Analytical Methods of Destabilizing Factors of Improving the Technical Systems Efficiency

A. Zhilenkov, A. Nyrkov, S. Chernyi and S. Sokolov

Abstract—According to the Navy Register rules, ship electrical power system voltage fluctuations within ±10% of the nominal voltage are admissible if not lasting longer than 5 seconds; longer fluctuations are admissible if they are within ±5% of the nominal voltage. For the operation of a rotational speed Automatic Control System with a sliding-mode regulator, there is no need to identify the diesel and propeller parameters; however, one needs a quantitative assessment of the limits within which such parameters could change. To implement the algorithm of such sliding-mode regulator, it is enough to control the rotational speed deviation for the specified value

Keywords— fluctuations; shaft generators; automatic control system; algorithm; diesel.

I. Introduction

When the dynamic characteristics of the ship propeller, the generator, the main engine (ME), or the rotation frequency regulator wear are changed, the free component of the main shaft rotational speed transient process is changed as well. If the ship is equipped with shaft generators (SG), such changes result in the fluctuations of the voltage they generate. Experimental studies identified [1] that the real transient process of ME rotational speed frequency changes is accompanied by large-amplitude fluctuations in exceed of 10% and 5 seconds depending on the navigation conditions. If the transient process lasts longer than 5 seconds, there emerges a risk of SG desynchronization, which is why SG are not enabled for constant parallel operation with the diesel generators of the ship power plant, especially in storms. On the other hand, such SG and DG parallel operation is cost-effective as it reduces the *kWh* costs of ship power, reduces fuel consumption, and increases the service life of the additional power plants [2].

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II. Solution of problem

To enable the shaft generator for long parallel operation with the diesel generators of the ship power plant, one has to reduce the fluctuations in the shaft generator rotational speed (the diesel rotational speed) and the torque angle under the effect of the destabilizing factors. When operating the ME, it is impossible to identify the diesel and propeller parameters affecting the dynamic characteristics of the loaded ME under various conditions of ship navigation. Under such ME operating conditions, the dynamic characteristics of the rotational speed Automatic Control System (ACS) can be stabilized by adaptive controls this paper proposes, which are based on a sliding-mode regulator. For the operation of a rotational speed ACS with a sliding-mode regulator, there is no need to identify the diesel and propeller parameters; however, one needs a quantitative assessment of the limits within which such parameters could change. To implement the algorithm of such sliding-mode regulator, it is enough to control the rotational speed deviation for the specified value.

Below is the equation of the dynamics of the ME rotational speed ACS in the parallel operation of SG and power plant generators:

$$\begin{aligned}\Delta\omega = {} & K_{T3}\cdot\frac{1+T_{\kappa}\cdot p}{1+T_{\kappa}\cdot K_{\kappa}\cdot p}\cdot\frac{1}{Jp+F_{\partial}}\cdot\Delta h-\left(\frac{\partial M_{\text{г}}}{\partial R_{\text{н}}}\right)_0\cdot\frac{1}{Jp+F_{\partial}}\Delta R_{\text{н}}- \\ & -\left(\frac{\partial M_{\text{г}}}{\partial x_{\text{н}}}\right)_0\cdot\frac{1}{Jp+F_{\partial}}\Delta X_{\text{н}}-\left(\frac{\partial M_{\text{г}}}{\partial i_f}\right)_0\cdot\frac{1}{Jp+F_{\partial}}\Delta i_f-a_1\cdot\frac{1}{Jp+F_{\partial}}\frac{\Delta H}{H_0}+ \\ & +a_4\cdot\frac{1}{Jp+F_{\partial}}f(t)-\left(\Delta M_{sk}+\Delta Q\right)\frac{1}{Jp+F_{\partial}}\end{aligned} \quad (1)$$

Where $a_1=\dfrac{h_0\cdot K_{T3}}{D\cdot 6{,}28\cdot n_{diz}}$; $a_4=\dfrac{M_{eo}}{6{,}28\cdot n_{diz}}$,

$$\Delta M_{\text{винт}}=a_1\cdot\frac{\Delta H}{H_0}-a_4\cdot f(t) \quad (2)$$

h_0, M_{eo} are the initial conditions on the position of the control rack and the diesel torque; $n_{diz}=428$ *rpm*; $J=610\ldots678$ $kg\cdot m^2$ is the total moment of inertia of the ME, the flywheel, the SG, the propeller shaft, the propeller; partial derivatives are calculated per formulas

