1}^2 m_{s1} + B_{s2}^2 m_{s2}),$$
$$p_b = U_b I_f,$$
$$p_c = m_1 I_1^2 r_1 m_t + m_2 I_2^2 r_2 m_t,$$
$$p_{mech} = 8(n_1/1000)^2 (D_1/100)^3. \tag{1}$$

In (1) are used η_{SM} – synchronous machine efficiency P_1 – power consumption, p_Σ – total losses in a machine, p_i – iron losses, p_b – brush friction losses, p_c – copper losses, p_{add} – additional losses, p_{mech} – mechanical losses, $p_{1,0/50}$ – specific magnetic losses, f – stator voltage frequency, B_{s1}, B_{s2} – induction corresponding to stator finger and lamination, K – correcting coefficient, β — coefficient, considering the steel losses dependency on the magnetization ratio; m_{s1} — stator finger mass; m_{s2} — stator lamination mass, r_1 – effective resistance of stator coil phase, m_t – ratio considering the coil heat.

Fig 2 shows the efficiency dependencies on stator primary voltage frequency for a synchronous machine MCK1250-1500 ($P_N = 1000$ kW, $n = 1500$ min^{-1}). The dependencies correspond to load power $P_1 = 0{,}25 P_N$; $0{,}5 P_N$; $0{,}75 P_N$; P_N.
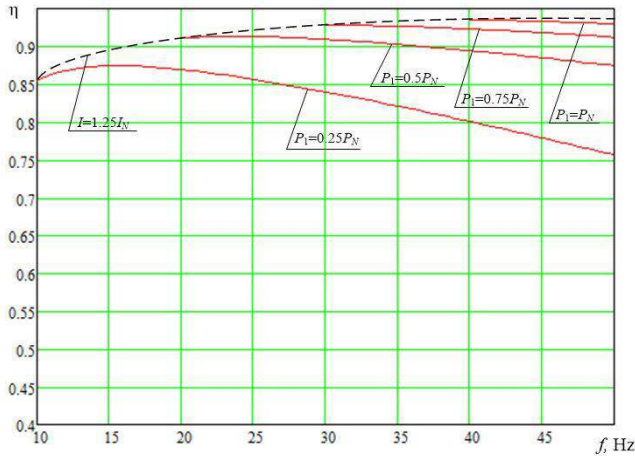

Figure 2. Dependency of MCK1250-1500 SM efficiency on frequency of power voltage at variable power P_1.

According to [1] synchronous machines of MCK series the operate duration at stator current $I=1{,}25I_N$ is not to exceed 0,5 h. Fig.2 and the following ones the dotted line limits the area of currents control $I \le 1{,}25I_N$.

3.2. Efficiency of transformer

The transformer efficiency is determined by mainly the following equations

$$\eta_T = 1 - {p_\Sigma}\big/{P_1},$$
$$p_\Sigma = p_{w1} + p_{iT} + p_{w2},$$
$$p_{iT} = v'(f/50)^\beta B^\alpha G_c, \tag{2}$$
$$p_{w1} = m I_1^2 r_1 m_t,$$
$$p_{w2} = m I_2^2 r_2 m_t.$$

In (2) the following notations are used η_T – transformer efficiency; p_Σ – total losses, p_{w1}, p_{w2} - electrical losses ones in winding, p_{iT} – steel losses, v'- specific steel losses [1, 5], G_C –core steel mass, m – the transformer phase number, m_t – coil heat ratio; I_1, I_2, r_1, r_2 – respectively currents and resistance values of primary and secondary transformer windings.

Fig.3 shows dependencies of the efficiency of voltage frequency of transformer TC3M 1000-75.OM5.
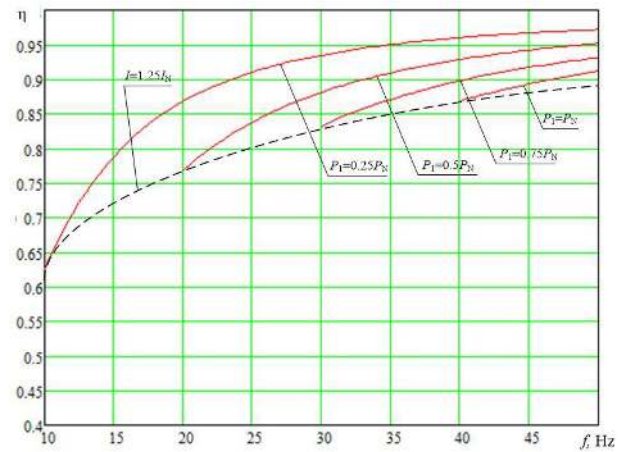

Figure 3. Dependency of transformer efficiency TC3M 1000-75.OM5 of supply voltage frequency.