$\left(\frac{\partial M_{\text{г}}}{\partial \omega}\right)_0$, $\left(\frac{\partial M_{\text{г}}}{\partial X_{\text{н}}}\right)_0$, $\left(\frac{\partial M_{\text{г}}}{\partial i_f}\right)_0$, $\left(\frac{\partial M_{\partial}}{\partial \omega}\right)_0$, $K_{T\text{З}}$; $\frac{\Delta H}{H_0}$ is the relative change in the propeller pitch; H_0 is the initial propeller pitch condition; *f(t)* is the equation taking into account the nature of propeller shaft resistance moment under storm conditions:

$$f(t) = 2\cdot\frac{\Delta\omega}{\omega_0} - \left(\frac{\Delta\omega}{\omega_0}\right)^2 + \left(1 - \frac{\Delta\omega}{\omega_0}\right)\cdot\left[\gamma_a\cdot\left(1-m_a\right) - \gamma_a\cdot\frac{\Delta\omega}{\omega_0}\right]\cdot\sin\left(\Omega\cdot t\right).$$

III. Preliminary generator block calculations

Calculate the partial derivatives of the generator moment based on various signals. On speed:

$$\frac{\partial M_{\text{г}}}{\partial \omega} = \frac{M_{\text{ном}} H^2 \left(i_f X_{ad} K_\mu K_\omega\right)^2 R_{\text{н}d}}{\left(X_{q\text{н}} X_{d\text{н}}\left(\frac{\omega}{\omega_c}\right)^2 + R_{s\text{н}dq}\right)^3}\cdot$$
$$\cdot\left(\left(3X_{q\text{н}}^2\frac{\omega^2}{\omega_c^3} + \frac{R_{s\text{н}dq}}{\omega_c}\right)\left(X_{q\text{н}} X_{d\text{н}}\left(\frac{\omega}{\omega_c}\right)^2 + R_{s\text{н}dq}\right) - \quad (3)$$
$$-4X_{q\text{н}} X_{d\text{н}}\frac{\omega}{\omega_c^2}\left(X_{q\text{н}}^2\left(\frac{\omega}{\omega_c}\right)^3 + R_{s\text{н}dq}\left(\frac{\omega}{\omega_c}\right)\right)\right),$$

On the active load resistance:

$$\frac{\partial M_{\tilde{a}}}{\partial R_{\acute{\imath}}} = \frac{M_{\text{íîì}} H\left(i_f X_{ad} K_\mu K_\omega\right)^2}{\left(X_{q\acute{\imath}} X_{d\acute{\imath}}\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^2 + R_{s\acute{\imath}\,dq}\right)^4}\cdot$$
$$\left[\cdot\left\{\begin{matrix} K_d X_{d\acute{\imath}}^2\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^3 + \left[R_s + R_{\acute{\imath}} K_d\right]\left(\frac{\omega}{\omega_{\tilde{n}}}\right) \\ \left(R_s\left(2K_d + K_q\right) + 3R_{\acute{\imath}} K_d K_q\right)\end{matrix}\right\}\cdot\right.$$
$$\cdot\left(X_{q\acute{\imath}} X_{d\acute{\imath}}\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^2 + R_{s\acute{\imath}\,dq}\right)^2 - 2\left(X_{q\acute{\imath}} X_{d\acute{\imath}}\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^2 + R_{s\acute{\imath}\,dq}\right)\cdot \quad (4)$$
$$\cdot\left[R_s\left(K_d + K_q\right) + 2R_{\acute{\imath}} K_d K_q\right]$$
$$\left.\left[R_{\acute{\imath}\,d} X_{d\acute{\imath}}^2\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^3 + R_{s\acute{\imath}\,dq} R_{\acute{\imath}\,d}\left(\frac{\omega}{\omega_{\tilde{n}}}\right)\right]\right],$$

On the reactive load resistance:

$$\frac{\partial M_{\tilde{a}}}{\partial X_{\acute{\imath}}} = M_{\text{íîì}} H\left(i_f X_{ad} K_\mu K_\omega\right)^2$$
$$\left[\frac{2R_{\acute{\imath}\,d} X_{d\acute{\imath}} \hat{E}_d\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^3\left(X_{q\acute{\imath}} X_{d\acute{\imath}}\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^2 + R_{s\acute{\imath}\,dq}\right)^2 -}{\left(X_{q\acute{\imath}} X_{d\acute{\imath}}\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^2 + R_{s\acute{\imath}\,dq}\right)^4}\right.$$
$$-2\left(X_{q\acute{\imath}} X_{d\acute{\imath}}\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^2 + R_{s\acute{\imath}\,dq}\right)\left(X_{q\acute{\imath}} K_d + X_{d\acute{\imath}} K_q\right)$$
$$\left(\frac{\omega}{\omega_{\tilde{n}}}\right) R_{\acute{\imath}\,d} \qquad , \quad (5)$$
$$\left.\left(X_{d\acute{\imath}}^2\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^2 + R_{s\acute{\imath}\,dq}\right)\right]$$