3.3. Efficiency of frequency converter

Frequency converter (Fig. 4) efficiency as shown are calculated according to the following equations

$$\eta_{FC} = \eta_{rec} \eta_{pwc} \eta_{f1} \eta_{inv} \eta_{f2},$$
$$\eta_{rec} = \frac{P_d}{P_d + \Delta P_{rec}}, \Delta P_{rec} = \Delta P_{sem} + \Delta P_{sub},$$
$$\Delta P_{sem} = (U_{T0} I_{Fav} + r_T k_\phi^2 I_{Fav}^2) \cdot 6,$$
$$\Delta P_L = R_L I_D^2, \eta_{f1} = \frac{P_d}{P_d + \Delta P_L}, \tag{3}$$
$$\Delta P_{IGBT} = P_D + P_{SW} + P_{DF}, P_D = I_{cav} U_{CE}(I_c),$$
$$P_{SW} = E_{ts} f, P_{DF} = I_{FM} U_{FM}.$$

In (3) are used η_{FC} – efficiency of frequency converter, η_{rec} – efficiency of rectifier, η_{pwc} – efficiency of pulse-width converter, $\eta_{f1,2}$ – efficiency of filter, η_{inv} – efficiency inverter, P_d – active power at the rectifier outlets, ΔP_{rec} – rectifier losses, P_{sem} - semi-conducting equipment devices losses, ΔP_{sub} – cooling system, system protection and control system losses, $\Delta. P_{FAV}$ – diode losses resulting from direct current flow I_{FAV}, k_ϕ – current form ratio, r_T – differential resistance, U_{T0} – threshold voltage, ΔP_L –filter inductance losses, ΔP_{IGBT} – IGBT

losses, P_D - dynamic in IGBT transistor losses, P_{SW} - static in IGBT transistor losses, P_{DF} - built-in IGBT diode losses, I_{CAV} – the average impulse current conductivity collector value, $U_{CE(lc)}$ – saturation voltage at the given collector current , E_{ts} – total energy losses at the collector losses current together with block drive circuit , I_{FM} – diode average current; U_{FM} – diode voltage at current I_{FM}.
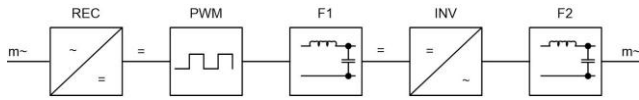

Figure 4. Flowchart of UPS frequency converter: rec – out-of-control rectifier, PWM – pulse width converter, F1, F2 – filters, Inv – stand-alone inverter.

Fig. 5 shows the dependencies of the efficiency of voltage frequency for the frequency converter having the nominal power 1000 kW.
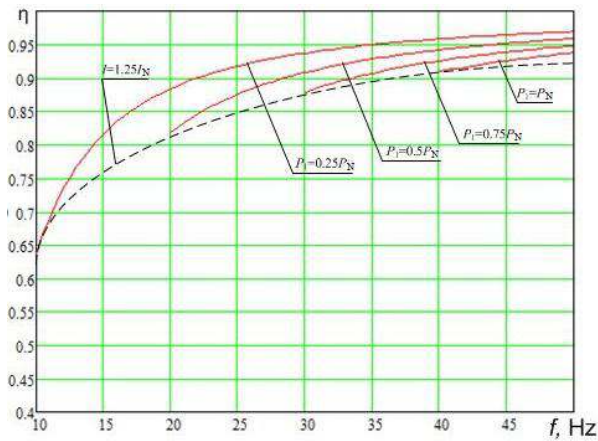

Figure 5. The dependence of the efficiency of the frequency converter power 1000 kW from the utility power frequency.

4 UPS fuel economy estimate at load power «propulsion engine»

Installed power of the SM is the sum propulsion power and the onboard ship power (fig. 1).

Fuel consumption of ICE is calculated in a range of screw-propeller (SP) speeds from 75 to 300 min^{-1} in increments of 25 min^{-1}.

To determine the ICE fuel consumption is used multivariable characteristic [6, 7]. ICE with a nominal speed of 400 min^{-1} and a power 1100 kW is selected to perform the calculations [1].