On the current in the excitation winding:

$$\frac{\partial M_{\tilde{a}}}{\partial i_f} = 2i_f\left(X_{ad} K_\mu K_\omega\right)^2 R_{\acute{\imath}\,d} H$$
$$\frac{X_{q\acute{\imath}}^2\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^3 + R_{s\acute{\imath}\,dq}\left(\frac{\omega}{\omega_{\tilde{n}}}\right)}{\left[X_{q\acute{\imath}} X_{d\acute{\imath}}\left(\frac{\omega}{\omega_{\tilde{n}}}\right)^2 + R_{s\acute{\imath}\,dq}\right]^2} M_{\text{íîì}} \quad ,(6)$$

where $H = \frac{n}{n_{\partial\text{из}}}$ is the diesel generator gear ratio, *n* is the nominal rotational speed of the generator, rpm, $n_{\partial\text{из}}$ is the nominal rotational speed of the dieses, rpm.

IV. Calculating the partial derivatives of the diesel torque per the rotational speed and the control rack position

We are going to calculate the partial derivatives of the diesel dynamics based on the universal characteristics of a *8NVD48A2U* ship diesel near the point with $n_\partial = 350$ *rpm* (see Figure 1).

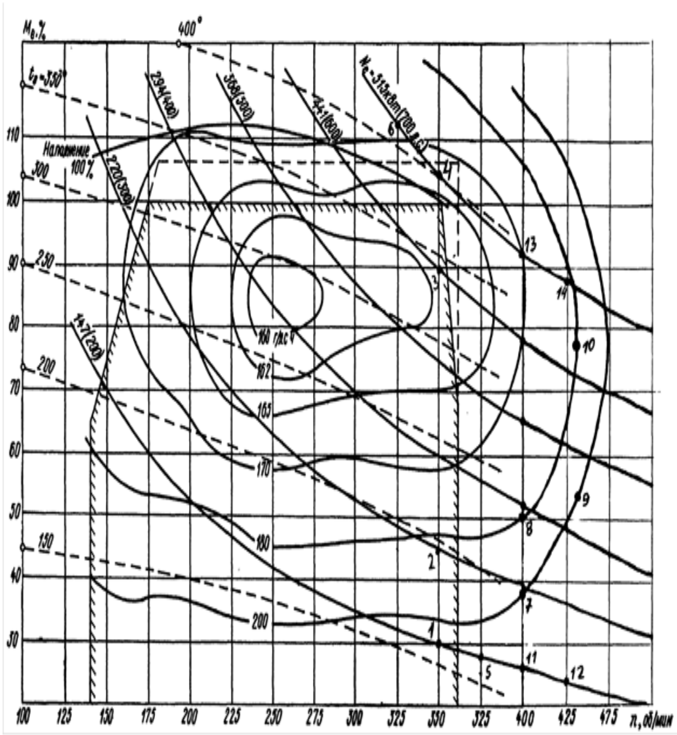

Fig. 1 structural plot

Derive the formula for calculating the partial derivative of the diesel torque based on the control rack position $\frac{\partial M_\partial}{\partial h} \approx \frac{\Delta M_\partial}{\Delta h} = K_{T3}$. The increment of the diesel torque is calculated as the difference between the actual diesel power values at a constant rotational speed:

$$\Delta M_\partial = \frac{N_{e2} - N_{e1}}{\omega_\partial}. \qquad (7)$$

From the power equation, the position of the control rack:

$$h = \frac{g_e N_e}{G_T} = \frac{g_e N_e}{c\omega_\partial^{\ 3}} \qquad (8)$$

Fuel consumption per hour:

$$G_T = c_4 \omega_\partial^{\ 3} = h \cdot c \cdot \omega_\partial^{\ 3}.$$

From equation (8), we obtain:

$$\Delta h = \frac{g_{e_2} N_{e_2} - g_{e_1} N_{e_1}}{c\omega_\partial^{\ 3}}. \qquad (9)$$

Divide (7) by (9):

$$\frac{\Delta M_\partial}{\Delta h} = \frac{c\omega_\partial^{\ 2}\left(N_{e2} - N_{e1}\right)}{g_{e_2} N_{e_2} - g_{e_1} N_{e_1}}. \qquad (10)$$

Coefficient c can be calculated based on the nominal engine specifications: $g_{еном1}=224$ g/kWh, $\omega_\partial=\omega_{\partial ном1}=36{,}6$ rad/s (350 rpm), $N_{еном1}=492$ kWh (670 hp), $h_{ном1}=0.04$ m,

$$c = \frac{g_{еном} \cdot N_{еном}}{h_{ном} \cdot \omega_\partial^{3}}. \qquad (11)$$

Substitute (11) in (10):

$$\frac{\Delta M_\partial}{\Delta h} = \frac{\left(N_{e2} - N_{e1}\right)}{g_{e_2} N_{e_2} - g_{e_1} N_{e_1}} \cdot \frac{g_{еном1} \cdot N_{еном1}}{h_{ном1} \cdot \omega_{\partial ном1}}. \qquad (12)$$

Minimum partial derivative value at $K_{emin}=0.8$:

$$\left(\frac{\Delta M_{ä}}{\Delta h}\right)_{min} = \frac{K_{emin}\left(N_{e41} - N_{e31}\right)}{g_{e_{41}} N_{e_{41}} - g_{e_{31}} N_{e_{31}}} \cdot \frac{g_{eíîì\ 1} \cdot N_{eíîì\ 1}}{h_{íîì\ 1} \cdot \omega_{äíîì\ 1}} = \frac{0{,}8\left(515 - 441\right)}{123 \cdot 515 - 120 \cdot 441} \cdot \frac{224 \cdot 492000}{0{,}04 \cdot 36{,}6} = 427317.$$

Maximum partial derivative value at $K_{emax}=1.04$:

$$\left(\frac{\Delta M_{ä}}{\Delta h}\right)_{max} = \frac{K_{emax}\left(N_{e21} - N_{e11}\right)}{g_{e_{21}} N_{e_{21}} - g_{e_{11}} N_{e_{11}}} \cdot \frac{g_{eíîì\ 1} \cdot N_{eíîì\ 1}}{h_{íîì\ 1} \cdot \omega_{äíîì\ 1}} = \frac{1{,}04\left(220 - 147\right)}{135 \cdot 220 - 151 \cdot 147} \cdot \frac{224 \cdot 492000}{0{,}04 \cdot 36{,}6} = 762000.$$

The gear ratio of the *8NVD48A2U* fuel link can change within these limits:

$$\frac{\Delta M_{\partial}}{\Delta h} = K_{T3} = 427317...762000 \quad (13)$$

Derive the formula for calculating the partial derivative of the diesel torque based on the rotational speed $\frac{\partial M_{\partial}}{\partial \omega_{\partial}}$:

$$\frac{\partial M_{\partial}}{\partial \omega_{\partial}} = \frac{\left(M_{e2\%} - M_{e1\%}\right)}{\left(\omega_{\partial 2} - \omega_{\partial 1}\right)100} \frac{N_{eном1}}{\omega_{\partialном1}} . \quad (14)$$

Minimum partial derivative value at $K_{emax}=1.04$:

$$\left(\frac{\partial M_{ä}}{\partial \omega_{ä}}\right)_{min} = \frac{K_{e\,max}\left(M_{e41\%} - M_{e61\%}\right)}{\left(\omega_{ä41} - \omega_{ä61}\right)100}$$

$$\frac{N_{eíîì1}}{\omega_{äíîì1}} =$$

$$= \frac{1,04\left(105-112\right)}{\left(36,6-34\right)} \frac{492 \cdot 10}{36,6} = -391$$

Maximum partial derivative value at $K_{emax}=0.8$:

The partial derivative of the *8NVD48* diesel torque, based on the rotational speed, changes within these limits:

$$\frac{\partial M_{\partial}}{\partial \omega_{\partial}} = -391...-83 . \quad (15)$$

Recalculate the partial derivatives for the *8NVD48A2U* diesel using the nominal data: $g_{еном2}=218$ g/kWh, $\omega_{дном2}=45$ rad/s (428 rpm), $N_{еном2}=970.2$ kW (1320 hp), $h_{ном2}=0.04$ m.

Conclusions

We have analytically obtained the qualitative assessments of the limits within which the diesel and propeller parameters could change depending on their technical condition. These data will be used in designing a sliding-mode regulator.

V. Reference

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