The shat moment on the SP is determined according to the equation

$$M = K\rho n^2 D_p^5 \qquad (4)$$

where K –torque coefficient SP, ρ – medium density, n – frequency of rotation SP, D_p – diameter SP.

The supply voltage frequency SM is determined through the expression

$$f = f_0 \frac{n_{SP}}{n_{SP\_0}} \qquad (5)$$

where f_0 – nominal frequency SM, n_{SP} – current frequency SP, n_{SP_0} – nominal frequency of DGI.

Determine the efficiency of the FC, T, SM for each specified speed of SP.

The power SM is determined through the following equation

$$P_{SM} = P_{SP}/(\eta_{SM} \cdot \eta_{FC} \cdot \eta_T). \qquad (6)$$

There have been obtained the graphs of specific fuel consumption rate (G_e) on the SP rotation (n) for the two UPS modes with the controlled and uncontrolled DGI (Fig. 6-9). The obtained figures show UPS with the controlled rotation frequency of DGI as compared to UPS without frequency control of DGI.
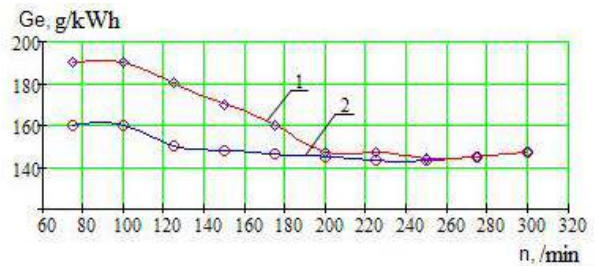

Figure 6. ICE fuel consumption rate of UPS power 1000 kW: 1 –without regulation of speed DGI, 2 – with frequency regulation of speed DGI.
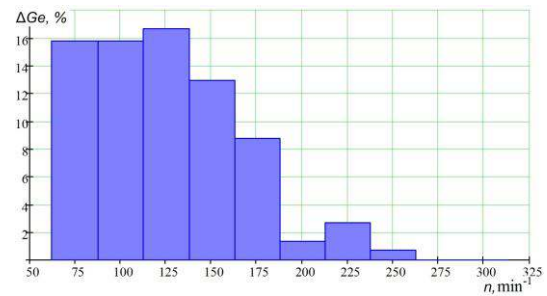

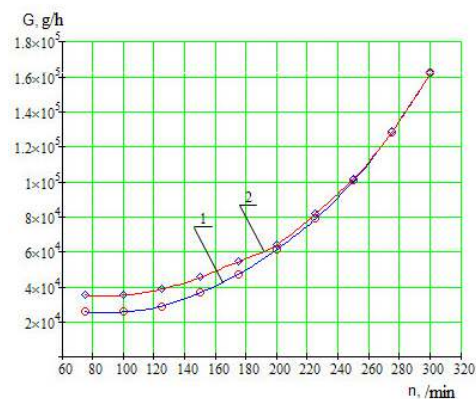**Figure 7.** ICE fuel consumption rate UPS powered by 1000 kW.

Figure 8. ICE absolute fuel consumption of UPS powered by 1000 kW: 1 – with the regulation of frequency DGI; 2 – without the frequency regulation of DGI.
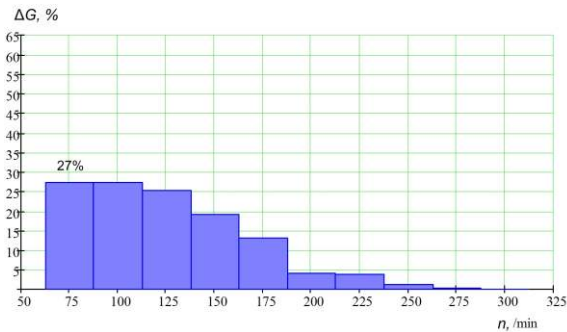
Figure 9. Absolute fuel consumption of ICE in UPS of 1000 kW.

In absolute fuel consumption UPS with regulation frequency of DGI economical system without regulation by 25-27%.

5 UPS calculation of fuel economy considering at the SM control

The above characteristics of specific and absolute fuel consumption rate have been obtained without taking into account SM excitation control. To enhance the economy of UPS, it is necessary to control the SM with respect to load power as related to the expression [1, 8, 9]

$$i_{ex} = \sqrt{\frac{1 + p_1^2 x_d^2 + 2 p_1 x_d \sqrt{1 - \cos^2 \varphi}}{1 + x_d^2 + 2 x_d \sqrt{1 - \cos^2 \varphi}}} \qquad (7)$$

where $i_{ex} = I_{ex}/I_{ex\_nom}$, $p_1 = P_1/S_{NOM.}$

As shown in graphs (Fig.10, 11), at the excitation control (Fig.10, curves 1,3), the fuel consumption rate increases by the range of light and average loads.
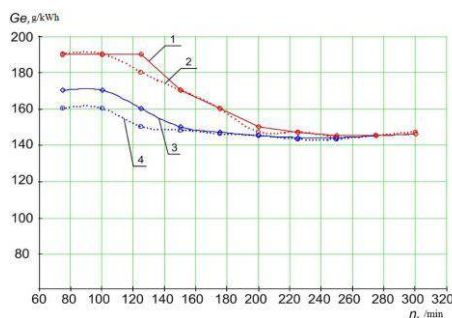

Figure 10. ICE average consumption rate of UPS power 1000 kW: 1,2 –without the speed regulation of DGI; 3,4 - with speed regulation of DGI; 1,3 – with regulation current excitation of SM; 2,4 – without regulation current excitation of SM.
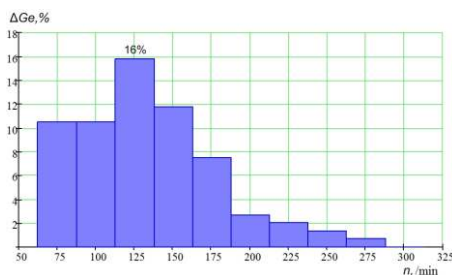

Figure 11. The ICE fuel consumption rate economy in UPS power 1000 kW with SM excitation control.

According to a multivariate characteristic, within the range of ICE light loads is displaces into the range of higher fuel consumption rate. The fuel calculation data are shown in fig.12, 13.
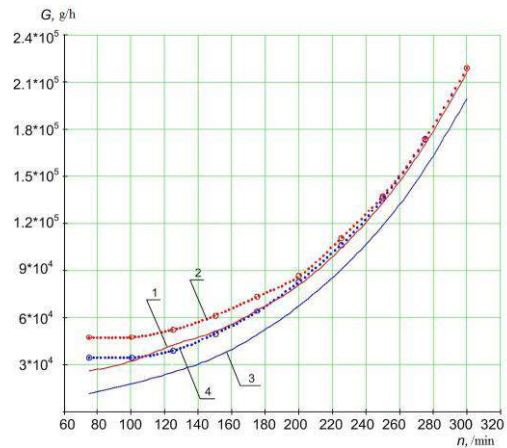

Figure 12. Absolute fuel rate consumption of ICE in UPS: 1,2 – without regulation speed of ICE, 3,4 – with speed regulation of ICE, 1,3 – with regulation current excitation of SM, 2,4 – without with regulation current excitation of SM.
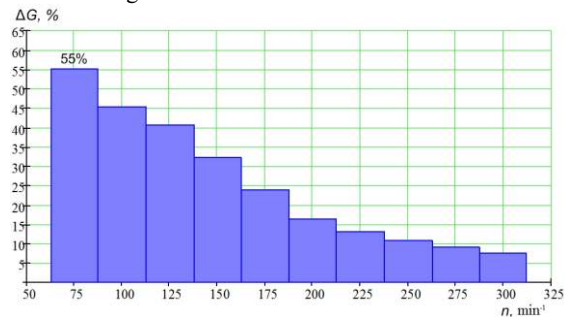

Figure 13. . Absolute fuel consumption of ICE in UPS power 1000 kW with regulation current excitation of SM.

6 Conclusion

Application UPS on the variable speed of ICE allows to efficiently economizing fuel consumption rate and reduces air emissions. Providing optimal mode of ICE in terms of fuel efficiency requires a new approach to the fuel supply control and can be implemented on modern management tools, including intelligent neural network-type control systems.

In the paper calculated the fuel efficiency of unified power station on the basis of a variable speed DGI power of 1000 kW. On the basis of the calculation results obtained by the comparative characteristics of the specific and absolute fuel consumption for the two modes of operation: a speed control of rotation DGI, depending on the load and a constant frequency of rotation of the DGI. In UPS of 1000 kW fuel savings can be up to 31% in absolute consumption.

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